National Association of Broadcasters

ENGINEERING HANDBOOK

SEVENTH EDITION

E. B. Crutchfield, Editor
Manager, Technical Information Services

Department of Science and Technology
National Association of Broadcasters
Washington, DC

Copyright © 1985 by the National Association of Broadcasters.

All Rights Reserved.

Copyright 1935, 1938, 1946, 1949, 1960, 1975 by the National Association of Broadcasters. All rights reserved. Printed in the United States of America. No part of this book may be reproduced in any form or by any means without permission in writing from the National Association of Broadcasters, 1771 N Street, NW, Washington, DC 20036.

The content of manuscripts provided by individual authors to the National Association of Broadcasters for inclusion in this publication is solely the effort of those individuals. The National Association of Broadcasters is not responsible for and makes no claim as to the veracity of statements contained therein or any omissions thereto.

Library of Congress Cataloging in Publication Data
Main entry under title:

National Association of Broadcasters Engineering Handbook.

Includes bibliographies and index.
1. Radio—Transmitters and transmission. 2. Radio stations—Design and construction. 3. Television—Transmitters and transmission. 4. Television stations—Design and construction. I. Crutchfield, E.B. II. National Association of Broadcasters.
TK6561.N3 1985 621.3841 85-3023

ISBN 0-89324-000-1

TO THE BROADCAST ENGINEER

"Broadcast quality" is a term in which our industry can take great pride. It has come to be almost a generic phrase for excellence in the communications field, a tribute to the skill, inventiveness and stringent adherence to sound engineering principles of our broadcast engineers. The result in the United States is the most superb, high quality system of free over-the-air broadcasting in the world—the model upon which other nations develop their communications system.

Technology continues to advance at an awesome pace. Technical regulations are being swept away. It is our challenge and our responsibility to maintain the superior quality of our system and to develop even further in an increasingly competitive marketplace.

This new edition of the *NAB Engineering Handbook* takes into account the technological and regulatory changes since the book's last revision in 1975. We hope that broadcast engineers will find it a valuable resource as they seek to maintain the high standards of performance which our audiences have come to expect.

Edward O. Fritts
President, National Association of Broadcasters

FOREWORD

With publication of this 7th Edition, we mark the fiftieth anniversary of NAB's first *Engineering Handbook*, published in 1935. Those years have seen tremendous growth in our industry and extensive change in our technology, reflected in the development of this book from the slim, 100-page First Edition.

When the First Edition went to press, AM radio was well established and directional antenna technology was developing; television and FM radio were still experimental, and the Communications Act of 1934 had just gone into effect, replacing the Federal Radio Commission with the Federal Communications Commission. For five decades, then, the FCC developed regulations in greater number and detail to guide development of a broadcasting system serving "the public interest, convenience, and necessity."

In the new era of deregulation and "unregulation," the Commission has recognized that the broadcast industry has matured and has scrapped its technical rules, finding them burdensome, outdated, and unnecessary. It left the broadcaster with considerable freedom, but greater responsibility, for what to do, and how to do it, to stay in compliance with overall requirements.

Technology and regulation have changed, and the nature of the *Handbook* must change as well. The emphasis of this edition is less on quoting rules and more on providing the broadcast engineer with a tool to ensure that the best engineering practices are the norm at every radio and television station—in other words, that the lofty standards inherent in the term "broadcast quality" are maintained. With deregulation, we no longer have precisely defined operating procedures and routines imposed on us and cannot be content with simply meeting FCC requirements. As broadcasters, we are clearly challenged to develop voluntary standards to hold on to this freedom and to use it to our advantage. This means applying our skills and imagination not only to maintain technical compliance but to do so in a way that will benefit our stations, our industry and, most important, our audiences.

A primary responsibility of the NAB Department of Science and Technology is to assist the broadcast industry by gathering and making readily available broadcast technical information related to interference control, spectrum efficiency, compatibility and technical quality. The 7th Edition of the *Handbook* represents an important part of that effort and we are indebted to the many companies, members and associate members and the literally hundreds of individuals whose efforts have made this book possible. We welcome your comments and suggestions to help us develop updates and future editions of the *NAB Engineering Handbook*.

Thomas B. Keller
Senior Vice President, Department of Science and Technology
National Association of Broadcasters

EDITOR'S NOTES

USING THE HANDBOOK

If you are not familiar with this edition, please take a few minutes to read the following notes.

Purpose

The *NAB Engineering Handbook* is a general reference for all engineers and technicians working in broadcast stations as well as those working in related or similar facilities such as production, closed-circuit, and cable studios, and for engineering consultants and equipment manufacturers.

The authors are experienced engineers, active in the fields on which they are writing. Each was asked to review theory, where applicable, but to emphasize practical information such as design approaches and criteria, applications, and techniques for system planning, installation, operation and maintenance. We have tried to avoid, on the one hand, the highly theoretical information found in design textbooks and, on the other hand, the very detailed instructions found in manuals supplied with equipment. Some things, such as towers and transmission lines, do not usually come with instruction manuals, and there we have tried to provide more details.

The *Handbook* is not a primer. Some understanding of electronics and general engineering principles is expected, but the level depends on the subject matter of the individual chapter.

Organization

The material in this Handbook is divided into 7 sections.

Section 1. Procedures and Practices: Working with the Federal Communications Commission, frequency coordination committees and consultants.

Section 2. Antennas and Towers: Radiating systems, transmission lines, measurements and towers.

Section 3. Transmitters: Transmitters, subcarriers, remote control and measurements.

Section 4. Program Transmission Facilities: Terrestrial and satellite systems and measurements.

Section 5. Production Facilities: Studio facilities, production equipment and systems.

Section 6. Remote Program Origination: Remote production equipment and pickup systems.

Section 7. Special Systems: Broadcast engineering and related items not covered in the above sections, including NTSC and other color systems, news room computers, ac power systems, and others.

The Table of Contents lists the main headings within each chapter to make it easier to find which chapter or chapters cover a particular subject. In coordinating the preparation and review of manuscripts, we have tried to avoid

duplication, but in some cases it is neither practical nor desirable to eliminate all overlap. A good example of this is in planning and coordinating auxiliary service frequency use; this increasingly important subject is addressed in several chapters.

Please take some time to browse through the Table of Contents and become familiar with its organization. Section and chapter titles may look familiar if you have an earlier edition of the *Handbook*. We have retained the previous general organization, but all material in this edition is completely new or has been updated.

Each page number includes the section and chapter numbers, and individual pages are numbered from the start of each section. For example, the Table of Contents shows Transmission Lines as the third chapter of Section 2, starting on the 33rd page of that section, or "2.3-33."

FCC Rules

As we go to press, the FCC is completing a major effort toward "technical deregulation." A number of requirements affecting operation and performance have been deleted completely. In some instances, an operating parameter is specified (*e.g.:* carrier frequency tolerance), but how the broadcaster monitors and maintains compliance is not specified.

We have tried to reflect changes in the Rules, not by citing Rules or FCC decisions, but rather by emphasizing what might be called "good engineering practice." Where a specific Rule is cited, it is because there is good reason to believe it will remain in effect. In any event, every broadcaster is responsible for knowing and maintaining compliance with all applicable FCC Rules and other regulations and laws.

Acknowledgements

Production of this edition of the *NAB Engineering Handbook* has taken almost two years and required the efforts of many people in the broadcasting industry and related fields. In addition to the individual authors, who are identified with their chapters, there were many others who spent considerable time assisting NAB staff with overall planning of this edition, reviewing manuscripts, offering suggestions and supplementary material. It is not possible to list everyone, but the following reflects the breadth of technical and editorial support NAB received.

NAB Engineering Advisory Committee Members

Robert Flanders
McGraw-Hill Broadcasting Company, Inc.

William E. Garrison
Multimedia Broadcasting Company

Ron Graiff
LIN Broadcasting Corporation

Warren Happel
Scripps-Howard Broadcasting Company

William Loveless
Bonneville International Corporation

Martin H. Meaney
National Broadcasting Corporation

Charles T. Morgan
Susquehanna Broadcasting Company

Robert O'Connor
CBS, Inc.

David W. Palmer
WATH/WXTQ

Gerald T. Plemmons
Outlet Broadcasting Company

R. LaVerne Pointer
American Broadcasting Company, Inc.

William J. Wisniewski
Mutual Broadcasting System

And thanks to the many others who helped.

Norm Avery
WBZ

Oded Ben-Dov
RCA Broadcast Systems Division

Robert Bousman
Delta Electronics, Inc.

Neil Braswell
Enterprise Electronics

John A. Carlton
Monaco Labs

Harry Clapp
Agfa-Gevaert NV

Jules Cohen
Jules Cohen & Associates

Julius Cohen
Cohen and Dippell, PC

Gus Dato
American Broadcasting Company

John Dooley
Hubbard Broadcasting, Inc.

Eli Drexler
Fuji Photo Color Film USA, Inc.

Shirley C. Earlewine
Federal Communications Commission

Carl Eilers
Zenith Electronics Corporation

Keith Ericson
KOSI

R. E. Fisk
Harris Corporation

John Francioni
WRVA

Jeffrey B. Friedman
Society of Motion Picture
and Television Engineers

David Garner
WTOP

M. Lynwood Heiges, Jr.
CBS, Inc.

Wayne Hetrich
National Public Radio

Albin Hillstrom
KTSP Radio & TV

Don Hobson
KJQY-FM

James H. Hoke
Harte-Hanks Radio, Inc.

Robert Hurst
RCA Broadcast Systems Division

Richard Jackson
Grass Valley Group

Mike Keller
Landy Associates

J. M. Kinn
Electronic Industries Association

Harrison Klein
Westinghouse Broadcasting

Greg Kozikowski
National Broadcasting Company, Inc.

Jim Kussman
American Broadcasting Company

Harry Larkin
Belar Electronics Laboratory, Inc.

Noel Luddy
RCA Broadcast Systems Division

Alan MacIntyre
UNC Center for Public Television

Verne S. Mattison
RCA Broadcast Systems Division

J. B. McPherson
WMAL-AM

B. F. Melchionni
RCA Broadcast Systems Division

Robert J. Monaco
Monaco Video

Henry R. Owen
WDVM-TV

Chris Payne
Utility Tower Company

Oscar Reed
Atlantic Research Corporation

John Reiser
Federal Communications Commission

Ed Ries
Porta-Pattern, Inc.

Richard Schumeyer
WJR-AM

John Serafin
American Broadcasting Company

Jerry Smith
Harris Corporation

Steven A. Smith
Broadcast Technology Consultants

Harris Sullivan
National Broadcasting Company, Inc.

Jim Tharp
KING Radio

E. M. Tingley
Electronic Industries Association

Theodore "Bud" Untiedt
American Broadcasting Company

Donald Voros
Harris Corporation

John Wang
Federal Communications Commission

Paul Wescott
Shively Labs

Editorial

Design and production were supervised by Teryn Wright. Text processing and telecommunications were supervised by assistant editor M. Elizabeth Andleman. JoAnn Pileggi was in charge of proofreading and authors' reviews. Their skills and extraordinary efforts made the expeditious delivery of this edition possible. The editor accepts full responsibility for editorial errors which may have slipped by; it was his decision that an up-to-date *Handbook,* in your hands, is more important than a perfect *Handbook* inching its way toward the press.

E. B. Crutchfield
Editor

NAB ENGINEERING HANDBOOK
Supplement to the 7th Edition

Introduction

As the 7th Edition of the Handbook was being prepared, the broadcast industry was in a period of rapid change in both technology and regulation. This situation was likely to continue for some time, and it was affecting planned contents of the Handbook.

The chapters supplied as part of the Supplement to the Handbook are, for the most part, those which contained important materials being affected by technical and regulatory changes. It was felt that the industry would be better served by publishing the main body of material, particularly in the basic areas of transmission, as soon as that was ready.

Now that these remaining chapters are completed, they should be placed in their appropriate sections. An up-dated Table of Contents is supplied, along with new Section dividers and a complete Index.

Acknowledgements

In addition to those persons whose help is acknowledged in the Editor's Notes, we would like to thank the following persons who helped with preparation of the Supplement.

David Chancey
Moseley Associates, Inc.

Bernie Dickens
CBS

John Fesler
ITC-3M

Don Himus
RCA Broadcast Systems Division

Michael Leader
Electro-Voice, Inc.

Bill Lorenz
Capitol Video Communications, Inc.

Mac McClanahan
Marti Electronics

John Phelan
Shure Brothers, Inc.

Ronald Rackley
duTreil Rackley

Karl Renwanz
WNEV-TV

Jack Williams
Pacific Recorders &
Engineering Equipment

Yoshi Yao
Panasonic

Fred Zimmerman
Moseley Associates, Inc.

Editorial

We were fortunate to have the high quality of design and production maintained by Teryn Wright. Assistant Editor for the Supplement was Janet Elliott who also coordinated communications and proofreading.

The Index was prepared by David Bialik, who also compiled the information in Chapter 1.6, Information Sources.

E. B. Crutchfield
Editor

TABLE OF CONTENTS

SECTION 1. PROCEDURES AND PRACTICES

1 FCC Organization and Administrative Procedures 1.1-1

Statutory authority
FCC organization
Mass Media Bureau organization
The licensing process
The FCC Rules and Regulations
The rule making process
FCC telephone directory

2 FCC Field Operations Bureau 1.2-19

The Field Operations Bureau
The inspection
Inspection checklists: radio stations, television stations

3 Frequency Coordination 1.3-49

What is frequency coordination
Some history of coordination
Terrain, user density and propagation considerations
Essence of the broadcast coordination process
What does it take to build a successful coordinating committee
Coordination considerations for various broadcast uses of Part 74 spectrum
Aural STL considerations
TV microwave considerations

4 Consultant Services: When and How to Use Them 1.4-67

Working with consultants
Types of consulting services

5 Frequency Allocations for Broadcasting and the Broadcast Auxiliary Services 1.5-71

How is spectrum allocated
AM broadcasting frequency allocations
FM broadcasting allocations
Television broadcasting allocations
Auxiliary broadcast services

6 Source Guide: Broadcast Standards and Information ... 1.6-87

Federal government
State and local governments
Trade associations
Professional associations
Related organizations
Broadcast engineering and related periodicals
Broadcast abbreviation reference list

SECTION 2. ANTENNAS AND TOWERS

1 Design, Erection and Maintenance of Antenna Structures 2.1-1

Tower characteristics, designs and materials
Lighting and electrical systems
Design standards
Loads, analysis, and safety factors
Effects of antennas and transmission lines
Foundations and anchors
Erection
Inspection and maintenance procedures

2 Lightning Protection for Broadcast Facilities 2.2-21

The thunderstorm cell
The lightning discharge
The lightning conductor
Grounding
Bonding
Surge suppression
Shielding-general guidelines

3 Transmission Lines 2.3-33

Transmission lines
Coaxial transmission lines
Semirigid transmission line
Installation
Waveguide

4 AM Broadcast Antenna Systems 2.4-63

Part I: System Design
Radiation versus field strength
The single tower nondirectional antenna
Two tower directional antenna

Part II: Antenna Coupling and Phasing Systems
The function of a directional antenna phasing system
Phasor performance objectives
Basic networks
Antenna monitor and sampling system
Detuning and decoupling systems
Transmitter load optimization
Diplexers and multiplexers
Overall system performance
A simple bandwidth test
Sampling source to feed a modulation monitor

Part III: Maintenance
Routine maintenance
Sudden component failures
Environmental changes
Readjusting an array

5 Antennas for FM Broadcasting 2.5-117
Propagation
Circular polarization
General coverage standards
Antenna site selection
Commercially available antennas
Directional antennas
Antenna gain and transmitter power
Diplexing and community antenna systems
FM antenna installation on AM towers
Pattern optimization
Installation procedures
Transmission line systems
FM SCA multiplexing
Spurious frequencies

6 Antennas for Television Broadcasting 2.6-155
Requirements
Specifications-General
Specifications-Technical
Design and theory
Types of antennas
Antenna tests
Installation
Maintenance

7 Measurement of FM and TV Field Strengths 2.7-203
Measurement objectives
Propagation and other special studies
Basic equipment principles
Measuring procedures and techniques
Practical problems encountered in making field-strength surveys
Emergency procedure
Safety precautions

8 AM Field Strength Measurements and Proof of Performance 2.8-217
Quick reference guide-FCC Rules
Proof of performance
General requirements for measurements
FCC form for license
License

9 Radio Wave Propagation 2.9-235
Quantifying propagation
Free space propagation
Medium frequency propagation
Propagation above 30 MHz
Coverage areas

10 Radio and TV RF Systems 2.10-251
Switching
Filters
Transmitter systems

SECTION 3. TRANSMITTERS

1 AM Transmitters **3.1-1**

Amplitude modulation theory
Radio frequency power amplifiers
Discussion of basic AM systems
Transmitter circuitry
Transmitter performance measurements
Factory tests
Important AM stereo transmitter characteristics
International shortwave broadcast transmitters
Representative commercial production transmitters

2 AM Stereo Systems **3.2-37**

System descriptions:
"Motorola C-Quam AM stereo system"
"Harris Linear AM stereo system"
"AM stereo system transmission and reception—Kahn"
"Belar AM stereo system"
"AM stereo and the PMX AM stereo system"

3 FM Transmitters **3.3-63**

Characteristics of FM
The FM transmitter
RF power amplifiers
Power supplies
Transmitter control systems
Transmission line and SWR measurements
Combined transmitters
Filterplexing
Operational measurements
Tuning for best performance
Installation considerations
FM transmitter plant maintenance

4 Subcarrier Transmission and Stereophonic Broadcasting **3.4-113**

The composite baseband
Stereophonic transmission standards
Generating the stereophonic baseband signal
FM SCA transmission
SCA data systems
Monophonic, stereophonic and SCA performance

5 Television Transmitters **3.5-137**

Visual exciter
Aural exciter
UHF klystron
Triodes, tetrodes, and television transmitters
Combining circuits
Precise frequency control
Performance measurements

6 Multichannel Television Sound 3.6-185
The BTSC system objectives
Transmission format
The companding system
The separate audio program channel
Other subcarriers
Modulation summary
Performance specifications
Compatibility with receivers, translators and CATV
Operating practice

7 Transmitter Control Systems 3.7-197
Current FCC regulations concerning transmitter control systems
Basis theory of operation
Elements of a transmitter remote control system
Control terminal
Remote terminal
Control terminal/remote terminal communication
Transmitter facility interfacing
Television monitoring equipment

8 Frequency and Aural Modulation Monitoring 3.8-211
Why monitor your transmitter
FCC rules affecting monitoring
Essential features of frequency monitors or meters
Essential features of an aural modulation monitor
Monitoring techniques
Calibration and maintenance of monitors

SECTION 4. PROGRAM TRANSMISSION FACILITIES

1 Television Signal Transmission Standards 4.1-1
Comparison of NTC-7 and EIA RS-250-B standards
General and waveform technology
Video measurements
Audio measurements

2 Microwave Engineering for the Broadcaster 4.2-59
Path performance
Antenna and waveguide considerations
Radio considerations
Power plants
Frequency planning
FCC licensing

3 Satellite Earth Stations 4.3-79
System description
Satellite earth station components
Site selection
Interference
FCC license
Installation
Operation and maintenance

4 Fiber Optic Video Transmission Systems 4.4-93

Introduction to fiber optics
Light and fiber characteristics
Optical device characteristics
Installation considerations
Fiber optic system planning

5 Aural Broadcast Studio Transmitter and Intercity Relay Service 4.5-105

STL selection
FCC requirements
STL equipment
STL equipment configurations
System planning

SECTION 5. PRODUCTION FACILITIES

1 Planning and Costs of Broadcast Facilities 5.1-1

General planning considerations
Television facility planning outline
Acoustic considerations and reverberation time
Estimating costs
AM and FM studio facilities
Control room announce booth design
Radio studios on a low budget

2 Planning and Design of Studio Lighting Equipment 5.2-29

Studio size
Suspension systems
Architectural criteria
Lighting control
Lighting fixtures

3 The Broadcast Television Camera System 5.3-45

Components of the basic camera system
Studio, ENG and EFP camera types
The optical system: lenses and beamsplitters
Camera tubes
Solid state imagers
Measurement and performance of imaging devices
Camera performance
Choosing a camera

4 Video Signal Switching, Timing and Distribution 5.4-73

The video signal
Interconnection conventions
Potential system problems
Video system design
Distribution amplifiers
Video signal switching
Video signal timing and genlock
Timing concepts in the modern studio
Guide to plant timing

5 Video Tape Recording 5.5-89
History
Quadruplex recorders
C format helical recorder
Video tape editing
Other formats
Magnetic disc recorders

6 Radio Studio Audio 5.6-107
Typical studio layouts
The audio console
Turntables
Microphones
Studio odds and ends
Audio production

7 Magnetic Recording Media 5.7-121
Part I: Care and Handling of Magnetic Tape
The recording and operations area environment
Operating practice recommendations
Storage environment
Accidental erasure
Part II: Principles and Current State of the Art
Basic principles
Magnetic recording media
Progress toward higher recording densities

8 Film for Television 5.8-137
Attributes of film
Advantages of low contrast print films
Film density to electronic output
Optimum television pictures from film
Advantages of choices
Setup (procedures and alignment)
Survey of new generation telecines
Corley telecine test film
Color bars for setting up telecines
Film sound
Stills
Recommended practices for television films and slides
Color television test films and slides
Film cleaning and handling practices
Film splicing
Storage of film and slides

9 3/4″ and 1/2″ Video Recording Systems 5.9-159
3/4″ video recording systems
Basic definitions
Color-under recording
Principles and characteristics
Typical performance specifications
Maintenance
Half-inch format video tape systems

Principles and current state of the art
Principles and characteristics
System features
Maintenance

10 Video Tape Editing 5.10-175

History
VTR edit timing
Editor VTR control
Medium level time-code editing controller hardware systems
VTR interfaces
Editing suite design considerations

11 Audio Magnetic Recording 5.11-217

An historic perspective
Tape composition and types
The recording process
The need for bias
Self erasure
The playback process
Equalization
Playback head contour effects
Mechanical alignment
System performance summary
The future of analog recording
Tape machine electronics
Tape machine performance comparison
Future tape machine developments
Audio tape machine maintenance

12 Microphones 5.12-239

Transducer types
Phantom power
Frequency response
Polar patterns
Limiting the working distance
Going for the distance
Sensitivity ratings
Output impedance
Dynamic range
Durability and reliability
Voiding and avoiding noise problems
Handling or mechanical noise
AC hum rejection
Acoustic phase interference
Microphone polarity reversal
Stereo miking
Care and feeding

SECTION 6. REMOTE PROGRAM ORIGINATION

1 Radio Field Production 6.1-1

Planning the network
Wired systems
Wireless systems

2 Microwave Electronic News Gathering 6.2-19

Frequency considerations
Receiver site selection
Transmitter
The ENG van
Central receive site
Remote control
Interference and central receivers
Airborne considerations

3 Television Field Production 6.3-29

What is field production
Planning for field production
Lease or buy
Equipment selection
Operation tips and techniques

4 Telephone Systems and Interfacing 6.4-41

Part I: Interfacing to the Dial-up Network

Part II: Telco Audio Program Service

SECTION 7. SPECIAL SYSTEMS

1 Color Television: NTSC Basics, PAL and SECAM 7.1-1

Part I: The Color System
Fundamentals
Electronic aspects of compatible color television
Color fidelity
The color encoder
Camera alignment
Color test equipment NTSC time base specifications

Part II: Worldwide Color Television Standards
Background
"Monochrome-Compatible" Color TV Systems
NTSC, PAL, and SECAM Systems Overview
The NTSC Color System
PAL Color System
SECAM Color System
Additional Systems of Historical Interest
Summary and Comparisons of Systems Standards and Specifications
Comments on International Exchange of Images

2 Using Operational Amplifiers in Broadcasting 7.2-69
Active filters and equalizers
Improving equipment

3 AC Power Systems 7.3-77
The utility power system
Standby power systems
The efficient use of energy

4 Translators and Low Power Television Systems 7.4-95
Regulatory framework and definitions
The multiple output FM translator
Site selection
Translator and LPTV coverage
Input signal considerations
Transmitting systems
Translator/LPTV installation considerations
Progress into the future

5 Instructional Television Fixed Service and Multipoint Distribution Service 7.5-115
Technical system considerations
Response channels

6 Broadcast Newsroom Computer Systems 7.6-123
Newsroom computer system architecture
Planning a newsroom computer system
Choosing a vendor
Installation
Maintenance
Security
Glossary

7 Weather Radar Systems 7.7-159
Radar history
Radar principles
Radar displays
History of colorizers and remoting
Typical applications
Dial-up weather radar data

8 The Emergency Broadcast System 7.8-167
System organization
System operation
Emergency broadcast system (EBS) checklist for participating stations
Nonparticipating stations
State and local level instructions

9 Broadcast Audio Measurement 7.9-185

Audio measurement
Amplitude measurement
Frequency analysis
Distortion measurement
Noise measurement
Relative program/loudness measurement
Phase monitoring and measurement

Chapter 1: FCC Organization and Administrative Procedures
Chapter 2: FCC Field Operations Bureau
Chapter 3: Frequency Coordination
Chapter 4: Consultant Services: When and How to Use Them
Chapter 5: Frequency Allocations for Broadcasting and the Broadcast Auxiliary Services
Chapter 6: Source Guide: Broadcast Standards and Information

1.1

FCC Organization and Administrative Procedures

Ralph A. Haller
Chief, Technical & International Branch
*Federal Communications Commission**
Washington, DC

STATUTORY AUTHORITY

Congress, through adoption of the Communications Act of 1934 (the Act), created the Federal Communications Commission (FCC) as an independent regulatory agency. Section 1 of the Act specifies that the FCC was created:

> "For the purpose of regulation of interstate and foreign commerce in communication by wire and radio so as to make available, so far as possible, to all the people of the United States a rapid, efficient, nation-wide, and world-wide wire and radio communication service with adequate facilities at reasonable charges, for the purpose of the national defense, for the purpose of promoting safety of life and property through the use of wire and radio communication, and for the purpose of securing a more effective execution of this policy by centralizing authority heretofore granted by law to several agencies and by granting additional authority with respect to interstate and foreign commerce in wire and radio communication..."

*The opinions expressed in this chapter are those of the author and not necessarily those of the FCC.

THE "COMMISSION"

The "Commission" consists of five Commissioners appointed by the President, by and with the advice and consent of the Senate. The President designates one Commissioner as Chairman. Except for limited actions of delegated authority by the staff, the Commissioners personally consider each new rule or regulation and either adopt or reject it by vote in regularly scheduled public meetings.

FCC ORGANIZATION

The staff of the FCC performs day-to-day functions of the agency, including: 1) license and application processing, 2) drafting of rule making items, 3) enforcing rules and regulations, and 4) formulating policy. The staff is divided along functional lines into various offices and bureaus. Normally, broadcasters deal with the Mass Media Bureau (MMB) or the Field Operations Bureau (FOB); however, actions by other elements of the agency may directly affect broadcasters. The major organizational units, as shown in Fig. 1, are:

Office of the Managing Director (OMD):

The Managing Director serves as the chief operations and executive official, as supervised and directed by the Chairman. OMD recommends,

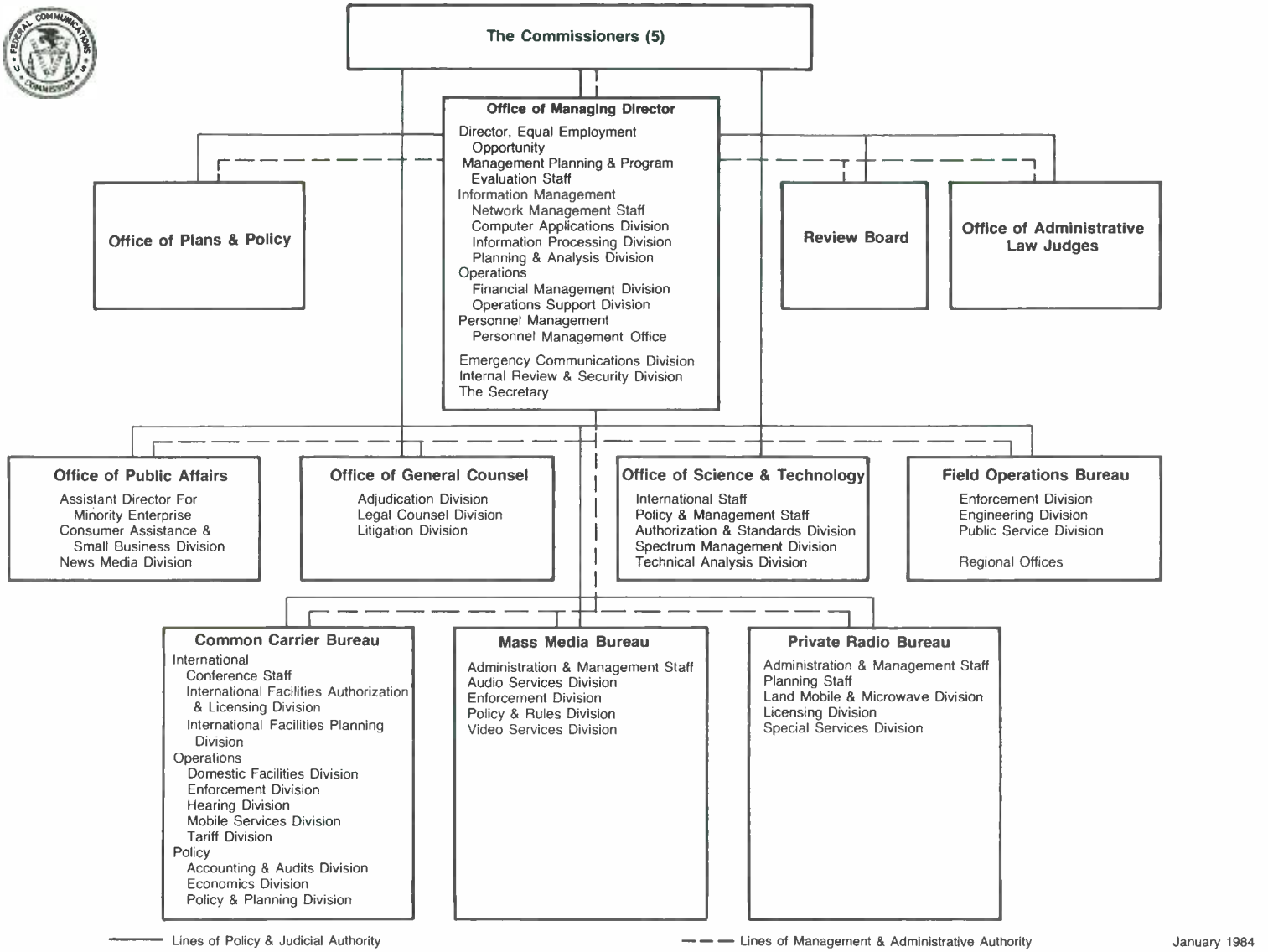


Fig. 1. Federal Communications Commission organization chart.

to the Chairman, program priorities, resources and position allocations, management and administrative policies. OMD operates the agency's personnel office. This Office, along with the Defense Commissioner, has responsibility for emergency communications policies.

Office of Public Affairs (OPA):

OPA functions as the FCC's primary point of contact with the public in dissemination of information about the Commission.

Office of Plans and Policy (OPP):

This Office makes recommendations to the Commission on development and implementation of communications policies.

Office of General Counsel (OGC):

The General Counsel advises the Commission in all matters of law and litigation, and interprets and implements statutes and treaties.

Office of Administrative Law Judges (ALJ):

The Law Judges have responsibility for hearing and conducting all adjudicatory cases designated for any evidentiary adjudicatory hearing other than those to be heard by the Commission en banc.

Office of Science and Technology (OST):

OST conducts scientific and technical studies related to communications and operates the FCC Laboratory in Columbia, Maryland. This Office has primary responsibility for overall spectrum management. The Chief Scientist administers the equipment authorization program (type acceptance, certification, etc.). Additionally, the Office issues authorizations for experimental communications work.

Review Board (RB):

The Review Board (three or more FCC personnel) is set up within the FCC to review decisions of Administrative Law Judges in all adjudicative proceedings, unless the Commission specifies otherwise.

Common Carrier Bureau (CCB):

CCB develops, recommends, and administers policies and programs for the regulation of services, facilities, rates and practices of entities (excluding maritime) which furnish communications services for hire.

Private Radio Bureau (PRB):

PRB develops, recommends, and administers policies and programs for development and regulation of the private radio services, such as those used by persons, businesses, state and local governments, and other organizations licensed to operate their own communications systems for their own use (not for hire).

Field Operations Bureau (FOB):

FOB operates the Commission's field offices, monitoring stations, and mobile monitoring vehicles. It administers the radio operator licensing programs, the field enforcement programs, and the field public service programs. The Bureau has responsibility for the nationwide program of lighting and marking of antenna structures.

Mass Media Bureau (MMB):

MMB develops, recommends, and administers policies and programs for development and regulation of the broadcastng and cable television industries. This includes auxiliary services such as translators, low power television, and operational circuits.

MASS MEDIA BUREAU ORGANIZATION

Because the Mass Media Bureau regulates broadcasting and cable television, most broadcast engineers will deal primarily with this Bureau. (Certainly, contact with the Field Operations Bureau can also be expected; see Section 1.2: "FCC Field Operations Bureau.") There are four major operational Divisions within MMB. Each Division has subdivisions, called Branches, to handle specific areas of regulation, enforcement, licensing, or policy development, as shown in Fig. 2.

Audio Services Division

Licensing, license modification, and license renewal of AM and FM broadcasting stations fall under the Audio Services Division. The Division also handles the aural auxiliary services, such as Broadcast Remote Pickup, Studio Transmitter Links, and FM Translators. Questions concerning pending applications, processing policies, and filing requirements should be directed to the appropriate branch as listed below. Also, requests for waivers of the Rules, requests to operate with parameters at variance (e.g., directional AM antenna out of tolerance), and other requests to operate inconsistently with the station's instru-

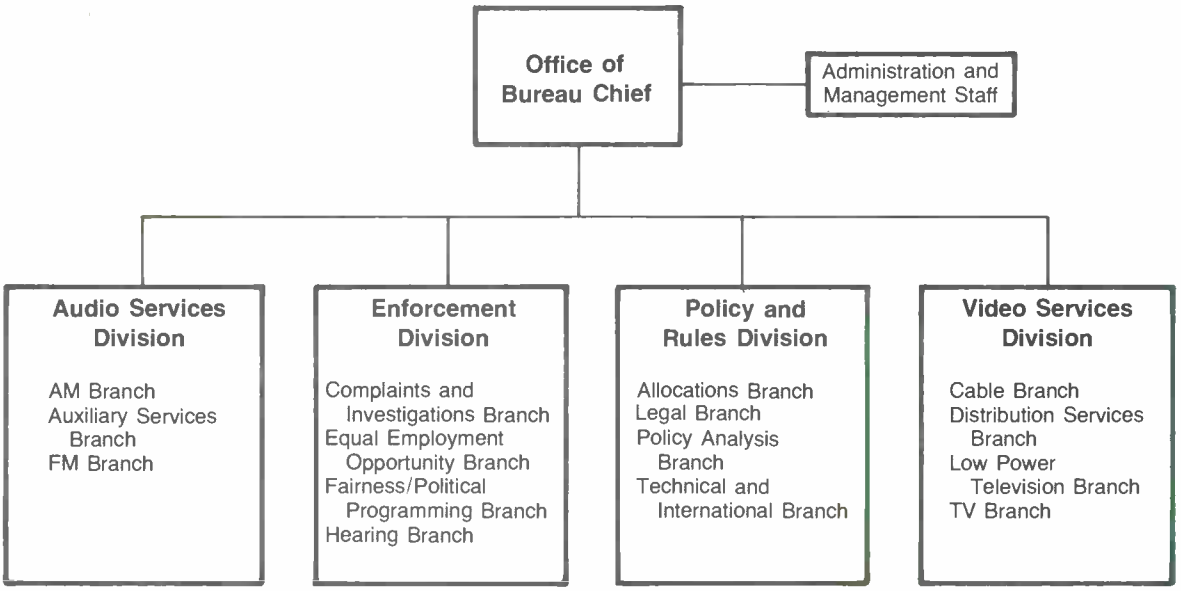


Fig. 2. Mass Media Bureau organization chart.

ment of authorization (license or construction permit) are handled by this Division. The Audio Services Division branches are:

AM Branch— AM Broadcast radio

FM Branch— FM Broadcast radio

Auxiliary Services Branch—Broadcast Remote Pickup, FM Boosters, and Translators, Aural STL

Video Services Division

Licensing, license modification, and license renewal of television stations are handled by the Video Services Division. In addition to over-the-air television, the Division's responsibilities include Low Power Television (LPTV), Direct Broadcast Satellite (DBS), Cable Television (CATV), Instructional Television Fixed Service (ITFS), and video auxiliary services. Questions concerning pending applications, processing policies, and filing requirements should be addressed to the appropriate branch as listed below. Also, requests for waivers of the Rules or for authority to operate inconsistently with the station's instrument of authorization (license or construction permit) are handled by this Division. The Video Services Division branches are:

Cable Television Branch— CATV, CARS Microwave

Distribution Service Branch — ITFS, TV-STL, DBS

Low Power Television Branch — LPTV and TV Translators

Television Branch— TV Broadcast

Enforcement Division

Although the Field Operations Bureau generally conducts station inspections and enforcement monitoring, their work normally concentrates on violations of the technical rules. Enforcement actions in other areas, such as equal employment opportunity or political broadcasting, are handled by the Enforcement Division in Washington, DC. This Division also works closely with FOB in enforcement of the technical regulations. Questions regarding enforcement matters should be addressed to the Enforcement Division. The Enforcement Division branches are:

Complaints and Investigations Branch — General

Equal Employment Opportunity Branch — EEO matters

Fairness/Political Broadcasting Branch — Fairness Doctrine, Political Broadcasts

Hearing Branch — Broadcast and CATV hearings

Policy and Rules Division

New broadcast and CATV rules and regulations generally are written in the Policy and Rules Division. The Division also regularly reviews the rules to eliminate unneeded ones or to modify those that have not kept pace with technology, policies, or legal decision. The Division also interprets broadcasting and CATV rules and regula-

tions. The Division can grant waivers of the Rules to permit experimentation with new technology on broadcast frequencies. The Policy and Rules Division also represents the United States at international forums. Rules and regulations can be classified as: frequency allocations related, legal, policy, or technical. The branches are accordingly aligned as:

Allocations Branch — Petitions for Rule Making to Amend the FM or TV Table of Allotments

Legal Branch — Legal rules such as ownership or community ascertainment

Policy Branch — Rules that are primarily policy decisions such as lottery procedures

Technical and International Branch — Technical rules, international representation, and AM and short wave station coordination internationally

THE LICENSING PROCESS

Any qualified citizen, firm, or group may apply to the Federal Communications Commission for authority to construct and operate an amplitude modulated (AM), frequency modulated (FM), or television (TV) broadcast station. More recent changes in the rules have permitted low power television (LPTV) and direct broadcast satellite (DBS) stations to be licensed. The FCC does not license cable television (CATV) systems; however, it does have rules and regulations governing CATV operation and some filings are required. The licensing procedures are outlined in Part 73 of the FCC Rules and Regulations. In general, applicants must satisfy the Commission that they are legally, technically, and financially qualified, and that operation of the proposed station would be in the public interest.

Types of Facilities

Applicants must propose specific station parameters to the Commission. In the case of AM broadcast, applicants generally conduct an interference study to assure that certain field strength contours of the planned station will not overlap existing stations. There are no preplanned AM broadcast assignments to cities or locations. Each application must be uniquely engineered to: 1) serve the community of interest, and 2) prevent interference. Use of a directional antenna will often be required to limit radiation in one or more directions. AM broadcast assignments are made at 10 kilohertz intervals, from 540 kilohertz to 1600 kilohertz, inclusive. Each channel has a designation of Class I, II, III, or IV (with additional subdivisions). The classes relate to coverage area ranging from Class I stations that serve only one locality. Power of AM broadcast stations varies from 250 watts to 50,000 watts.

Commercial FM and all TV applications differ from AM broadcast in that the Commission already has a Table of Allotments in these services. An application for a station in a city need not contain a mileage separation study if the city is listed in the Table of Allotment and no station currently operates on that channel. If no assignment exists in the table, then the applicant must first file a petition for rule making to have the proposed city added to the Table, based solely on specified mileage separations from other stations or assignments. If the proposal meets the Commission's criteria, the assignment will be added to the appropriate Table of Allotments and the application can then file for the station. Unfortunately, being successful in amending the Table does not guarantee being granted a station. Once the Table has been amended, other qualified applicants may also file for the station.

Commercial FM stations operate on channels spaced every 200 kilohertz, from 92.1 megahertz to 107.9 megahertz. Stations are classified as A, B1, B, C2, C1, and C, based on location in the country, channel, and power. Class A station operate between 100 watts and 3,000 watts, while class B stations may operate with up to 50,000 watts and class C stations are permitted 100,000 watts. Television stations have three categories: low VHF, high VHF, and UHF. Channels 2-6 are considered low VHF and 100,000 watts is authorized. High VHF stations operate on channels 7-13 and are permitted 316,000 watts. Finally, UHF television stations can radiate up to 5 million watts. The coverage areas of all television stations should be relatively equal with the above power levels. The power level differences in television relate to the more difficult propagation conditions at the higher frequencies.

Non-commercial FM (educational) stations have assignments between 88.1 megahertz and 91.9 megahertz. These stations may radiate up to 100,000 watts, but are allocated by actual predictions of service contour overlap rather than by the absolute mileage separations of commercial FM stations. LPTV stations are secondary to full service television stations. LPTV service contours may not overlap full service stations' contours and cause interference. Successful applicants for direct broadcast satellite transponders receive an exclusive right to use a particular DBS "slot" in space. Finally, licensees in the ITFS have exclusive use of a set of frequencies in a given community and may, to a limited extent, merge their facilities with common carrier operations in the Multipoint Distribution Service (MDS).

Applicants may represent themselves before the Commission in licensing matters; however, most applicants employ the services of communications attorneys and consulting engineers. By necessity, to prevent interference and assure license grants to qualified entities, the license process is complex. Professional advice can speed the process along and help prevent costly errors.

The First Step to a Broadcasting (AM, FM, or TV) License

Assuming that the engineering work has been done to determine that an AM or educational FM station can be designed and built in a community or that the FM or TV station can be designed and built in a community or that the FM or TV assignment is now contained in the appropriate Table of Allotments, the next step is to file for a construction permit (CP). Commercial applicants file on FCC Form 301, "Application for Authority to Construct a New Broadcast Station or Make Changes in an Existing Station." Educational station applicants use FCC Form 340 for the same purpose. The application for CP requests considerable information about the applicant(s) and the proposed facility. Commercial applicants must certify the financial ability to operate the station, without revenue, for three months after construction of the station.

If the Commission accepts the application for filing, a Public Notice will be released to inform interested parties of the action. At least 30 days after the release of the Public Notice will pass before the Commission again acts on the application. If no objections to the application are received and the Commission otherwise finds the applicant(s) qualified, a construction permit will be issued by the Mass Media Bureau under delegated authority. Again, the Commission issues a Public Notice and allows 30 days for interested parties to file for reconsideration of the grant. After grant of the CP, the applicant (now called a "permittee") should file for a call sign. Construction must be completed within 12 months for all classes of stations (except TV, which is 18 months) after the grant. Extensions of time may be requested for legitimate reasons.

Contested Applications

Not all applications for construction permits flow smoothly through the FCC. Often other parties will either file applications in competition with the original application or they will contest the application on some grounds. For example, an existing station licensee may disagree with the applicant's basic qualifications or intentions. Any of these protests will undoubtedly delay issuance of the CP, even if the applicant can resolve the conflicts outside the FCC forum. Absent any other method of resolution, the Commission will designate the application for a hearing.

Once designated for hearing, the applicant and other parties have 60 days to prepare their respective cases. The hearing will be conducted by an Administrative Law Judge (ALJ). The ALJ has authority to administer oaths, examine witnesses, and rule on the case based on the evidence presented. After the ALJ closes the record, an initial decision will be issued. The applicant, or any other interested party, may then file exceptions to the finding. The Commission or its Review Board may then hear oral arguments and adopt, modify, or reverse the ALJ's initial decision. If the decision was by the Review Board, the matter may be contested and the case taken to the Commission. Court appeals may be filed after the final decision by the Commissioners.

Station Construction and Equipment Testing

Construction should be exactly in accordance with the terms of the construction permit. If deviations must be made, then an amended FCC Form 301 must be filed. If the station cannot be constructed within the required time period, the permittee must file FCC Form 701 (Application for Additional Time to Construct a Radio Station). It is important to remember that filing of the form 301 or 701 does not guarantee that an extension of the CP will be granted.

Applying for the Station License

After the technical parameters of the station are in line, program testing may begin for non-directional AM and FM stations and TV stations. At this time, the permittee files for the station license on FCC form 302. AM and FM stations with directional antennas must apply for and secure authority from the FCC before beginning program testing. Stations operate in the program test mode until a license is received. Processing time varies, but the station license should arrive within a few months, assuming the FCC finds no problems with the form 302. The FCC may suspend the program test authority because of interference or other appropriate reasons.

License Renewal

Broadcast licenses have a life of 5 years for TV stations and 7 years for radio stations. Renewal is not automatic. Licensees file for license renewal on FCC form 303. If the licensee's record is good and if no one contests the renewal, the renewal process remains relatively simple. On the other hand, the renewal may be placed in hearing status for disposition if the licensee's per-

formance during the previous period is in question or if someone contests the renewal.

Sales and Transfers

If the holder of a construction permit or license desires to assign it to someone else, application is made on FCC Form 314 (Application for Consent to Assignment of Radio Broadcast Station Construction Permit or License). Should the permittee or licensee wish to transfer corporate control, FCC Form 315 (Application for Consent to Transfer Control of Corporation Holding Broadcast Station Construction Permit or License) is used. FCC Form 316 (Application for Assignment or Transfer-Short Form) may be used when the transfer or assignment involves no substantial change in interest.

Auxiliary and Translator Services

Broadcast station permit and license holders can apply for several types of auxiliary radio stations. For example, Aural Studio-Transmitter Links are available. Also, Broadcast Remote Pickup (two-way) stations can be used for program production communications or remote broadcasts.

FM licensees and other interested parties may operate FM Translators to fill in areas of the coverage pattern. Likewise, TV licensees and other interested parties may operate TV translators. Each application varies slightly. Details of these services are contained in Part 74 of the FCC Rules and Regulations.

DBS and LPTV

The application process for these services differs considerably from regular processing for broadcast stations. Unless an application for an LPTV station is not contested (which is very rare), the decision for the best qualified applicant is made by weighted lottery. Each applicant receives a weighting in the lottery based on factors such as minority ownership. DBS applicants apply to the Commission for a slot in space in the geostationary orbit. The construction permit can be retained only if a showing of due diligence has been shown in the construction of the facility. Final licensing comes after the station has been placed in operation.

THE FCC RULES AND REGULATIONS

Broadcasters should be familiar with the FCC Rules and Regulations. Every station should have at least one copy of the Rules. The Government Printing Office, not the FCC, sells the Rules through their local stores or by mail. New editions are printed yearly. This service provides no updates throughout the year as Rules are changed; however, the service is relatively inexpensive.

The following Rule Parts pertain to broadcasting and CATV:

Part 0: Commission Organization
Part 1: [FCC] Practice and Procedures
Part 2: Frequency Allocations and Radio Treaty Matters; General Rules and Regulations
Part 17: Construction, Marking, and Lighting of Antenna Structures
Part 73: Radio Broadcast Stations
Part 74: Experimental, Auxiliary, and Special Broadcast and Other Program Distribution Services
Part 76: Cable Television Service
Part 78: Cable Television Relay Service

All of these Rule Parts can be obtained by purchasing two rules books. The FCC Rules are contained in the Code of Federal Regulations (CFR), Title 47. Parts 0-19 are contained in one book and Parts 70-79 are contained in another. The Government Printing Office, Washington, DC, 20402, phone (202) 738-3238, or your local GPO sales office, should be contacted directly to order the books.

One or more private publishers offer subscription services to the FCC Rules. Generally, these services are more costly, but regular updates of the Rules are provided to subscribers. Subscriptions can also be obtained to receive copies of daily releases from the FCC.

THE RULE MAKING PROCESS

The FCC, like all other federal government agencies, enacts new rules and regulations through the terms of the Administrative Procedures Act (APA). The APA specifies how rules may be proposed, adopted, and appealed. The APA assures that the public has input into the rule making process. Fig. 3 is a flow chart of the process and may be helpful in understanding the steps. Part 1 of the FCC Rules and Regulations provides detailed information on the FCC's general rules of practice and procedure.

Initiation of Actions

Rule making actions can be proposed by anyone through a petition for rule making. Such petitions bring the desires of individuals or groups to the attention of the Commission. The FCC will evaluate the petitions and either dismiss them for one of the reasons in Section 1.401 of the Rules or accept them for action. If accepted, a Public

Notice will be released giving a brief description of the details of the petition. Others may then submit comments in support of or against the petition.

Other rule makings may begin by direction of Congress, the President, or the courts. The FCC may also initiate rule makings on its own motion.

Early Options

Initiation actions are handled in one of four ways. A petition can be dismissed directly through a *Memorandum Opinion and Order* (MO&O). Minor rules changes can be made effective directly through a *Report and Order* (R&O). Generally, however, either a *Notice of Inquiry* (NOI) or *Notice of Proposed Rule Making* (NPRM) will be drafted by the staff. If enough information is at hand to draft the proposed rule changes, an NPRM will be issued without first gathering background material in an NOI. After adoption of an NPRM by vote of the Commissioners, the *ex parte* rules become effective (see section below). Because this inhibits direct contact between FCC staff and concerned parties, the NOI may be considered an essential first step in many matters. *Ex parte* does not apply at the NOI stage.

Comment periods are provided to allow interested parties to express their views. If, based on a review of the comments received, the Commission finds that an NOI should be terminated without further action, it will issue an MO&O stating the reasons for the termination. Otherwise, the matter will be considered for specific rule making in an NPRM. The MO&O is subject to a 30 day period in which parties may file petitions for reconsideration if they have good reason to believe the Commission acted incorrectly.

Notice of Proposed Rule Making

Most rule making items begin as a *Notice of Proposed Rule Making*. The staff prepares the NPRM for consideration by the five Commissioners. An NPRM normally presents the issues and alternatives, may ask specific questions to help finalize the matter, and sets forth proposed rules or rule amendments. An NPRM may address one or multiple topics.

Comments must be filed by the close of the comment period, usually 30 days. Reply comments may then be filed in response to comments, usually for a 15 day period. These two comment periods provide the Commission with a "written debate" of the issues.

The comments and reply comments received are reviewed and enter heavily into the Commission's final actions. However, a comment does not represent a vote for the proposed rules. The Commission must decide in each issue based on the public's interest, convenience, and necessity. Even if the majority of the comments oppose an item, the FCC can nevertheless adopt the proposal. The FCC can also schedule items for oral argument among the interested parties.

Filings should be clear, concise, and address the issues in the NPRM. Emotional responses or uninformed responses are of little value. Copies of the actual texts of the NPRM need to be studied before making comments. All NPRMs are published in the Federal Register and will be available at most larger libraries or law libraries.

The comments are reviewed by Commission staff at the Branch or Division levels. Recommendations are then passed to the Bureau level and ultimately to the Commissioners. The Commissioners will then approve, disapprove, or direct the staff to modify the recommendations.

The staff or the Commissioners may also decide that that record still does not support a decision, and a *Further Notice of Proposed Rule Making* (FNPRM) will be released. Like an NPRM, the comment periods apply. Once the record supports a final decision, the FCC will act by adoption of a *Report and Order*.

Report and Order

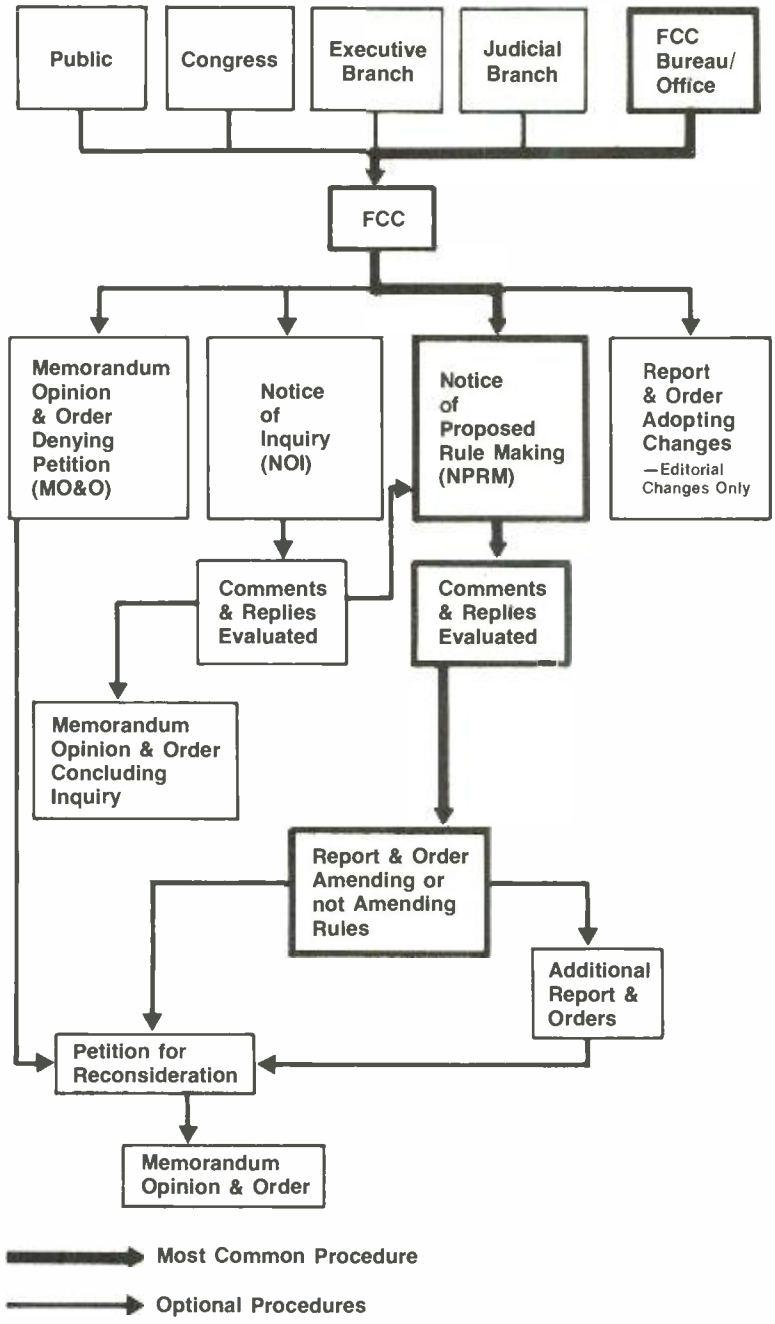
A *Report and Order* may be used to dismiss the proposals in the NPRM, adopt some of the proposals (possibly modified based on the comments), or adopt the rules as proposed. Rules will normally not become effective until 30 days after publication of the R&O in the Federal Register. The R&O constitutes the Commission's final action unless a petition for reconsideration is filed.

Petition for Reconsideration

Any interested person may petition for reconsideration of a final action. The petitions for reconsideration must be filed within 30 days of the date the R&O was published in the Federal Register. The Commission will act on a petition for reconsideration by *Memorandum Opinion and Order*. The initial decision may be modified or the petition may be denied in the MO&O.

Ex Parte Considerations

Most rule making proceedings become *ex parte* upon adoption of an NPRM and remain *ex parte* until 30 days after the Commission's final action (R&O or MO&O for reconsiderations). An *ex parte* contact is any written presentation made to FCC decision making personnel by another person, which is not served on all parties to the proceeding. It is also any oral presentation made to the FCC decision makers, without advance notice to the parties to the proceeding and op-



This brief account of how Rules are made at the FCC merely highlights the major components of the process. For details, contact the Dockets Branch.

This article was prepared with the assistance of staff members from several Bureaus and Offices, particularly Sharon Briley, Cable Television Bureau.

Steps:

1. Initiation of Action. Suggestions for changes to the FCC Rules and Regulations can come from sources outside of the Commission either by formal petition, legislation, court decision, or informal suggestion. In addition, a Bureau/Office within the FCC can initiate a Rule Making proceeding on its own.

2. Bureau/Office Evaluation. When a petition for Rule Making is received, it is sent to the appropriate Bureau(s)/Office(s) for evaluation. If a Bureau/Office decides a particular petition is meritorious, it can request that Dockets assign a Rule Making (RM) number to the petition. A similar request is made when a Bureau/Office decides to initiate a Rule Making procedure on its own. A weekly notice is issued listing all accepted petitions for Rule Making; the public has 30 days to submit comments. The Bureau/Office then has the option of generating an agenda item requesting one of four actions by the Commission. If an NOI or NPRM is issued, a Docket is instituted, and a Docket number is assigned.

3. Possible Commission Actions. Major changes to the Rules are presented to the public as either an NOI or NPRM. The Commission will issue an NOI when it is simply asking for information on a broad subject or trying to generate ideas on a given topic; an NPRM is issued when there is a specific change to the Rules being proposed. If an NOI is issued, it must be followed by either an NPRM or an MO&O concluding the inquiry.

4. Comments & Replies Evaluated. When an NOI or NPRM has been issued, the public is given the opportunity to comment initially, and then respond to the comments that are made. When the Commission does not receive sufficient comments to make a decision, a further NOI or NPRM may be issued, again calling for comments & replies. It may be determined that an oral argument before the Commission is needed to provide an opportunity for the public to testify before the Commission, as well as for the Bureau(s)/Office(s) to present diverse opinions concerning the proposed Rule change.

5. Report & Order Issued. A Report & Order is issued by the Commission stating the new or amended Rule, or stating that the Rules will not be changed. The proceeding may be terminated in whole or in part.

6. Additional Reports & Orders Issued. The Commission may issue additional Reports & Orders in the docket.

7. Reconsideration Given. Petitions for reconsideration may be filed by the public within 30 days; they are reviewed by the appropriate Bureau(s)/Office(s) and/or by the Commission.

8. Modifications Possible. As a result of its review of a petition for reconsideration, the Commission may issue a MO&O modifying its initial decision or denying the petition for reconsideration.

Fig. 3. How FCC rules are made.

portunity for them to be present. Certain proceedings are "restricted" and no *ex parte* contacts can be made. These would be, for example, contested applications for licenses. Most rule makings are "non-restricted" and do not involve competing claims to a valuable privilege.

Appeal to the Courts

Once the Commission has considered and reconsidered a matter, interested parties may appeal the decision to the federal courts. Ultimately, the Supreme Court could hear the case. Under current law, however, the Federal Communications Commission need not wait for the court decision before enacting the new rules and regulations. As long as the matter has been given full consideration under the Administrative Procedures Act, the FCC may place the new rule in effect until a court rules to the contrary or orders a "stay." The courts typically defer to the expertise of the Commission in technical matters and will often look more to assure that the APA was followed than to try to second-guess the Commission's decision.

FCC Telephone Directory
Functional Listing

(Please Note: Telephone numbers are subject to change.)

Subject	Telephone Number
—A—	
Access charge tariffs (CCB)	632-6387
Accounting systems (CC)	634-1861
Administrative Sanctions (FOB)	632-7354
Advisory Committees	
• Advisory Committee on Cable Single Leakage	632-2706 / 254-3420
• National Industry Advisory Committee	632-7232
• Radio Technical Commission for Marine Service	296-6610
Agriculture (including Crop Spraying, Bee Keeping, Farming, Ranching, Harvesting, Seeding, Livestock, Nurseries, Orchards) (PRB)	(717) 337-1212
Alien Restricted Permits (FOB)	632-7240
All-Channel TV Receivers (OGC)	632-6990
Allocation	
• Call Signs	634-1923
• Call Sign Block	653-8144
• Call Sign Policy	653-8144
• Charts and Tables (OST)	653-8162
• Frequency	
— Government (OST)	653-8137
— Non-Government (OST)	653-7434
— International (OST)	632-8144
Amateur applications/Licenses (PRB)	(717) 337-1212
Ambulance & Rescue Squads (PRB)	(717) 337-1212
Annual Report Form (CC)	632-7084
Annual Employment Report Form 395) (CCB)	632-7500
Annual Employment Report (395A) Cable TV Systems	632-7069
Antenna Structures & Towers— Includes Lighting and Marking (FOB)	632-7521
Application Status	
• Air to. Ground Public Correspondence	254-6810
• Amateur (PRB)	(717) 337-1212
• Aviation (PRB)	
— Aircraft	(717) 337-1212
— Aviation Ground	(717) 337-1511
• Business (PRB)	(717) 337-1511
• Cellular	632-6400
• Commercial Operator (FOB)	632-7240
• Common Carrier (Wire Line Facilities)	634-1800
• Digital Electronic Message Service —DEMS—(CCB)	634-1706
• Domestic Satellite	634-1624
• Mobile Services (CCB)	254-6810
• Microwave (CCB)	634-1706
• Multipoint Distribution Service— MDS—(CCB)	634-1706
• International (CCB)	632-7265
• Experiment (OST)	653-8137
• General Mobile (PRB)	(717) 337-1511
• Industrial (Includes Power, Petroleum, Manufacturers, Forest Products, Industrial Ratio Location, Motion Picture, Relay Press and Telephone Maintenance) (PRB)	(717) 337-1511
• Land Transportation (Includes Railroad, Taxicab, Auto Emergency, Motor Carrier—Interurban Passenger, Urban Property, Urban Passenger) (PRB)	(717) 337-1511
• Equipment Authorization	(301) 725-1585
• Telephone Equipment Registration (CCB)	634-1833
• Marine (PRB)	
— Ships	(717) 337-1212
— Marine Coast	(717) 337-1511
— Offshore Radio Telecommunications Service (CCB)	632-6400
— Rural Radio Service (CCB)	632-6400
• Microwave (Industrial) (PRB)	(717) 337-1421
— Public Safety (Includes Police, Fire, Local Government, Highway Maintenance, Forestry Conservation Special Emergency and State Guard) (PRB)	(717) 337-1511
— Radio, TV and Aux. Serv. (MM)	632-6634
Assignment of Microwave Common Carrier Licenses (CCB)	634-1706
Automobile Emergency (PRB)	(717) 337-1212
Aviation Services (PRB):	
• Applications/ Licenses	See "Application Status Aviation"
• Rules/Hearings	632-7175
—B—	
Bills (Legislative) (OGC)	632-6405
Broadcast, Inspection of Stations (FOB)	632-7014
Broadcast Services—(MMB)	
■ AM SERVICE	
• Engineering Rules:	
— Existing Stations	632-7010
— Minor Changes Applications	245-9570
— New Stations and major changes Applications	254-9570
— STL's; Remote Pickups, Intercity Relays	634-6307
• Non-Engineering Rules:	
— Advertising Questions/Comments	632-7551
— Application Forms	632-7272
— Assignment & Transfer Applications	254-9470
— Construction Permit Applications	254-9570
— Emergency Broadcast System	634-1600
— Political Programming/Fairness Doctrine	632-7586
— Programming Questions/Comments	632-7048

*Unless noted, all numbers are in Area Code 202, Washington, D.C., Area Code 717 refers to the Gettysburg, PA Office, Area Code 301 refers to the Laboratory in Laurel, MD.

Subject	Telephone Number
• Renewal Applications	254-9570
• Equal Employment Opportunity	632-7069
• Reports	
— Employment (Form 395)	632-7069
— Ownership (Form 323)	632-7258
■ FM SERVICES	
• Engineering Rules	
— Existing Stations	632-6908
— Minor Changes Applications	632-6908
— New Stations/Major Changes Applications	632-6908
— SCA	632-7166
— STL's; Remote Pickup; Intercity Relays	634-6307
— Translators/Boosters	632-7505
• Non-Engineering Rules	
— Advertising Questions/Comments	632-7551
— Application Forms	632-7272
— Assignment & Transfer Applications	632-6908
— Construction Permit Applications	632-6908
— Educational FM	632-6098
— Emergency Broadcast System	634-1600
— Political Broadcasting/Fairness Doctrine	632-7586
— Programming Questions/ Comments	632-7551/632-7048
• Renewal Applications	632-6908
• Equal Employment Opportunity	632-7069
— Reports	
— Employment (Form 395)	632-7069
— Ownership (Form 323)	632-7258
• SCA's Stereo-Multiplex	632-7166
• Translators/Boosters	633-7505
• Petitions for Rulemakings	634-6530
■ TV SERVICES	
• Engineering Rules	
— Existing Stations	632-6495
— New Stations/Major or Minor Changes Applications	632-6495
— STL's; Remote Pickups, Intercity Relays	634-6307
— Translators	632-7698
• Non-Engineering Rules	
— Advertising Questions/Comments	632-7551
— Applications Forms	632-7272
— Assignment & Transfer Applications	632-6357
— Educational TV	632-6357
— Emergency Broadcast System	634-1600
— Political Broadcast/Fairness Doctrine	632-7586
— Programming Questions/ Comments	632-7551/632-7048
• Rebroadcast	632-3894
• Renewal Applications	
— General	632-6357
• Processing	632-6357
— Equal Employement Opportunity	632-7069
— Engineering	632-6495
• Reports	
— Employment (Form 395)	632-7069
— Ownership (Form 323)	632-7258)
• Subscription TV	632-6357
• Translators	632-3894
• Petitions for Rulemakings	634-6530
• Broadcast Stations International	
— New & Existing Stations	632-6955/254-3394
■ ITFS	
• Engineering	
— Existing Stations	632-9356
— Governmental Material (except International)	632-7025/653-8137
— New Stations/Major Changes	632-9356
• Non-Engineering	
— Application Preparation	632-9356
— Existing Stations	632-9356
— New Stations/Major Changes	632-9356
• Educational/Non-Commercial	
— TV	632-6357/632-7531
— EEO—Industry (General)	632-7069
• Rule Making Petitions	
— General	634-6530
Budget (MD)	632-7194
Bulletins, Request for (Other than those supplied at field installations) (OPA)	632-7260
Business Radio (PRB)	(717) 337-1212
Busses (PRB)	(717) 337-1212

—C—

Cable—	
• Aerial or Underground/Coaxial (CCB)	634-1800
• Landing Licenses/Ocean Systems (CCB)	632-7265
Cable—	
• Telephone/TV Cross Ownership	634-1830
Registration (MMB)	632-7076
• Complaints (Subscribers)	632-7048
• Fees	632-7076
• Franchising	632-7076
• General—as it relates to Radio and TV	632-7048
• Microwave	
— Legal	632-7480
— Engineering	254-3420
• Pole Attachments (CCB)	632-4890
• Policy	
— Access	632-7480
— Pay Cable	632-7480
— Rule Making re CATV	632-7792
• Public Reference Room	632-7076
• Research (Industry Statistics)	632-7792
• Special Relief	632-7480
• Technical Standards & Rules	254-3420
Cablegrams (CCB)	632-7265
Call Letters (Signs—)	
• Amateur	(717) 337-1212
• Others	634-1923
Campus Radio Stations (OST)	632-8247
Carrier Equipment (OGC)	634-1800
Cases in Court (OGC)	632-7112
CATV—See Cable TV	
CCIR—International Radio Consultative Committee (OST)	653-8102
CCIT—International Telegraph Consultative Committee (CCB)	632-3214
Cellular Mobile Radio	632-6400
Certification of RF Devices (Pt. 15)(OST)	653-8247
Civil Air Patrol (PRB)	
• Applications/Licenses	(717) 337-1212
• Rules	632-7175
Coast Stations (PRB)	
• Applications/Licenses	(717) 337-1212
• Rules/Hearings	632-7175
Commercial Operators—(FOB)	
• Examinations (Washington, D.C. Area)	(301) 962-2728
• Examinations (Other Areas)	632-7240
• All other matters	632-7240
Commission Proceedings, Tape Recordings	632-7000
Common Carrier Radio (CCB)	
• International & Satellite	632-7265
• Mobile Services	632-6400
• Microwave Services	634-1706

Subject	Telephone Number
Community Antenna TV—SEE CABLE TV	
Complaints—	
• Broadcast (TV & Radio)	632-7048
— Advertising Questions	632-7551
— Political Broadcasting/Fairness Doctrine	632-7586
— Programming Questions/Religious Petitions	632-7048
• Cable Television (MMB)	632-7048
• Common Carrier—	
• Informal Complaints & Public Inquiries	632-7553
— Telephone	632-7553
— Telegraph/Telegram	632-7553
— Interconnect	634-1800
— Pole Attachments (CCB)	632-4890
— Rates	632-5550
• Interference to Radio & TV	
— Washington, D.C. Area	(301) 962-2728
— All Other Areas—Refer to local field installations listed in backs of telephone book	
Compliance—	
• Registration (MMB)	254-3407
• Common Carrier Accounting (CCB)	634-1861
• Experimental (OST)	653-8139
• Incidental and Restricted Radiation Devices (OST)	653-8247
• Land Mobile (PRB)	632-7125
• Aviation & Marine (PRB)	632-7197
• Personal & Amateur (PRB)	632-7197
Computing Device Emission Standards (Pt. 15) (OST)	653-8247
Conferences	
International—CCIR, WARC (OST)	653-8102
CCITT (CCB)	632-3214
Conflict of Interest Interpretations (OGC)	632-6990
Congressional and Public Affairs, Office of	254-7674
Consumer Assistance and Small Business	632-7000/632-7260
Control Devices (unlicensed) Part 15 (OST)	653-8247
Copy Contractor (Int'l Transcription Svs.)	296-7322
Cordless Telephone (Pt. 15)(OST)	653-8247
Court Cases (OGC)	632-7112
Coverage—Radio (OST)	653-8247
Curtailment of Service (Telephone or Telegraph) (CCB)	632-7553
Customer Owned Equipment—	
• Attach to Telephone (CCB)	634-1833
Customer Toll Dialing (CCB)	632-7553

—D—

Defense Activities (EBS)	632-7007
Depreciation Rules (CCB)	634-1861
Development Stations	
• Aviation or Marine (PRB)	(717) 337-1431
• Common Carrier (CCB)	634-1706
• Experimental (OST)	632-8139
Diathermy Approval (OST)	(301) 725-1585
Direct Broadcasting Satellites	632-9356/632-7792
Direct Distance Dialing (CCB)	632-5550
Discontinuances—Carrier Comm. Svcs. (CCB)	634-1800
Domestic Public (CCB)—	
• Auxiliary Test, Base, Control and Repeater Stations	632-6450
• Cellular Radio	632-6400
• Land Mobile Radio Service	632-6450
• Microwave	634-1706
• Rural Radio	632-6450

Subject	Telephone Number

—E—

Eavesdropping (Electronic)(OGC)	632-6990
Electronic Switching (Telephone)(CCB)	634-1800
Emergency Broadcasting System (EBS)	634-1600
Emergency Medical Services (PRB)	337-1212
Employment	632-7106
Enforcement—Private Radio Bureau Forfeitures Show Cause Orders.	
• Revocations, Suspensions	632-7197
— Land Mobile (PRB)	632-7125
— Aviation & Marine	632-7197
— Personal & Amateur	632-7197
• Requests for Enforcements	
— Washington, D.C. Area (FOB)	(301) 962-2728
— All other areas—Refers to local field office (FOB)	
Engineering Surveys—Field Strength (OST)	632-7080
Environmental Law (NEPA)(OGC)	632-6990
Equipment Measurement Authorization (OST)	(301) 725-1585
Examinations—(FOB)	
• Washington, D.C. Area	(301) 926-2728
• Outside Washington, D.C.	632-7240
Ex Parte Rules (Interpretations of)(OGC)	632-6990

—F—

Facsimile—Wire (CCB)	634-1800
Fairness Doctrine	632-7586
FCC Rules (Legal Interpretations of)(OGC)	632-6990
Field Disturbance (Pt. 15)	653-8247
Field Offices	
• Common Carrier (CCB)	634-1861
• Field Operations Bureau (See Field Office Directory)	
• Field/Public Service Staff	634-1940
Financial Data—	
• Common Carrier (CCB)	632-7084
Fire (PRB)	(717) 337-1212
Foreign Attachments—	
• Telephone (CCB)	634-1833
• Interconnection (CCB)	634-1800
Forest Products (PRB)	(717) 337-1212
Forfeitures/Fines	
• Mobile Services (includes CB)	632-7197
• Collection of (OGC)	632-6444
Forms Distribution—	
• By form number only	632-7272
• General form request	632-7000
Franchising (CATV)	254-3407
Freedom of Information (OGC)	632-6990
Frequencies for—(Ask for which service and refer to that service)	
Frequency Allocations—	
• Government (OST)	653-8137
• Non-Government (OST)	653-8162
• Allocation Treaties Agreements and Arrangements (International)(OST)	653-8144
• Chart and Tables (OST)	653-8144
• Coordination/Spectrum	
• Government (OST)	632-7025
• Non-Government (OST)	632-7025
• International (OST)	653-8144
• Lists	
• Government (OST)	653-8162
• Non-Government (OST)	653-8162

Subject	Telephone Number
• Notification and Registration (OST)	653-8144
• Usage Data & Utilization (OST)	653-8162

—G—

Garage Door Openers—Licensed (PRB)	(717) 337-1212
Garage Door Openers—not licensed	653-8247
General Counsel (OGC)	632-7020
General Mobile Radio Service (PRB)	(717) 337-1212
Government—	
• Broadcasting, Frequency Coordination, List, Interference, Radio Stations, Telecommunications Committees (OST)	632-7025

—H—

Health Unit (FCC)	632-1618
Harrassing Telephone Calls (CCB)	632-7553
Hearing Calendar (OLJ)	632-7680
Highway Maintenance (PRB)	(717) 337-1212
Highway Patrol (PRB)	(717) 337-1212

—I—

Incidental Radiation Devices (Rules)(OST)	653-8247
Industrial Heating Equipment (OST)	653-8247
Information—General (OPA)	632-7000/632-7260
Information—Technical Research (OST)	632-7040
Infraction Reports—International (OST)	653-8144
Injunctions (OGC)	632-7112
Inspections (FOB)	632-7014
Integrated Data Processing (common carrier transmission of)(CCB)	632-5550
Interception of Radio Communications (OGC)	632-6990
Interconnection (CCB)	634-1800
Interference Complaints	
• Washington, D.C. Area (FOB)	(301) 962-2728
• All Others (Refer to local Field Office)	
• Requests for Monitoring (FOB)	632-6975
• Direction Finding Assistance (FOB)	632-6975
• Radio—Government (OST)	653-8137
• Radio—International (OST)	653-8144
• Research (OST)	632-7040
• Standards (OST)	632-7093
International—International Conferences (Future), CCIR	653-8108
Conferences (past)	632-7025
WARC (OST)	653-8102
Broadcasting	632-9660
• Conferences and Meetings (OST)	653-8102
• Frequency Allocations (OST)	632-7025
• Frequency Allocation Charts & Tables (OST)	632-7025
• Frequency Coordination (OST)	653-8144
• Frequency Lists, Notification & Registration (OST)	653-8144
• Interference (OST)	653-8144
• Permits to Operate in Canada	653-8144
• Radio Publications/Regulation (OST)	653-8144
• Satellites Systems Coordination	653-8153
• Telecommunications Convention/Union (OST)	653-8144
• Telegraph & Telephone Rates (CCB)	632-5550
• Treaties, Agreements & Arrangements (OST)	653-8144
Intrusion Alarms (OST)	653-8247
Investigations—	
• Unlicensed Operations	
— Washington, D.C. Area (FOB)	(301) 962-2728
— All other areas refer to local Field Office (FOB)	
• Interference	
— Washington, D.C. Area (FOB)	(301) 962-2728
— All other areas refer to local Field Office (FOB)	
Ionosphere (OST)	632-7080
IRAC (Interdepartment Radio Advisory Committee) (OST)	632-7025
ISM (Industrial, Scientific & Medical Equipment) (OST)	653-8247

—L—

Land Mobile—	
• Common Carrier (CCB)	632-6450
• Other than CC (PRB)	(717) 337-1212
— Public Safety	(717) 337-1212
— Special Emergency	(717) 337-1212
— Business	(717) 337-1212
— Other Industrial	(717) 337-1212
— Land Transportation	(717) 337-1212
Land Mobile Frequency Assignment Techniques (PRB)	(717) 337-1411
Land Mobile Operational Review of Radio Systems	632-6497
Land Transportation (PRB)	(717) 337-1212
Law Suits Litigation (OGC)	632-7112
Leased Facilities (OGC)	632-7553
Library (FCC)(MD)	632-7100
Licenses—(See "Application Status" also)	
• Amateur (PRB)	(717) 337-1212
• Aviation (PRB)	(717) 337-1212
• Business (PRB)	(717) 337-1212
• Commercial Operator (FOB)	632-7240
• Common Carrier	
• Domestic Satellite	634-1624
— Mobile Services (CCB)	632-6400
— Cellular	632-6400
— Microwave (CCB)	634-1706
— Wireline (Authorization or Cert.)(CCB)	634-1800
— International & Satellite (CCB)	632-7265
• Experimental (OST)(PHS)	653-8137
• General Mobile (PRB)	(717) 337-1212
• Industrial (PRB)	(717) 337-1212
• Land Transportation (PRB)	(717)337-1212
• Marine (PRB)	(717) 337-1212
• Microwave (Industrial) (PRB)	(717) 337-1421
• 1st, 2nd, 3rd Class Operators (FOB)	632-7240
• Public Safety (PRB)	(717) 337-1212
• Radio & TV (See Broadcast Services)	
Lighting devices (RF) (Pt. 18)(OST)	653-8247
Local Government Radio (PRB)	(717) 337-1212
Local Television Transmission (CCB)	634-1706
Locator—Personnel	632-7106
Lotteries (OGC)	632-6990
Low Power Transmitters for operation without a license (OST)	653-8247
Low Power Television	
■ Engineering Rules	
• Existing Stations	632-7426
• New Stations/Major or Minor Change Applications	632-7426
■ Non-Engineering Rules	
• Application Processing	632-3894
• Existing Stations	632-3894

Subject	Telephone Number

—M—

Manufacturing (PRB) ..... (717) 337-1212
Marine Services (PRB)
- Applications/Licenses ..... (717) 337-1212
- Rules/Hearings 632-7175

Marketing Rules 632-7068
MD's Licensing 634-1706
Measurement for
- Type Acceptance ..... (301) 725-1585
- Type Approval ..... (301) 725-1585
- Certification ..... (301) 725-1585

Medical Equipment (including diathermy) (OST) 653-8247
Metered Service—Message Units (CCB) 632-7553
Microwave—
- Auxiliary—Common Carrier (CCB) 634-1706
- Auxiliary—Mass Media (MM) 634-6307
- Cable TV Relay Service (MM) 254-3420
- Closed Loop (CCB) 634-1706
- Data Base (OST) 653-8163
- Digital Electronic Message (CCB) 634-1706
- Monitoring Stations, Protection from Interference (FOB) 632-7593
- Multipoint Distribution (MDS)(CCB) 634-1706
- (PRB) operational review 632-6497
- Ovens (OST) (Pt. 18) 653-8247
- Radio Relay (CCB) 634-1706
- General/Operational 632-6497
- Satellite (OST) 653-8107
- TV—Pickup (CCB) 634-1706

Military Stations (OST) 653-8137
Mining (PRB) ..... (717) 337-1212
Mobile Telephone Services (CCB) 632-6450
Mobilization Planning (OST) 632-7025
Model Airplanes (PRB) ..... (717) 337-1212
Monitoring (FOB) 632-6975
- Monitoring Stations, Protection from Interference (FOB) 632-7593

Monitoring Telephone Svc. (CCB) 632-5550
Motor Carrier (PRB) ..... (717) 337-1212

—N—

National Environmental Policy Act (OCG) 632-6990
Navigation (Air or Water) (PRB) 632-7175
News Gathering and Publishing (PRB) ..... (717) 337-1212
Noise—Radio (OST) 632-7040

—O—

Obstruction Markings—Antenna (FOB) 632-7521
Offshore Radio Telecommunications Service (CCB) 632-6450
Off-the-Air Pickup (CCB) 634-1706
Off-Track Betting (OGC) 632-6990
One-Way Paging and Signaling (CCB) 632-6450
Operating Revenues—
- Int'l., Telephone & Telegraph (CCB) 632-7084

Operator Licenses (FOB)—
■ Commercial
- Administration & Suspension of 632-7240
- Examinations (1st, 2nd & 3rd Class)
  - — Washington, D.C. Area ..... (301) 962-2728
  - — All Other Areas 632-7240
- License Records (Commercial) 632-7240

Subject	Telephone Number

■ Restricted Radiotelephone Permit (FOB)
- U.S. Citizens—Wash., D.C. Area ..... (301) 962-2728
- U.S. Citizens—All Other Areas 632-7240
- Aliens—All Areas 632-7240

Oral Arguments (OMD) 632-7535
Original Plant Cost (Telephone & Telegraph) (CCB) 632-3772
Over-the-Horizon or Scatter Technique (OST) 632-7080

—P—

Paging—Common Carrier (CCB) 632-6450
Paging—One-Way (PRB) ..... (717) 337-1212
Pay Cable TV (CATV) 632-7480
Personnel—Employment (OMD) 632-7106
Personnel—Health Benefits Retirement, Employment Verification 632-6279
Personnel—Locator 632-7106
Petroleum Off-Shore Drilling (PRB) ..... (717) 337-1212
Physicians Radio—Private (PRB) ..... (717) 337-1212
Physicians Radio—Common Carrier (CCB) 632-6400
Point-to-Point Microwave—
- Common Carrier (CCB) 634-1706
- Private (PRB) ..... (717) 337-1212

Pole Attachments (CCB) 632-4890
Political Programming 632-7586
Power (Electric, Gas, Water) (PRB) ..... (717) 337-1212
Press Relations (OPA) 254-7674
Press (Relay) (PRB) ..... (717) 337-1212
Privacy Act—Procedures (OGC) 632-6990
Private Carriers Communications (PRB) ..... (717) 337-1212
Private Operational Fixed Services (PRB)
- Microwave Applications
  - — Technical Questions ..... (717) 337-1212
  - — Status of ..... (717) 337-1212

Private Wire Systems—Telephone & Telegraph (CCB) 634-1800
Procurement (OMD) 634-1528
Propagation—Radio Waves (OST) 653-8108
Property Records—Common Carrier (CCB) 634-1861
Public Information—
- Consumer Assistance ..... 632-3860 / 632-7000
- Press & News Media 254-7674

Public Reference Rooms—
- Mass Media (MMB) 632-7566
- Cable (MMB) 632-7076
- Carrier Reports (CCB) 632-7084
- Carrier Tariffs (CCB) 632-5550

Public Safety (PRB) ..... (717) 337-1212

—Q—

Quality Control—Common Carrier (CCB) 634-1800
Quality Control—Common Carrier (CCB) 632-7553

—R—

RACES (PRB) ..... (717) 337-1212
Radar—
- Intrusion Alarms (Unlicensed) (OST) 653-8247
- Aviation or Marine (PRB)
  - — Applications/Licenses ..... (717) 337-1212
  - — Rule Interpretations 632-7175

Radiation hazards (OST) 632-7074

Subject	Telephone Number
Radio Astronomy—	
• Frequencies (OST)	632-7025
• Technical (OST)	632-7040
Radio Broadcasting (See Broadcasting Services)	
Radio Complaints	632-7048
Radio Control Devices	
• Unlicensed (Pt. 15) (OST)	653-8247
• Unlicensed (Pt. 95) (OST)	653-6288
• (PRB)	632-4964
• Unlicensed (other Pts.) (PRB)	632-4964
• (OST)	653-8247
Radio Frequency Devices (OST)	653-8247
Radiograms (CCB)	632-7265
Radiolocation—Industrial (PRB)	(717) 337-1212
Radio Propagation (OST)	653-8108
Radiotelegraph—	
• Common Carrier (CCB)	632-7265
• Marine (PRB)	
— Applications/Licenses See "Application Status—Marine"	
• Operator License, Issuance of (FOB)	632-7240
Radiotelephone—	
• Aviation or Marine (PRB)	
— Applications/Licenses	(717) 337-1212
— Rule Interpretations	632-7175
• Common Carrier Services (CCB)	632-6450
• Equipment	(301) 725-1585
• Operator License Issuance of (FOB)	632-7240
• Permits, Restricted Radiotelephone (FOB)	632-7240
Railroad (PRB)	(717) 337-1212
Rate Base (International, Telegraph and Telephone) (CCB)	632-3772
Rate Level (International, Telegraph and Telephone) (CCB)	632-5550
Rate of Return (International, Telegraph and Telephone) (CCB)	632-3772
Rate Structure (International, Telegraph and Telephone) (CCB)	632-5550
Real Property (FOB Field Installations)	632-7593
Recording Telephone Conversations (CCB)	632-7553
Reduction of Carrier Service (CCB)	632-7876
Relay—Microwave (CCB)	634-1706
Relay Press (PRB)	(717) 337-1212
Religious Petition (RM 2493)	632-3860/632-7000
Rescue Squads (PRB)	(717) 337-1212
Research (Technical) (OST)	632-7040
Restricted Radiation Devices (OST)	653-8247
Retirements (Telephone Plants) (CCB)	634-1861
Rules and Regulations—	
• Aviation and Marine	632-7175
• Business	634-2443
• Industrial, Scientific and Medical (ISM) Equipment	653-8247
• Other Industrial	634-2443
• Land Transportation	634-2443
• Low Power Communication Devices (unlicensed) (Pt. 15) (OST)	653-8247
• Microwave (PRB)	634-2443
• Personal and Amateur	632-4964
• Public Safety	634-2443
Rules—Ship Earth Station	632-7175
• Interpretation of (Gen. Inquiries) (OGC)	632-6990
Rural Radio (CCB)	632-6400

—S—

Subject	Telephone Number
Safety—Sea (PRB)	632-7175
Safety Manager (OMD)	632-7541
Satellite—Sanction (FOB)	
• International Facilities (CCB)	632-7265
• Domestic Facilities (CCB)	634-1624
• International Coordination	653-8144
• Maritime (PRB)	632-7175
• Rates (CCB)	632-5550
• Systems (CCB)	634-1624
• Spread Spectrum (OST)	632-7073
• Coordination and Interference (OST)	653-8107
Scatter Technique—Technical (OST)	653-8108
Search & Rescue—Assistance for (FOB)	632-6975
Security Officer (OMD)	632-7143
Ship Inspections (FOB)	632-7014
Ship Licensing (PRB)	(717) 337-1212
Ship Rules/Exemptions	632-7175
Single Side Band—Standards (OST)	653-6288
Special Emergency or Industrial (PRB)	(717) 337-1212
Spectrum Allocation (See Allocation)	
Speed of Service—	
• Telephone or Telegraph (CCB)	634-1800
Split Channel Operations (CCB)	632-6400
Sports Blackout (MMB)	632-7048
Standards—Licensed Equipment (OST)	653-6288
State Guard (PRB)	(717) 337-1212
Statistics—	
• Common Carrier (CCB)	632-7084
Studio Transmitter Links—	
• Mass Media (MMB)	634-6307
• Common Carrier (CCB)	634-1706
Submarine Cable (CCB)	632-7265
Sunspot Cycle (OST)	632-7040

—T—

Subject	Telephone Number
Taping of Phone Calls (OGC)	632-6990
Tariff Schedules (International, Telegraph and Telephone) (CCB)	632-5550
Taxicab (PRB)	(717) 337-1212
Technical Research (OST)	632-7040
Telephone Equipment Interconnection (CCB)	634-1800
Telegraph Service (CCB)	632-7876
Telephone Lines (CCB)	634-1706
Telephone Telegraph Service Complaints (CCB)	632-7553
Telephone Telegraph Rates (CCB)	632-5550
Teleprinter (Telephone, Telegraph) (CCB)	634-1800
Teletypewriter Exchange Svs. (TWX) (CCB)	632-5550
Television Broadcasting (See Broadcast Services)	
Television Complaints—	
• Advertising Questions	632-7551
• Political Broadcasting Fairness Doctrine	632-7586
• Programming Questions	632-7048
• Religious Petitions	632-3860/632-7000
TELEX	
• International & Domestic (CCB)	632-7265
Tie-line—Telegraph Telephone (CCB)	632-5550
Toll Charges (CCB)	632-5550
Tort Claims (Legal) (OGC)	632-6990
Towers—Painting and Lighting of (FOB)	632-7521
Towing (PRB)	(717) 337-1212
Transfers—	
• Microwave Common Carrier License (CCB)	634-1706
Transit Systems (PRB)	(717) 337-1212
Transportation—Land (PRB)	(717) 337-1212

Subject	Telephone Number
Treaties—	
• Administrative Interpretation (OGC)	632-6990
• Frequency Allocation (OST)	632-8144
Treaty Library (OST)	653-8144
Troposphere (OST)	632-7040
• Interference to (Wash., D.C. Area) (FOB)	(301) 962-2728
— All other areas—Refer to Local Field Office (FOB)	
• Military (OST)	653-8157
• Pickup (Common Carrier) (CCB)	634-1706
TV (and Radio) Complaints—Other than Interference	632-3860
TV STL—	
• Mass Media (MMB)	634-6307
• Common Carrier (CCB)	634-1706
Type Acceptance (OST)	(301) 725-1585
Type Approval (OST)	(301) 725-1585

—U—

Ultrasonics Equipment (OST)	653-8247
Unlicensed Operators—	
• Investigation of (FOB)	632-6345
• Administrative Sanctions (FOB)	632-7240

—V—

Video Transmission—	
• Common Carrier (CCB)	634-1706
Violations Records (Ask what service and refer to that service)	
• FOB Violation Records (FOB)	632-7278

—W—

Walkie-Talkies (That may be operated without a license) (OST)	653-8247
Watch Officer (Monitoring) (Open 24 hrs. per day—7 days per week) (FOB)	632-6975
Wire Facilities (CCB)	634-1800
Wireless Microphones—	
• Non-licensed (OST)	653-8247
• Licensed (PRB)	(717) 337-1212
• Licensed (MMB)	632-7505
Wiretapping (OGC)	632-6990

—Y—

Yellow Page Advertising (CCB)	632-7553

1.2

FCC Field Operations Bureau

Ralph A. Haller
Chief, Technical & International Branch
*Federal Communications Commission**
Washington, DC

THE FIELD OPERATIONS BUREAU

The FCC's Field Operations Bureau operates a series of 25 field offices and 13 monitoring stations throughout the United States, including Alaska, Hawaii, and Puerto Rico. These offices and monitoring stations perform the day-to-day enforcement work of the Commission. Additionally, the offices provide a local contact point between the public, licensees, and the FCC.

FOB Headquarters (Washington, DC)

The headquarters of FOB is divided into 3 functional Divisions:

1) Engineering Division
2) Enforcement Division
3) Public Service Division

Although these divisions support the field installations and formulate policies, normally broadcasters will not deal directly with the headquarters Divisions. FOB headquarters Divisions should be considered as "second level" contacts as these offices are not intended for direct public contact. Nevertheless, knowledge of the headquarters functions may prove useful in specific instances.

*The opinions expressed in this chapter are those of the author and not necessarily those of the FCC.

Engineering Division

The Engineering Division serves the in-house engineering consulting function for FOB. The Engineering Division develops enforcement measuring procedures, designs and builds enforcement vehicles, and develops new enforcement tools such as direction finders. Questions concerning any of these areas may be directed to the Engineering Division.

Enforcement Division

The Enforcement Divison directs all field inspections, investigations, and monitoring (signal sampling) operations. This Division sets priorities for enforcement actions and administers the violations sanctions program. Inquiries concerning enforcement actions may be addressed to the Enforcement Division; however, such inquiries should begin with the local enforcement facility.

Public Service Division

The Public Service Division administers the Bureau's public service program. The program assists the public, licensees, and other government agencies with telecommunications-related matters. It also reports to the FCC, trends and problems learned of through public contact. The Division also provides information to people with interference problems, supervises the mailing out of forms and publications from field installations, and administers the radio operator examination program. This Division handles approvals for

tower construction and lighting. Questions in these areas may be addressed to the Public Service Division.

Field Facilities

Operationally, the field installations are divided into six regions, which cover large areas of the country. Although policies may vary slightly between regions, based on available resources, basic enforcement guidance flows from headquarters.

Regional Directors

Regional directors are located in Atlanta, Boston, Chicago, Kansas City, San Francisco, and Seattle. Their primary function is to support the operations of the field facilities under their control. The regional directors set regional priorities and provide a first-level supervisory function over local offices and monitoring stations. Again, like headquarters, the regional offices are primarily administrative and are not intended regularly to handle inquiries from licensees or the public. Generally, the regional offices should be contacted only if a problem cannot be resolved with the local office.

Field Offices

Most direct contact between broadcasters and the FCC enforcement team comes at the field office level. Each office is headed by an Engineer in Charge. Most offices also have public contact representatives, staff engineers (inspectors), and clerical personnel. These are multi-purpose offices which provide forms, technical assistance, rule interpretations, and radio operator testing. Broadcasters should make an effort to become acquainted with their local FCC office staff, as these offices can be of invaluable assistance. Offices are located in Anchorage, AK; Atlanta, GA; Baltimore, MD; Boston, MA; Buffalo, NY; Chicago, IL; Dallas, TX; Denver, CO; Detroit, MI; Honolulu, HI; Houston, TX; Kansas City, MO; Long Beach, CA; Miami, FL; New Orleans, LA: New York, NY; Norfolk, VA; Philadelphia, PA; Portland, OR; St. Paul, MN; San Diego, CA; San Francisco, CA; San Juan, PR; Seattle, WA; and Tampa, FL. In addition to inspecting FCC licensed stations, these offices solve interference problems, administer the Safety of Life at Sea Act, find and close down illegal stations, and investigate any use of radio energy that does not comply with the Rules and Regulations.

Monitoring Stations

Monitoring stations provide most of the functions of a field office in addition to sampling signals off-the-air. Because many signals cannot be heard beyond line-of-sight distances, these stations operate several monitoring vehicles that travel around the country and sample signals, especially in the VHF region and above. Monitoring stations are located in Allegan, MI; Anchorage, AK; Belfast, ME; Douglas, AZ; Ferndale, WA; Fort Lauderdale, FL; Grand Island, NE: Kingsville, TX; Laurel, MD; Livermore, CA; Powder Springs, GA; Sabana Seca, PR; and Waipahu, HI. Six of the stations also have special TV/FM/microwave enforcement vehicles, called Enforcement Monitoring Units (EMU), to handle most broadcast and microwave work. Although these units are not needed for AM stations, these stations will often be included in enforcement schedules for convenience. These monitoring stations and vehicles can analyze signals with amazing accuracy. Originally, monitoring stations were not intended for direct public contact. More recently, however, such contact has been welcomed as an added public service of the Commission.

THE INSPECTION

Perhaps the most feared activity of the FCC is the inspection program. Although this reaction is understandable, the inspection need not be cause for concern in well managed and operated stations. The FCC inspectors are engineering professionals, not policemen. As such, they will normally be very understanding of problems and often will be eager to offer advice. The inspections provide an opportunity for one-on-one exchanges with the FCC and should be viewed positively. The inspectors have no violation quotas to meet, so an inspection need not end with a violation notice.

Elements of an Inspection

Most inspections follow a similar pattern. The inspector will be primarily interested in the technical operation of the station. Although some attention may be paid to the required records, the majority of the time will be devoted to a review of technical parameters. In the case of AM directional antenna stations, the inspection will include visits to the monitoring points.

The following topic areas are included in inspections; however, a particular inspection need not cover all of the areas:

1. Station Documents and Records
2. Transmitter Operation
3. Studio and Control Point Operation
4. Tower and Antenna
5. Emergency Broadcast System Compliance
6. Remote Control Operation
7. Extension Metering

8. Tower Light Inspection Log
9. Other Logs, as may be required
10. Automatic Transmission System
11. Radio Operator Licenses
12. Directional AM Antenna Performance
13. Auxiliary Broadcast Stations
14. Signal Analysis

The FCC publishes checklists to assist broadcasters in checking their own operation. One checklist covers AM and FM stations, while a second checklist pertains to TV stations. FCC field offices can supply copies of one or both checklists to stations upon request.

After the inspection, the inspector will hold a review session with the chief operator and station licensee or general manager. All areas that need improvement will be discussed. Depending on the severity of a particular violation, FCC actions could range from simply a warning to a monetary forfeiture.

Notification of Violations

If violations were noted during the inspection, the inspector will return to the FCC office and mail a list of the violations to the station. Three levels of notices are provided, and a given inspection may result in issuance of one or more of these notices.

Advisory Notice (FCC Form 790)

Near violations will be brought to the attention of licensees in the form of an FCC Form 790. This level indicates that an observation in some area of the station operation has a high probability of becoming a violation if the problem is not corrected. No reply to the notice is required. (See Fig. 1)

Tier Two Violation (FCC Form 790)

Violations that have little probability of causing the station to interfere with other stations will be notified by the tier two advisory notice (FCC Form 790). Although no reply is required, licensees should immediately correct the discrepancies. Left unchecked, these violations could lead to more serious actions (See Fig. 1)

Tier One Violation (FCC Form 793)

Violations that involve safety of life or property, have a high potential to cause interference, or are of a serious nature for some other reason will be notified on FCC Form 793. This is an Offical Notice of Violation. Licensees must reply to such notices within 10 days of receipt. Failure to reply could result in a monetary forfeiture or ultimately in license revocation. Even if the response cannot be fully complete within the 10 days, as a minimum an extension of time must be requested. Violations in this category are serious and require immediate attention. Depending on the nature of the violation, whether it is a repeated or willful violation, and the licensee's response, additional sanctions could be imposed. (See Fig. 2)

Monetary Forfeitures

Serious violations can result in a forfeiture. In most cases, the local field office will issue the forfeiture; however, in a few cases, some forfeitures will be issued by the FCC in Washington, DC. Field issued forfeitures may not exceed $2,000. The field issued forfeitures may be for items related to safety, interference, tower lighting, or important administrative matters (like not having a licensed operator on duty). More serious violations may have forfeitures of up to $20,000 or more if repeated. These higher levels do require the approval by the Commissioners before being issued. Failure to pay a forfeiture may result in license revocation or criminal charges being filed by the US Attorney.

Criminal Penalties

Broadcasters normally will not be involved in violations so serious as to be handled as criminal violations. These types of violations often are, for example, by people operating unlicensed stations.

Appeals

As with any governmental enforcement actions, licensees have the opportunity throughout the sanction process to appeal the action. If the broadcaster feels that the sanction action is inappropriate or the amount of a monetary forfeiture should be reduced, the office issuing the sanction should be contacted. It may also be useful to obtain professional counsel.

OFF-THE-AIR MONITORING

Technical parameters of station operation may be monitored off-the-air. This occurs at the monitoring stations or in FCC enforcement vehicles. Licensees do not usually know about the Commission's monitoring until after-the-fact. Violations will be brought to a licensee's attention through an advisory notice, a tier two notice, or a tier one notice (see above).

UNITED STATES OF AMERICA
FEDERAL COMMUNICATIONS COMMISSION
WASHINGTON, D.C. 20554

NOTICE OF RADIO STATION CONDITIONS

FREQUENCY	CALL SIGN	
EMISSION	DATE OBSERVED	TIME OBSERVED
LOCATION OF STATION OR NAME OF CRAFT	RADIO SERVICE OR CLASS OF STATION	

NO REPLY IS NECESSARY

☐ Items are violations of the Commission's Rules detected during monitoring or an inspection. These items must be corrected promptly.

☐ Items identify unsatisfactory or marginal conditions noted during monitoring or an inspection. We suggest you correct these items to avoid violations or operating problems.

PARTICULARS:

SAMPLE DOCUMENT

FCC OFFICE ADDRESS	DATE SERVED	ISSUING OFFICER
		SUPERVISOR

CAUTION: Violations, if repeated or willful, may result in imposition of sanctions, including monetary fine, revocation or suspension of operating authority or prosecution. (See Sections 501, 502, 503, 312, and 303 (m) of the Communications Act of 1934, as amended and Section 1.89 of the Commission's Rules.) We are retaining a copy of this notice.

(All previous editions of this form are canceled.)

FCC Form 790
November 1978

Fig. 1. Sample FCC advisory notice.

United States of America
FEDERAL COMMUNICATIONS COMMISSION

OFFICIAL NOTICE OF VIOLATION

1. Name and Address of Licensee

WRITTEN REPLY REQUIRED IN DUPLICATE

(See Instructions and Privacy Act Notice on reverse side)

WARNING: Violations, if repeated or willful, as well as your failure to reply to this notice, may result either in the imposition of monetary forfeitures, the revocation of your station license or suspension of operator license. (See Sections 503, 312, and 303 (m) of the Communications Act of 1934, as amended and Section 1.89 of the Commission's Rules.)

SAMPLE DOCUMENT

2. FREQUENCY			3. Emission	
2a. Authorized	2b. Measured	2c. High/Low (Hertz)		
4. Location of Station or Name of Craft	5. Radio Service or Class of Station	6. Hour(s) of Violation (EST-GMT)	7. Date(s) of Violation	8. Call Sign

9. VIOLATION(S)

ISSUING OFFICER	SUPERVISOR - LOCATION	DATE MAILED/SERVED

The knowing and willful making of any false statement in reply to this NOTICE is punishable by fine or imprisonment under Title 18, United States Code, Section 1001.

(All previous editions of this form are canceled.)

(See Reverse Side)

FCC Form 793
April 1978

Fig. 2. Sample FCC office Notice of Violation.

TO THE LICENSEE:

The facts set forth herein indicate that you have violated the requirements of law or treaty. This Notice is issued in accordance with Section 1.89 of the Commission's Rules.

1. Within 10 days from receipt of this Notice, a written reply in DUPLICATE shall be addressed to "Federal Communications Commission" and SENT TO THE ADDRESS SHOWN ON THE FACE HEREOF AT THE TOP OF THE PAGE. DO NOT address your reply to an individual.

2. **MAKE CERTAIN THAT YOUR ANSWER:**
   a. Fully explains each violation.
   b. Specifically describes the action taken to correct and to prevent continuation or recurrence of each violation.
   c. Is identified as a reply to this Notice. Include the *call sign* of your station so that your answer may be properly associated with the station file.
   d. Does not refer to a reply to another notice, but is complete in itself.
   e. Is dated and is signed by the licensee or, if appropriate, an officer of the licensee.
   f. Includes all the information requested above in addition to any other information requested in Items 3 and 4, below.

3. **CHANGE OF ADDRESS:**
   If the address appearing in Block 1 on the face of this Notice is not your correct address for receipt of mail, include the correct address in your letter of reply to this Notice.

4. If an "X" appears in the box preceding any of the following instructions, comply with the instruction(s) so indicated and submit the information together with the above described letter.

☐ a. State the name of the person who operated the transmitter at the time of the violation. Does this person hold an operator license or permit issued by the Federal Communications Commission?

☐ b. A second copy of this Notice is enclosed for the operator to answer the following questions thereon. That copy must then be submitted with the letter of reply described in Item 2 above from the person addressed on the face of this notice. RETAIN THE ORIGINAL OF THIS NOTICE.

I, the undersigned, was the operator on duty at the time of the violation noted hereon, and hereby acknowledge this NOTICE. I hold FCC-issued Radio Operator (Not Station) License or Permit as follows (if none, so state): _____
Number (If unnumbered, so state): _____
Issuance date: _____ Birth date: _____
Name (print): _____
Address: _____
Signature: _____

NOTICE REQUIRED BY THE PRIVACY ACT OF 1974, P.L. 93-579, DECEMBER 31, 1974, 5 U.S.C. 552a(e)(3):

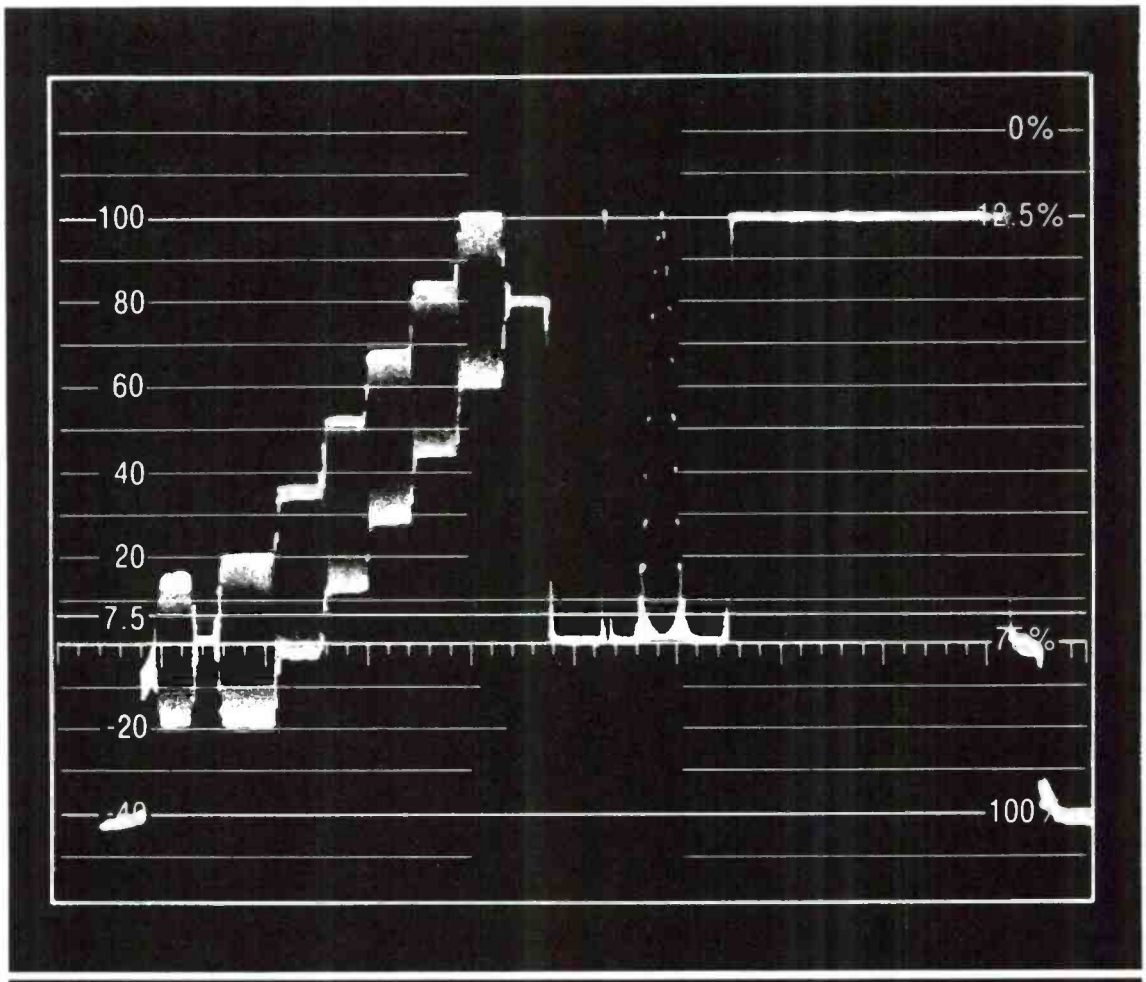
The staff will use all relevant and material information before it, including the information disclosed in your reply, to determine what, if any, enforcement action is required to ensure current and future Rule compliance.

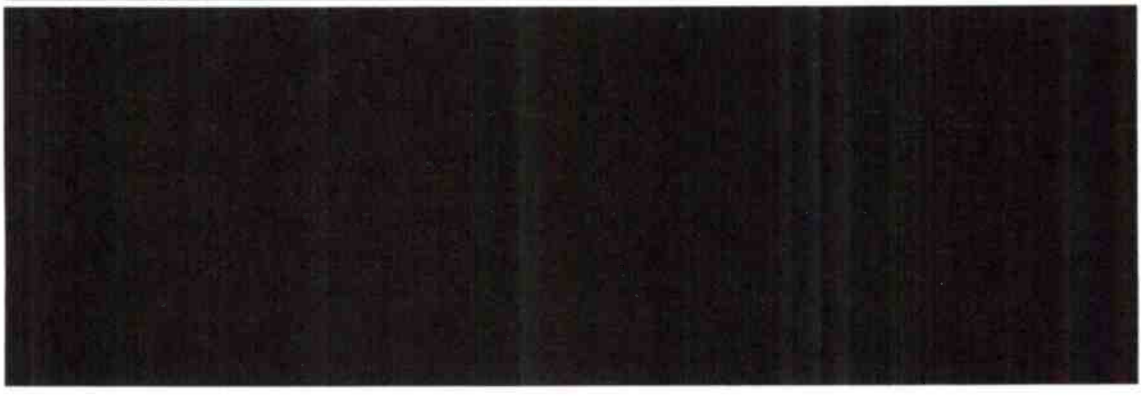
Willful or repeated violation or failure to reply may result in a monetary forfeiture or license revocation.

FCC Form 793
April 1978 (page 2)

SAMPLE DOCUMENT

Fig. 2. Sample FCC office Notice of Violation. (Cont.)





FEDERAL COMMUNICATIONS COMMISSION
FCC
USA

Provided by
Field Operations Bureau

TV Station Checklist

This **TV Station Checklist** is provided to assist broadcast engineers and other technical staff in maintaining compliance with FCC Rules and Regulations.

For additional copies, contact the nearest field office or the FCC, Field Operations Bureau, Washington, D.C. 20554.

Provided by
Field Operations Bureau

December 1984

Partial Index By Subject To Rules For TV Stations

Since rules are subject to periodic revisions, listings should be checked with recent rule changes as they occur. This is not a complete listing of all rules to which stations may be subject.

1. Station Document & Records

☐	License, Construction Permit, Renewal, Program test posted	**73.1230 [a]**
☐	Operator licenses posted	**73.1230 [b]**
☐	Operators properly licensed	**73.1860 [a]**
☐	Auxiliary, antenna authorization	**73.1230 [a]**
☐	Logs and Records available	**73.1225 [c]**
☐	Station available for FCC inspection	**73.1225 [a]**
☐	Logs relinquished to Commission on request	**73.1226 [a]**
☐	Chief operator designation	**73.1870 [b]**

2. New Station Notices To Be Filed

☐	Equipment test notice with Washington and EIC	**73.1610 [a]**
☐	Program test commencement notice with Washington	**73.1620 [a]**
☐	License application filed within 10 days	**73.1610 [a]**

3. Transmitter

☐	Transmitter type-accepted or approved, or as shown on license	**73.1665**
☐	Aural O.K. not more than 22% visual	**73.1560 [c] [2]**
☐	Visual operating power 80-110% of authorized	**73.1560 [c] [1]**
☐	Function of meters labeled	**73.688 [d]**
☐	Meters accurate	**73.1215 [f]**

☐	Means for measuring aural modulation	**73.688 [a]**
☐	(Meters) proper scale/range all powers	**73.1215**
☐	Interlock and safety provisions	**73.687 [d] [3]**
☐	Power adjustment capability	**73.687 [c] [3]**
☐	Efficiency O.K.	**Good engineering practice**
☐	Transmitter modifications approved	**73.1690 [b] [2]**
☐	Vestigial sideband filter if necessary	**73.687 [a] [3]**
☐	Harmonics suppressed at least 60 dB	**73.687 [i]**
☐	Carrier frequencies within tolerance	**73.1545 [c]**

4. Studio and Control Point

☐	Main studio location O.K. and licensed	**73.1125**
☐	Operator's primary duty is operation of transmitter	**73.1860 [d]**
☐	Equipment/wiring—good engineering practice	**73.687 [j]**
☐	Transmitter/Monitor visible to operator	**73.1860 [a]**
☐	EBS alarm visible or audible	**73.932 [a]**
☐	EBS check list immediately available	**73.908**

5. Tower and Antenna

☐	Tower location and height as licensed	**73.1690 [b] [3]**
☐	Correct color (TSA)	**17.23**
☐	Correct number of bands (TSA)	**17.23**
☐	Lighting agrees with license	**TSA**
☐	Top and flashing lights work or FAA notified	**17.48 [a]**
☐	Photocell and flashing mechanism	**TSA**
☐	Authority obtained for changes in antenna	**73.1690 [b] [3]**

6. Visual Signal Monitors

☐	Visual signal monitoring equipment installed and working	**73.691**

7. EBS

☐	Receiver decoder installed and working	**73.932 [a]**
☐	Weekly test transmission made unscheduled	**73.961 [c]**
☐	EBS tests received off-the-air	**73.932 [c]**
☐	EBS check list immediately available	**73.908**
☐	Equipment loan inventory installed and operational	**Terms of Contract**
☐	EBS tone encoder installed/working	**73.932 [b]**
☐	Correct station assignment monitored	**73.932 [a]**

8. Remote Control Operation

☐	Positive on/off	**73.1410 [a]**
☐	Transmitter secure	**73.1410 [b]**
☐	Operation discontinued if operation beyond station authorization not correctable	**73.1410 [e]**
☐	Remote equipment calibrated and tested as needed	**73.1410 [c]**
☐	Provisions for remote tower light check if not directly observed	**73.1410 [a]**
☐	Fail-safe for false activation	**73.1410 [d]**
☐	Remote control point(s) secure	**73.1410 [b]**

9. Extension Metering

☐ Transmitter accessible within 100 feet	**73,1550 [a] [2]**
☐ All required meters extended	**73.1550 [b]**
☐ Meters have standard scales	**73.1550 [a] [6]**
☐ Extension meters calibrated	**73.1550 [c]**
☐ Extension meters agree within 2%	**73.1550 [c] [3]**
☐ Extension meters operate continuously	**73.1550 [a] [5]**

10. Station Log

☐ Retained for 2 years	**73.1840 [a]**
☐ Signed by operators making entries	**73.1800 [a]**
☐ Reviewed and signed by designated chief operator	**73.1870 [c] [3]**
☐ Pages numbered and dated	**73.1800 [b]**
☐ Indicated advanced or nonadvanced times	**73.1800 [b]**
☐ Tower light failures	**73.1820 [a] [1] [i]**
☐ Data as specifically required by FCC	**73.1835**
☐ EBS tests transmitted and received	**73.961**
☐ Corrections made properly	**73.1800 [c]**
☐ Reason for EBS test failures	**73.932 [c]**

11. Public Inspection File

☐ Records at accessible location	**73.3526 [d]**
☐ Applications tendered (after May 13, 1965)	**73.3526 [a] [1]**
☐ Ownership reports filed (after May 13, 1965)	**73.3526 [a] [3]**

☐	Political time requests in public file	**73.3526 [a] [4]**
☐	Annual employment reports	**73.3526 [a] [5]**
☐	Public and Broadcasting Procedural Manual	**73.3526 [a] [6]**
☐	Letters from public as required	**73.3526 [a] [7]**
☐	Materials available for reproduction	**73.3526 [f]**
☐	Materials retained for proper period	**73.3526 [e]**
☐	Quarterly Issues/Programs List	**73.3526 [a] [8]**

12. Automatic Logging

Station Log

☐	Accurately calibrated, time, date and circuit functions	**73.1820 [b]**
☐	Autologger does not affect accuracy	**73.1820 [b] [1]**
☐	Equipment accurate	**73.1820 [b] [2]**
☐	Calibration of logger as needed	**73.1820 [b] [3]**
☐	Aural alarm circuit	**73.1820 [b] [4]**
☐	Parameters read continuously or at least once each 30 minutes	**73.1820 [b] [5]**
☐	Logger located in vicinity of operator	**73.1820 [b] [7]**
☐	Conforms with 73.1215 (arbitrary scales not authorized)	**73.1820 [b] [8]**
☐	No alterations after entry recorded	**73.1800 [d]**

13. Operator

☐	Chief operator employed	**73.1870 [b]**
☐	Licensed operator on duty	**73.1860 [a]**
☐	Operator properly instructed	**73.1860 [c]**

14. Other Operating Requirements

☐	Licensee conducted contest	**73.1216**
☐	Required station identification	**73.1201 [a]**
☐	Sponsors identified on air	**73.1212**
☐	Broadcast of telephone conversation	**73.1206**
☐	Rebroadcasting other stations	**73.1207**
☐	Delayed-recorded broadcast announced	**73.1208 [a]**
☐	No fraudulent billing	**73.1205**
☐	EEO compliance	**73.2080**
☐	Compliance with rules re: personal attacks and political editorials, broadcasts by candidates for public office	**73.1920, 73.1930 73.1940**
☐	Letters to Commission describing any emergency operation conducted by the station	**73.1250 [e]**
☐	Broadcast of Lottery Information	**73.1211**

15. Technical Signal Analysis

☐	Visual carrier frequency Nom. 1.25 MHz above lower bound	**73.682 [a] [2]**
☐	Visual carrier frequency tolerance within ± 1000 Hz	**73.668 [a]**
☐	Aural-Visual separation 4.5 MHz ± 1000 Hz	**73.668 [b]**
☐	Horizontal scan rate within tolerance	**73.682 [a] [6]**
☐	Vertical scan rate within tolerance	**73.682 [a] [6]**
☐	Chrominance frequency 3.579545 MHz ± 10 Hz	**73.682 [a] [5]**
☐	Blanking level 72.5-77.5%	**73.682 [a] [12]**
☐	Reference white level 10-15%	**73.682 [a] [13]**
☐	Setup interval 5-10 IRE units	**73.682 [a] [17]**
☐	Horizontal sync pulse width 4.4-5.1 us	**73.699**

☐	Front porch duration 1.3 us min.	**73.699**
☐	Sync to end-of-burst 7.9 us max.	**73.699**
☐	Sync to start of video 9.2 us min.	**73.699**
☐	Horizontal blanking interval 11.5 us max.	**73.699**
☐	Color burst length 8-11 cycles	**73.699**
☐	Color burst amplitude 90-110%	**73.699**
☐	Breezeway duration .4 us min.	**73.699**
☐	Pulse rise time .3 us max.	**73.699**
☐	Equalizing pulse width 2.5 us Nom. (45-50% H. sync)	**73.699**
☐	Serration width 3.8-5.1 us	**73.699**
☐	Blanking sync tip variation 5% max.	**73.682 [a] [16]**
☐	Teletext lines & levels	**73.682 [a] [24]**
☐	Vertical blanking interval 21 lines	**73.682 [a] [24]**
☐	Aural carrier modulation within limits	**73.1570 [b] [3]**
☐	Subcarrier modulation within limits	**73.1570 [b] [3]**

16. Auxiliary Broadcast Stations

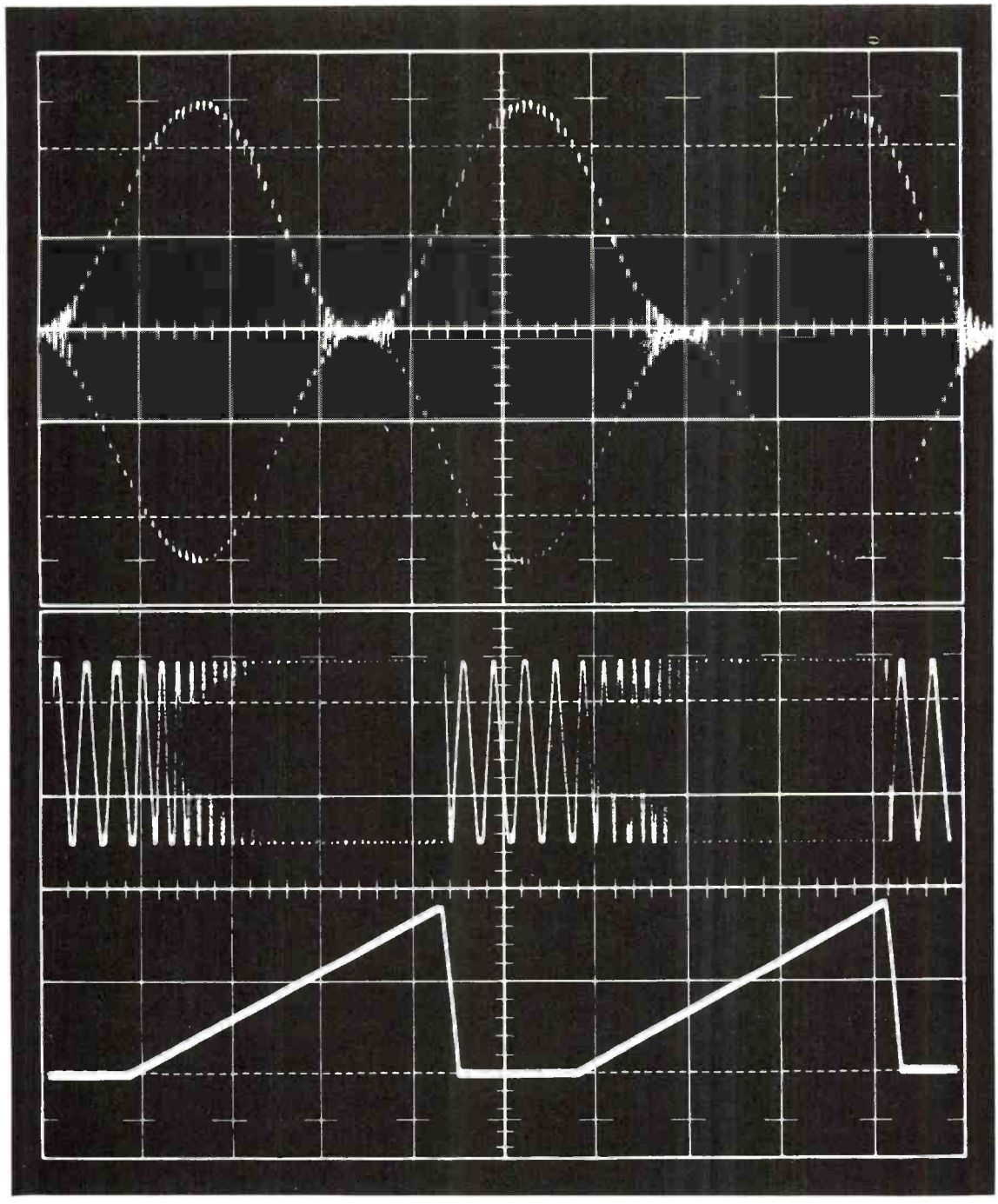
Remote Pickup Stations

☐	Operating power not in excess	**74.461**
☐	Frequency within tolerance	**74.464**
☐	License posted or attached to transmitter	**74.467 [a] or [b]**
☐	Operated under control of licensee	**74.18 [b]**
☐	Tower light entries required by Part 17	**74.30**
☐	Station identification given	**74.482**
☐	Repairs by qualified person	**74.18 [d]**

Remote Control Operation

☐	% modulation indicator or automatic modulation control	**74.434 [a] [1]**

☐	On/off control of RF stage	**74.434 [a] [2]**
☐	Protected against unauthorized operation	**74.434 [a] [3]**
	Aural Broadcasting Auxiliary Stations	
☐	Operating power not in excess	**74.534**
☐	Directional antenna required	**74.536**
☐	Frequency tolerance of .005% or for 18 GHz .003% maintained	**74.561**
☐	Station license posted	**74.564**
☐	Tower light records required by Part 17	**74.30**
☐	Station identification	**74.582**
	Remote Control Operation	
☐	RF or control activated device showing Tx is radiating	**74.533 [a] [2]**
☐	On/off control of RF stage	**74.533 [a] [3]**
☐	Protected against unauthorized operation	**74.533 [a] [4]**
	Unattended Operation	
☐	Notification to Commission 10 days prior to operation	**74.533 [b]**
☐	Protected against improper operation	**74.533 [b] [2]**
☐	Protected against unauthorized operation	**74.533 [b] [3]**
☐	Observations made at receiving end or operating position	**74.533 [b] [4]**



FEDERAL COMMUNICATIONS COMMISSION
FCC
USA

Provided by
Field Operations Bureau

AM & FM Broadcast Station Checklist

This **AM/FM Checklist** is provided to assist broadcast engineers and other technical staff in maintaining compliance with FCC Rules and Regulations.

For additional copies, contact the nearest field office or the FCC, Field Operations Bureau, Washington, D.C. 20554.

Provided by
Field Operations Bureau

December 1984

Partial Index By Subject To Rules For AM & FM Broadcast Stations

Since rules are subject to periodic revisions, listings should be checked with recent rule changes as they occur. This is not a complete listing of all rules to which stations may be subject.

TSA = Terms of Station Authorization
GEP = Good engineering practice

1. Station Document & Records	AM	FM
☐ License, CP, Renewal, Program test posted	73.1230 [a]	73.1230 [a]
☐ Operator licenses posted	73.1230 [b]	73.1230 [b]
☐ Alternate site, auxiliary antenna, PSRSA, PSSA, remote control (AM Directional) authority	73.1230 [a]	73.1230 [a]
☐ Designated chief operator agreement posted	73.1870 [a]	73.1870 [a]
☐ Contract chief operator agreement	73.1870 [b]	73.1870 [b]
☐ Antenna impedance measurement	73.1225 [c]	—
☐ Field strength measurement for directional systems	73.1225 [c]	—
☐ Contracts for brokers, etc.	73.1226 [c]	73.1226 [c]
☐ Logs and Records available	73.1225 [c]	73.1225 [c]
☐ Station available for FCC inspection	73.1225 [a]	73.1225 [a]
☐ Logs relinquished to Commission on request	73.1226 [a]	73.1226 [a]
☐ Common carrier SCA authorized	73.127 [b]	73.295 [b]

2. New Station Notices To Be Filed		
☐ Equipment test notice with Washington and EIC	73.1610 [a]	73.1610 [a]

☐ Program test authority advance notice with Washington or authorized for DA	73.1620 [a]	73.1620 [a]
☐ License application filed within 10 days	73.1610 [a]	73.1610 [a]

3. Transmitters

☐ Main transmitters acceptable	73.1665	73.1665
☐ Operating power correct	73.1560 [a]	73.1560 [b]
☐ Function of Meters labeled	73.58 [d]	73.258 [d]
☐ Meters accurate	73.1215 [f]	73.1215 [f]
☐ Meter(s) proper scale/range all powers	73.1215	73.1215
☐ Interlock and safety provisions	73.49	73.317 [b]
☐ Power adjustment capability	73.40 [a] [1]	73.317 [a] [8]
☐ Efficiency O.K.	GEP	GEP
☐ Transmitter efficiency factor available	—	73.267 [c] [3]
☐ Transmitter modifications approved	73.1690 [b]	73.1690 [b]
☐ Frequency in tolerance (AM—20 Hz, FM—2000 Hz)	73.1545 [a]	73.1545 [b]
☐ Modulation within tolerance (generally 85—100%)	73.1570 [b] [1]	73.1570 [b] [2]

4. Studio and Control Point

☐ Main studio location O.K. and licensed	73.1125	73.1125
☐ Operator's primary duty is operation of transmitter	73.1860 [d]	73.1860 [d]
☐ Equipment/wiring—good engineering practice	73.49	73.317 [c]
☐ Transmitter/control equipment visible to operator	73.1860 [b]	73.1860 [b]
☐ EBS alarm visible or audible	73.932 [a]	73.932 [a]
☐ EBS check lists immediately available	73.908	73.908
☐ Extension meters visible	73.1550 [a] [3]	73.1550 [a] [3]

☐	Operator can monitor/control SCA services	73.127 [e]	73.295 [e]

5. Tower and Antenna

☐	Authority obtained for change in radiating system	73.1690 [b] [3]	73.1690 [b] [3]
☐	Correct color (TSA—terms of station license)	17.23	17.23
☐	Correct number of bands (TSA)	17.23	17.23
☐	Lighting agrees with license	TSA	TSA
☐	Top and flashing lights work or FAA notified	17.48 [a]	17.48 [a]
☐	Photocell and flashing mechanism	TSA	TSA
☐	Radials protected and in good condition	73.189 [b] [4] & [5]	—
☐	Antenna & transmission line not exposed	73.49 [a]	—
☐	Base fence secure and grounded	73.49 [a] [8]	—
☐	Tuning house secure	73.49 [a] [8]	—
☐	Base ammeter 2% calibration to remote	73.57 [d] [3]	—
☐	Weeds cut in antenna area	GEP	—
☐	Satisfactory field strength at 1 mile	73.189 [b] [2]	—
☐	Spurious or harmonic emissions attenuated	73.44 [a]	73.317 [a]
☐	Base meters in range for all powers	73.58 [a]	—
☐	Remote antenna current pickup point located at, but below main meter	73.57 [b]	—
☐	Directional System Tolerances	73.62	—

6. Modulation Monitor

☐	Equipment for measuring modulation levels	73.58 [a]	73.258 [a]

7. EBS

☐	Receiver decoder installed and working	73.932 [a]	73.932 [a]
☐	Weekly test transmissions made unscheduled	73.961 [c]	73.961 [c]
☐	EBS tests being received	73.932 [c]	73.932 [c]
☐	Check list immediately available	73.908	73.908
☐	Equipment loan inventory O.K.	Terms of loan agreement	
☐	EBS tone encoder installed/working	73.932 [b]	73.932 [b]
☐	Monitoring correct station assignment	73.932 [a]	73.932 [a]

8. Remote Control Operation

☐	Positive on/off	73.1410 [a]	73.1410 [a]
☐	Transmitter secure	73.1410 [b]	73.1410 [b]
☐	Operation discontinued if operation beyond station authorization not correctable	73.1410 [e]	73.1410 [e]
☐	Remote equipment calibrated and tested as needed	73.1410 [c]	73.1410 [c]
☐	Remote control point(s) secure	73.1410 [b]	73.1410 [b]
☐	Fail safe for false activation	73.1410 [b]	73.1410 [d]
☐	Redundant control for automatic AM mode changes	73.1410 [a]	—
☐	Termination of remote control within three hours when required because of inaccurate readings	73.1410 [e]	73.1410 [e]
☐	Antenna monitor type approved for remote reading	73.53 [c] [9]	—
☐	Provisions for remote tower light check if not directly observed	73.1410 [a]	73.1410 [a]

9. Extension Metering

☐	Transmitter accessible within 100 feet	73.1550 [a] [2]	73.1550 [a] [2]
☐	All required meters extended	73.1550 [b]	73.1550 [b]
☐	Meters have correct scales	73.1550 [a] [6]	73.1550 [a] [6]

☐	Extension meters calibrated	73.1550 [c]	73.1550 [c]
☐	Extension meters agree within 2%	73.1550 [c] [3]	73.1550 [c] [3]
☐	Extension meters operate continuously	73.1550 [a] [5]	73.1550 [a] [5]

10. Station Log

☐	Logs retained for 2 years	73.1840 [a]	73.1840 [a]
☐	Signed by operator making entries	73.1800 [a]	73.1800 [a]
☐	AM DA field strength measurements	73.61 [a]	—
☐	Reviewed, signed and dated by designated chief	73.1870 [c] [3]	73.1870 [c] [3]
☐	Pages numbered and dated	73.1800 [b]	73.1800 [b]
☐	Indicated advanced or nonadvanced times	73.1800 [b]	73.1800 [b]
☐	Tower light observed failures	73.1820 [a] [1]	73.1820 [a] [1]
☐	Special technical data as required by FCC	73.1835	73.1835

AM Directional Antenna Stations Without Approved Sampling Systems

☐	Adjustments to transmitter parameters	73.1820 [a] [2] [i]	—
☐	Plate voltage and plate current	73.1820 [a] [2] [i]	—
☐	Antenna current or common point current	73.1820 [a] [2] [i] [B]	—
☐	Antenna monitor sample current, ratio or ratio deviation	73.1820 [a] [2]	—
☐	Phase indications	73.1820 [a] [2]	—
☐	Meter readings without modulation effects	73.1820 [a]	—
☐	No variation in readings for long periods	GEP	GEP
☐	Entries for commencement at each mode and at 3 hour intervals	73.1820 [a] [2]	—

☐	Efficiency factor derivation, Ep X Ip for indirect power	73.1820 [a] [2] [ii]	—
☐	EBS Tests transmitted and received	73.961 73.1820 [a] [1] [iv]	73.961 73.1820 [a] [1] [iv]
☐	Corrections made properly	73.1800 [c]	73.1800 [c]

11. Public Inspection File

☐	Records at accessible location	73.3526 [d]	73.3526 [d]
☐	Applications tendered after May 13, 1965	73.3526 [a] [1]	73.3526 [a] [1]
☐	Ownership reports filed after May 13, 1965	73.3526 [a] [3]	73.3626 [a] [3]
☐	Political use requests	73.3526 [a] [4]	73.3526 [a] [4]
☐	Annual employment reports	73.3526 [a] [5]	73.3526 [a] [5]
☐	Public and Broadcasting Procedural Manual	73.3526 [a] [6]	73.3526 [a] [6]
☐	Letters from public as required	73.3526 [a] [7]	73.3526 [a] [7]
☐	Issues/Programs list	73.3526 [a] [10]	73.3526 [a] [10]
☐	Materials available for reproduction	73.3526 [f]	73.3526 [f]
☐	Materials retained for proper period	73.3526 [e]	73.3526 [e]
☐	Donor announcement for non-commercial stations	73.3527 [a] [8]	73.3527 [a] [8]

12. Automatic Logging

Station Log

☐	Accurately calibrated, time, date and circuit functions	73.1820 [b]	—
☐	Autologger does not affect accuracy	73.1820 [b] [1]	—
☐	Equipment accuracy	73.1820 [b] [2]	—
☐	Calibration of logger as needed	73.1820 [b] [3]	—
☐	Aural alarm circuit	73.1820 [b] [4]	—

☐	Parameters read continuously or at least once each 30 minutes	73.1820 [b] [5]	—
☐	Logger located at control point	73.1820 [b] [6]	—
☐	Logger located in vicinity of operator	73.1820 [b] [7]	—
☐	Conforms with 73.1215 (arbitrary scales not authorized)	73.1820 [b] [8]	73.1820 [b] [8]
☐	No alterations after entry recorded	73.1800 [d]	73.1800 [d]

13. Radio Operator

☐	Chief operator employed or contracted	73.1870 [b]	73.1870 [b]
☐	Licensed operators on duty	73.1860 [a]	73.1860 [a]
☐	Operator properly instructed	73.1860 [c]	73.1860 [c]

14. Other Operating Requirements

☐	Required station identification	73.1201 [a]	73.1201 [a]
☐	Sponsors identified on air	73.1212	73.1212
☐	Presunrise authorized operation	73.99	—
☐	Time, power and modes of operation correct	73.1745	73.1745
☐	Broadcast of telephone conversation requirements	73.1206	73.1206
☐	Rebroadcasting other stations	73.1207	73.1207
☐	Delayed-recorded broadcast announced	73.1208 [a]	73.1208 [a]
☐	No fraudulent billing	73.1205	73.1205
☐	EEO Compliance	73.2080	73.2080
☐	Compliance with rules re: personal attacks and political editorials, broadcasts by candidates for public office	73.1920 73.1930 73.1940	73.1920 73.1930 73.1940
☐	Letter to Commission describing emergency operation	73.1250 [e]	73.1250 [e]

☐	Minimum Operating Schedule	73.1740	73.1740
☐	Licensee conducted contest	73.1216	73.1216
☐	Broadcast of Lottery Information	73.1211	73.1211

15. AM Measurements

		Required In Proof	Required Specifications
☐	Hum & noise referenced to 100% modulation at 400 Hz	—	73.40 [a] [6]

16. Directional Antenna System

		AM	FM
☐	Field strength measurements made as necessary	73.61	—
☐	Field strength meter available and working	73.61 [a] [1]	—
☐	Base current, sample loop current, phase angle agree with license	73.62	—
☐	Antenna monitor installed and working	73.69	—
☐	Field strength measured less than licensed maximum at monitoring points	TSA	—
☐	Monitor point satisfactory location and adequately described on license	GEP	—
☐	Antenna monitoring authorized type	73.69 [a]	—
☐	Approved sampling system O.K. if required	73.68	—

17. Stereo & SCA Operation

☐	Stereo pilot checked as necessary	—	73.297 [b]
☐	Stereo pilot injection 8 to 10%	—	73.322 [b]
☐	Stereo pilot frequency within 2 Hz	—	73.322 [b]
☐	Stereophonic subcarrier suppressed to less than 1% modulation of main carrier	—	73.322 [e]
☐	Subcarrier injections not excessive	—	73.319 [d]
☐	Subcarrier baseband within limits	—	73.319 [c]

18. Automatic Transmission Systems

☐	Authorization to use ATS	73.140 [c]	73.340 [c]
☐	ATS personnel licensee employees	73.146 [a]	73.346 [a]
☐	ATS personnel can perform monitoring & duties	73.146 [f]	73.346 [f]
☐	ATS personnel fully instructed on duties	73.146 [g]	73.346 [g]
☐	Tower lights checks either manual or automatic	73.146 [c] [3]	73.346 [c] [3]
☐	Only manual turn on used	73.140 [e]	73.340 [e]
	ATS control functions		
☐	Power adjust automatic	73.142 [b] [2]	73.342 [b] [2]
☐	Modulation adjust automatic	73.142 [b] [3]	73.342 [b] [3]
☐	Mode switching clock O.K. if needed	73.142 [d]	—
☐	Mode switching completely automatic	73.142 [d]	—
☐	Modulation control for SCA if used	—	73.342 [c]
☐	ATS auxiliary/alternate trans. O.K. if used	73.142 [g]	73.342 [g]
☐	Minimum modulation maintained	73.142 [b] [3]	73.342 [b] [3]
☐	Provision for indirect power function if used	—	73.342 [b] [1]
☐	ATS test system functioning	73.142 [i]	73.342 [i]
	ATS turn off and fail-safe functions		
☐	Over power uncorrected over 3 minutes	73.144 [a] [1]	73.344 [a] [1]
☐	Over modulation uncorrected over 3 minutes	73.144 [a] [2]	73.344 [a] [2]
☐	Clock for mode switching fails over 3 minutes	73.144 [a] [3]	—
☐	Loss of turn-on or turn-off control	73.144 [a] [4]	73.344 [a] [4]
☐	Loss of alarm device functioning	73.144 [a] [5]	73.344 [a] [5]
☐	Loss of alarm sampling circuits	73.144 [a] [6]	73.344 [a] [6]

	ATS alarm functions		
☐	Loss of signal (carrier or program) 3 minutes	73.146 [c] [1]	73.346 [c] [1]
☐	Power below 90% authorized over 3 minutes	73.146 [c] [2]	73.346 [c] [2]
☐	Tower lighting failure if alarms used	73.146 [c] [3]	73.346 [c] [3]
	ATS monitoring and alarm points		
☐	On/off controls functioning	73.146 [b] [1]	73.346 [b] [1]
☐	Off-air SCA program monitor for SCA	—	73.346 [b] [2]
☐	Off-air monitor	73.146 [b] [2]	73.346 [b] [2]
☐	Aural alarm signal functioning	73.146 [b] [3]	73.346 [b] [3]
☐	Point accessible & under licensee control	73.146 [a]	73.346 [a]
☐	Point controls protected from unauthorized operation	73.146 [a]	73.346 [a]
☐	EBS facilities provided as needed	73.146 [f]	73.346 [f]
☐	Licenses and ATS authorization posted	73.146 [h]	73.346 [h]

19. Auxiliary Broadcast Stations

Remote Pickup Stations

☐	License power not exceeded	74.461
☐	Frequency within tolerance	74.464
☐	License posted or attached to transmitter	74.467 [a] or [b]
☐	Operated under control of licensee	74.18 [b]
☐	Tower light records required by Part 17	74.30
☐	Station identification given	74.482
☐	Repairs by qualified person	74.18 [d]
	Remote Control Operation	
☐	% modulation indicator or automatic modulation control	73.434 [a] [1]
☐	On/off control of RF stage	74.434 [a] [2]

☐	Protected against unauthorized operation	74.434 [a] [3]
	Aural Broadcast Auxiliary Stations	
☐	Operating power not in excess	74.534
☐	Directional antenna required	74.536
☐	Frequency tolerance for offset operation	74.502 [a]
☐	Frequency tolerance of 0.005% or 0.003% for 18GHz maintained	74.561
☐	Station license posted	74.564
☐	Tower light records required by Part 17	74.30
☐	Station identification	74.582
	Remote Control Operation	
☐	Notification to Commission 10 days prior to operation	74.533 [a]
☐	RF or control activated device showing Tx is radiating	74.533 [a] [2]
☐	On/off control of RF stage	74.533 [a] [3]
☐	Protected against unauthorized operation	74.533 [a] [4]
	Unattended Operation	
☐	Notification to Commission 10 days prior to operation	74.533 [b]
☐	Protected against improper operation	74.533 [b] [2]
☐	Protected against unauthorized operation	74.533 [b] [3]
☐	Observations made at receiving end every day	74.533 [b] [4]

1.3

Frequency Coordination

Richard Rudman
Engineering Manager, KFWB
Los Angeles, California

WHAT IS FREQUENCY COORDINATION?

The push to leave the studio to originate programs has been a part of broadcasting from the beginning. Now, with over 9000 radio and 1150 TV stations on the air, the demand for reliable ways to get news, sports, public affairs and entertainment programming from the field back to the studio has naturally increased. Part 74 of the FCC's Rules deals with segments of the spectrum that have been assigned to the Broadcast Auxiliary Service to accommodate this demand. Part 74 also covers other services outside the scope of this discussion such as FM and TV translators, ITFS, and experimental broadcast stations.

While the number of stations requiring support spectrum has grown tremendously since 1970, the amount of spectrum allocated for this support has stayed relatively constant. Broadcasters using Part 74 spectrum began to experience competition for the limited number of channels allocated. Interference from other broadcasters has gradually become a critical problem in many markets and there are no provisions for exclusive licensing in Part 74. Consequently, broadcast frequency coordination is necessary to facilitate the allocation of limited spectrum for a growing number of uses among a growing number of users.

SOME HISTORY OF BROADCAST COORDINATION

Formal coordination has existed for some time for major events such as political conventions and space launches. In the case of the political conventions, the three national television networks have rotated the chairmanship of an "ad hoc" group, known as the National Political Conventions Frequency Coordinating Committee. Washington, D.C. has had unique coordination problems along with a history of cooperative effort for pool feeds to cover the workings of our Federal Government. Such committee activity has traditionally arisen out of a need, mutually felt by broadcast engineers, to discuss concerns before they become problems. Among the oldest groups formed to deal with mutual operational problems, including coordination, were the Washington Executive Broadcast Engineers (WEBE) and the TV Broadcasters All-Industry Committee in the New York metropolitan area.

The first major region to form a committee to deal exclusively with Part 74 coordination was

Several people made important contributions to both the new field of Part 74 coordination and this chapter of the NAB Engineering Handbook. They are: Don Wilson, present Chairman of the Southern California Frequency Coordinating Committee, for work on aural STL standards proposed in this chapter. Robert Van Buhler, Chairman of the Arizona Frequency Coordinating Committee for his case study on the AFCC, and work on frequency coordinating data bases. Larry Will, New Jersey Public Television, for his assistance on the TV microwave portion of this chapter.

TABLE 1. 1976 FCC 450 Channel Plan Showing SCFCC Waiver Changes.

Channel Designation	Channel Bandwidth	Peak FM Deviation	Total No. of Channels	SCFCC Waiver No.of Chs.
N1	50 kHz	10 kHz	12	0
N2	25	5	24	60
R	50	10	10	14
S	100	35	2	0
P	10	1.5	8	8

Note that since the SCFCC plan allows for center channel use of the "split" N1 50 kHz channels, the maximum number of 25 kHz channels can jump from 24 to 60 since the center channel can be used when geographic separation and or terrain shielding permit.

Southern California. In 1976, the FCC revised Part 74, Subpart D of its Rules which deals with the Remote Pickup Service used by radio and television stations for dispatch, on-air remote pickup, cues and orders, communications, and transmitter telemetry. Recognizing the use of narrowband FM technology, the Commission reallocated the UHF (450 and 455 MHz) frequencies from wideband 100 kHz channels to smaller bandwidth 50 kHz, 25 kHz and 10 kHz channels. Under the FCC's 1976 changes, R and S channels were intended for program material, and cues and orders necessary to implement that programming. N1 and N2 channels were to be used for broadcast program material, cues and orders necessary to that material, and operational communications. Microwave path setup and dispatch functions fall under this last category. P channels may be used only for Operational Communications and telemetry.

In the last half of 1976 CBS called a series of meetings in markets where they owned stations to discuss these changes with their fellow broadcasters. Prior to the FCC's 1976 changes, there were only ten 100 kHz channels in each 1 MHz band segment, for a total of 20 channels. With their 1976 Rulemaking, the FCC created five separate channel groups for specific uses. Southern California, already the scene of heavy 450 MHz activity, was the only region at that time to formally organize a group that held regular meetings.

The Southern California Frequency Coordination Committee (SCFCC) held its first official meeting in November, 1976. By early 1977, it had gained appoval of its membership to request a waiver of the FCC Rules. This waiver request proposed further splitting of the N1 50 kHz channels and the S 100 kHz channels. In 1980 the FCC granted this waiver. It was implemented successfully, and has become the basis for similar plans in other markets.

The SCFCC has been holding monthly meetings for the region since 1976 and has broadened its scope to deal with congestion in the Aural STL (Studio Transmitter Link) service, wireless mikes and RF cuing systems, as well as in the microwave bands for TV STL, Inter City Relay (ICR), and Television Pickup (ENG).

Regions such as Northern California, Arizona, Dallas, and New York organized according to the needs of their licensees. For example, the Northern California Frequency Coordinating Committee, building on bylaws prototyped by the SCFCC, recently incorporated as a non-profit organization. The Arizona group not only coordinates the entire state, but is deeply involved with coordinators for non-broadcast VHF, UHF, and microwave services, including public safety.

Coordination activity spans many aspects of broadcasting. Some regions have not experienced congestion and interference with their own licensees, but have organized committees to deal with problems associated with broadcasters who enter their regions for temporary operation. After conducting a survey at the chapter level on how this problem is viewed locally, the Society of Broadcast Engineers has identified frequency coordination as a chapter project. The SBE National Frequency Coordinating Committee (NFCC) was formed to assist any chapters interested in this project. In addition, the SBE NFCC publishes a list of volunteer coordinators who are responsible for over 80 regions in 50 states, plus Puerto Rico.

If there is one adjective that can be used to describe the nature of effective broadcast coordination, that word is local. Electronic news gathering for both radio and television introduces many unknowns. Mobile paths cannot be predicted from day to day, or even hour to hour. Large scale news, public affairs, or sporting events may mean interference for everyone involved unless technical personnel familiar with a number of factors are consulted. Since many of these factors concern local propagation anomalies, terrain considerations, and user patterns, experience has proven that engineers who work

with these factors at the local level on a day-to-day basis are the best people to consult with and to ask for advice for successful operations.

TERRAIN CONSIDERATIONS

Southern California is an excellent example of a region where most of the key two-way communication and microwave sites are located on mountains in line-of-sight relationship. In addition, there are numerous hilltop and building top sites lying along the 140 mile path between Mount Wilson near Los Angeles and the Mexican Border in San Diego. While adjacent and cochannel signal strength attenuation due to geographical separation between transmitters and receivers, along with some terrain shielding, allows some reuse of channels, frequency reuse and sharing under such conditions are severely limited in broadcast VHF, UHF, and microwave services and public safety. Regions such as New York-New Jersey-Philadelphia and Washington-Baltimore have unusual problems because licensees in different markets are so physically close that line-of-sight conditions exist.

When users are planning formal coordination, the use of topographical maps and engineers who have experience with the region's sites is strongly recommended. The word "regional" takes into account terrain influences. It transcends market and political divisions since RF does not respect man-made divisions and boundaries.

USER DENSITY

In the Southern California region, it is possible to tune in almost 70 AM and FM stations. There is television activity on more than 20 VHF and UHF channels. A large percentage of these stations need spectrum for the "backstage" needs of broadcasting: communications which support the on-air effort in any way. They include studio-to-transmitter links (STL), transmitter-to-studio links (TSL), intercity relay (ICR), remote pickup (RPU) for television and radio broadcasts from the field, news dispatch, wireless microphone, and telemetry and control links.

In a growing list of markets throughout the country, the sheer number of licensees requiring "backstage" support spectrum exceeds the capacity of the available spectrum. Part 74 licenses are issued on a non-exclusive basis. New licensees have a responsibility not to cause harmful interference to existing users. Because of this fact, broadcasters have voluntarily engaged in various types of coordination activities as a matter of survival in the highly competitive marketplace.

PROPAGATION ANOMALIES

A number of factors can modify the expected line-of-sight characteristics of VHF and UHF aural and visual transmission. Many of these can be understood best if the radio waves so affected are compared to light waves. Radio waves sometimes bend around corners in a manner that can be compared to light travelling through the reflective surfaces of a periscope so the viewer can see around corners.

The three most common propagation anomalies are (1) ducting effects, (2) reflection due to thermal inversion layers, and (3) obstacle gain (sometimes referred to as knife edge refraction).

These anomalies can occur for seconds at a time, or may exist in a predictable manner for much longer periods. For instance, obstacle gain can be used in some cases to provide permanent and quite dependable links. In the Part 74 environment, these anomalies have to be recognized and taken into account to assure cochannel and adjacent channel users of adequate protection for both fixed and mobile links. Known anomalies in a region must be factored into any coordinated environment. As in the case of terrain, licensees should seek out engineers who have long-time experience in the region to be coordinated so anomalies that have been identified, and the paths they affect, can be taken into consideration.

THE ESSENCE OF THE BROADCAST COORDINATION PROCESS

The successful coordination efforts mounted so far are all founded on one essential: *licensee-to-licensee contact*. The coordination effort, however it is structured, acts to *facilitate* this contact. As of this writing, Part 74 of the FCC's Rules places the burden of preventing interference squarely on the licensee. Since broadcasting is highly competitive, no local committee should place itself in a position where it "assigns" spectrum.

Successful committees never act as policemen. This role is left for the FCC if all other means of settling disputes fails. However, committees can and do use neutral mediators to try to solve the inevitable problems and disputes that arise in a competitive world. Successful committees are built on trust. This trust can be destroyed easily if committee leadership steps over the line between facilitating coordination and enforcing coordination.

In addition to the reasons mentioned that might lead broadcasters to start coordination activity, one more must be added. Many broadcasters now travel outside their markets to cover news, sports,

or public affairs events. In 1983 the FCC revised Section 74.24 of the Rules to make it easier for broadcasters to cover such events. A footnote to this Rules change asked that regional coordinators make themselves known to the Commission. The SBE NFCC was first formed to compile a list of coordinators to go beyond the Commission's request. The SBE NFCC updates this listing several times a year.

In Reply Comments filed in 1984 with the FCC concerning recognition of Part 74 coordination and the growing trend to enhance spectrum use by splitting wideband channels for both aural and visual needs, the Society of Broadcast Engineers National Frequency Coordinating Committee outlined several possible levels of coordination activity. These levels would be keyed to the actual needs of the licensees in a region where coordination appears to be desirable. These levels recognize that, while some regions require formal committees, many really do not. These guidelines may serve to help licensees achieve the level of coordination appropriate for their region:

Level One

Broadcasters do not form a regional committee. If any individual broadcaster wishes to implement an activity that requires group agreement, it must make a proper showing that it has taken steps to secure such agreement. This protects other licensees from harmful interference and insures operations will not be hampered by the actions of any one licensee. This level is appropriate for regions that are seldom visited by outside licensees and are exposed to little risk of interference from such sources and each other.

Level Two

Broadcasters, either independently, or through the auspices of their local SBE chapter, appoint a Data Base Administrator/Coordinator who serves as the contact for local broadcasters and those from outside the region who wish to operate under the 30 day/720 hour rule (Section 74.24). If modifications such as split channel operation are desired by any entity or entities, individual licensees are still responsible to make a showing to the FCC that other licensees are aware of their intentions and safeguards for their protection are in place. The appointed Coordinator or Administrator serves as a focal point for these activities. This person does not come in direct contact with the FCC. The SBE will list such Coordinators or Administrators and circulate this information to the Industry. This will support the ongoing program that facilitates transient coordination, and makes it easier for broadcasters in the same region to make others aware of changes in fixed and mobile operations.

Level Three

Broadcasters in a region form a Committee. A Data Base Administrator is appointed. The Committee serves as a forum to allow the region's licensees to do planning necessary to implement various types of operating practices. The impetus to form the Committee comes from a market's response to present or predicted Part 74 spectrum shortages. The region's licensees should be willing to invest time, effort, and financial backing to support data base maintenance, and regular meetings. The Committee and Administrator serve as the focal point to coordinate Section 74.24 activity.

Level Four

This level is based on groups like the Southern California Frequency Coordinating Committee, Northern California Frequency Coordinating Committee, Arizona Frequency Coordinating Committee, and the Washington Executive Broadcast Engineers. The organization and support given to the Committee are typical of major market level activity, or regional activity that involves an entire state. The Committee has usually been established for at least two years. It has adopted formal Bylaws, holds elections for officers, and may be incorporated.

Other typical characteristics are that it has been able to hold regular meetings that draw good attendance, publishes a newsletter on a regular basis, routinely interacts with other spectrum users regarding cochannel and adjacent channel assignments, provide a high level of informed technical advice to its members, and has had some experience and success in arbitrating disputes between members. It has an up-to-date data base maintained by a Data Base Administrator.

Such Committees have been able to build a level of communication and trust to bring about cooperative innovations such as ENG control point intercommunication, and state-of-the art computerized data base management.

WHAT DOES IT TAKE TO BUILD A SUCCESSFUL COORDINATING COMMITTEE?

Does Your Region Need a Committee?

If your market is experiencing the growing pains associated with Part 74 spectrum congestion, you and your fellow broadcasters might wish to form a Committee. Your analysis of terrain, user density, and propagation anomalies will help you and your fellow licensees find the right approach. Remember: This question can only be answered by the broadcasters in your region. No

outside force can or should make this decision for you.

We can speak with some degree of confidence on the adverse affects that interference can have on the operation of licensees in an uncoordinated environment. Aside from frustration and embarrassment of blown live shots and disrupted STL's, there is a real economic impact of time spent tracking interference, and of the possibility of lost revenue if there is lost air time.

Some Notes of Caution

There may be several key legal issues to be addressed before you proceed. A frequency coordinating committee is a type of trade association. The Southern California group and others have received legal advice from some of their member-licensees in an effort to develop safeguards against inadvertent antitrust activity. There is always a risk that some type of trade association activity could be interpreted as *restraint of trade.*

The other key issue is that of *membership.* If your market is typical, not all broadcasters will step forward to participate in committee activity. Yet, since Part 74 spectrum access remains non-exclusive, all licensees have the same access rights. Your committee exists to protect interference-free access for as many licensees as possible. Again, as a trade association, you must make sure this precept is planted clearly in the minds of all who participate. Actions perceived as limiting or preventing anyone's access could be viewed as a form of restraint of trade.

The best way to assure this never happens is to conduct committee business in as open a manner as possible. The Southern California group found the best way to accomplish this was to publish a newsletter and send it monthly to every broadcast licensee in the entire region.

With over 250 licensees in over 10,000 square miles, this represents a sizeable monthly mailing burden. Yet, the SCFCC Newsletter goes to each and every licensee. While some have never been to a meeting, the newsletter serves as an acknowledgement of their membership.

It is important to inform licensees who do not attend meetings as well as those who do that *every* licensee has equal status, membership rights, (including voting), and equal spectrum access. Many misunderstandings can be avoided if this point is made early in the formative process and repeated often.

Regarding legal questions, the best general advice is for you to consult legal counsel before proceeding to form your committee to avoid any possible legal complications. As formation takes place, advise each licensee to check with their legal advisors as well.

How to Start

If you are attempting to form a regional committee, your first challenge is to call the region's licensees together for a general meeting. The purpose of this meeting will be to outline why you feel a committee is necessary for your region. Since you will be trying to get as many licensees to send engineering representatives to attend this meeting as possible, you should consider drafting a written letter of invitation to each licensee. The *Broadcasting Yearbook* is a readily available source for licensee information. You should at this point have some idea of the RF considerations that will shape your region and committee. Remember that political and physical boundaries will not necessarily agree with what you might recommend as a RF coordination region.

Writing the Letter

The letter should include your reasons for calling the meeting, and some discussion of the benefits of forming a committee. Depending on the market, you may wish to ask a manufacturer or vendor to send the letter out on their letterhead. This approach may help some people in the area view the meeting more objectively. At this stage, a lot depends on the basic relationships between licensees in your region. If there has been little contact in the past, anything that helps promote a productive meeting of all licensees will in turn help to build the level of trust necessary to start your committee.

What About Inviting Non-Broadcasters?

It is far better to invite participation of cable systems, manufacturers, two-way site managers, and entities such as CNN and Wold (if they operate in your region) than to leave them out. First, we share spectrum with several non-broadcast services. Second, you will need the cooperation and input from site managers and manufacturers to give your committee access to the right people to get perspectives on mutual problems and to come up with solutions. If there are coordinating groups for Amateur or Public Safety in your region, invite them to come to your meetings once you are organized.

Another Benefit of Committee Activity

One of the most important contributions frequency committee activity can make to active participants is serving as a common meeting ground. The trust and mutual respect that must be the foundation for group cooperation and decision making are built on the simple act of people getting to know each other. Some simple things to help this process along are using name tags dur-

ing early meetings, and starting a tradition of everyone standing up at the beginning of each meeting and introducing themselves.

Basics for Running Meetings

Provide a sign-up list that is passed around at the beginning of each meeting. You might want to have space on the sign-up list so people can indicate their Amateur Radio call sign. Many engineers who will attend are involved in this hobby. If you decide to publish a monthly newsletter (strongly recommended) the names of everyone attending meetings should be included. Your monthly newsletter may start out just as a meeting notice, and a recap of what happened at the last meeting. It should also contain an agenda for the coming meeting.

This is important for two reasons. First, it will help meeting attendance if people know that specific issues will be discussed. Second, many legal authorities believe trade association meetings should be run by sticking to an agenda as a further way of eliminating any hint of actions that might involve restraint of trade. Someone should be appointed to keep notes during each meeting for the same reason. These notes will be the basis for newsletter information. Since each meeting should have time set aside for everyone to give reports on their own RF systems (including any proposed changes), accurate notes become the vehicle for up-to-date information on what is happening in the market. Good, clear notes can also be important should the committee become involved in some legal action.

Parliamentary procedure as outlined in *Roberts Rules of Order* should be used to run your meetings. While many committees are ultimately able to run meetings with a high degree of informality, it is best to start off with a chairman or leader. Members should raise their hands to be recognized. A good chairman will make sure everyone is heard on every issue.

Your Mailing List

Your mailing list is an important part of your data base. As mentioned above, make sure you include all actual and potential licensees, even (and especially) if they do not attend meetings. Include cable operators, two-way site managers, consultants, dealers, manufacturers, and other nearby coordination groups. You should consider including group or headquarter engineering management for stations in your region. There is no such thing as too much written communication to your members concerning the activities of a coordinating committee.

Leadership

Your group should decide on a chairman and vice-chairman to run the meetings and provide liaison and leadership for your efforts. If politics are an integral part of your market's facts of life, it is best to get everyone's views (and fears) out in the open concerning committee leadership in the early stages of formation. Since this is rarely possible, you should be aware that these considerations can and do affect committee effectiveness.

Voting vs. Consensus

There are relatively few issues that require a formal vote. If this issue comes up, your committee will have to decide what weight to give each licensee's membership. The SCFCC and several other committees decided to give each license a vote for each band of operation for which it is duly licensed. A television station engagted in ENG plus two-way dispatch would therefore have two votes. A radio station with an aural STL and a 450 MHz RPU would also have two votes. Manufacturers, and others not holding licenses can join in discussion, but do not vote. If your committee is truly operating as a facilitator and a vehicle for information exchange, voting should not be a significant issue.

The issue of consensus is a vital one. Your committee may be deciding how to implement a 450 MHz split channel plan. If you cannot get agreement from all involved licensees to, for instance, split the Group S 100 kHz channels down to four 50 kHz Group R channels, this does not easily fall under the heading of majority rule. In fact, taking group action that might limit a station's ability to do certain types of operation might be viewed as restraint of trade. As in other committee matters that involve legal considerations, work slowly, and get informed legal opinions before taking action.

Conflict

For conflicts that cannot be solved on technical merits, you will have to be creative. Try to get impartial parties involved in mediation. Do not overlook the benefits of subcommittee meetings, working lunches and dinners, and other semi-social occasions where consensus might be sought. If all else fails, you may have to go back to the drawing board and try another approach.

Sometimes a tactic termed "enlightened peer pressure" is useful. If a majority in your committee discusses their views in front of the minority in a constructive, logical manner, breakthroughs can sometimes be made.

Committee Costs

Most committees get their early backing for postage, meeting places, and refreshments from some of the larger stations in a market. Once you are established, you may decide to collect dues, sell advertising in your monthly newsletter, or rotate financial responsibilities among members on a monthly basis. As in other areas, you will have to find what will work in your region.

Goals

Especially in the early stages of your committee, pick one goal and see it through. If TV ENG operation is the leading problem area in in your region, tackle it first. It does little good to work on things that are working well. The tough projects are where committee action will be most appreciated. Your goal is to establish a credible working group.

Meeting Dates

It may seem simplistic to mention such a trivial topic, but it is vital to set your next meeting date before each meeting adjourns. Never skip months in the early stages of formation. In fact, in those early days, you might find it advisable to set up weekly meetings. Try to identify a specific day of the week, and a specific week of each month for your meetings. After a period of time everyone will know that is when your meetings are scheduled. This will help meeting attendance.

COORDINATION CONSIDERATIONS FOR VARIOUS BROADCAST USES OF PART 74 SPECTRUM

Dispatch and Aural Remote Pickup

Channels for this purpose are currently available in a range from 26 MHz to 455 MHz (see accompanying Part 74 tabular listing of frequencies). Spectrum allocated for this purpose just above the standard broadcast band is slated for new AM stations and will become unavailable for Remote Pickup.

In major markets experiencing congestion, and in other markets where older equipment is still in service, 26 MHz operation for dispatch and even some types of remote pickup are still being done. Low power cuing systems for TV field operations sometimes appear in this band. Since it is near to present Citizen's Band channels, it is subject to interference from this service. Propagation conditions at 26 MHz include "skip" so it is common to experience interference in this band from hundreds, or thousands of miles away at certain times of the year.

VHF dispatch and aural remote pickup are more common throughout the country. With the advent of excellent commercial narrowband FM mobile tranceivers and remotely operated base stations on hills and mountains many radio and TV stations have used the Part 74 VHF channels reliably for years. Until recently, it appeared repeater operation at VHF would never happen under Part 74. However, with the development of Remote Pickup Amplitude Compandored Sideband (ACSB) technology, repeater operation at VHF has become feasible. ACSB transmission can be accomplished using 5 kHz channels that can be interleaved between existing VHF narrowband equipment that operates in 25 and 30 kHz channels. The FCC has now approved VHF repeater operation. It is likely that hybrid FM/ACSB systems will be common for stations with heavy current investments in FM equipment. Hand held ACSB portable radios are also available for VHF.

Frequency committees will face a challenge to implement split channel operation as ACSB becomes known as a reliable communications medium. The challenge will come from other services whose licensees may resent broadcasters' expanding use of VHF channels, and from Part 74 licensees who may not be aware of the benefits of ACSB technology.

Tests show ACSB can equal FM performance, and even exceed FM in situations where impulse noise is a consideration. Noise energy that can enter an ACSB radio receiver is limited since bandwidth is only 5 kHz, and compandoring techniques further reduce apparent impulse noise in the received signal. This technology shows great promise for gaining the greatest possible use and efficiency in the limited spectrum available to meet the operational needs of the broadcast industry.

Fig. 1. Mobile communications gear used on a typical KFWB news vehicle. (Photo courtesy KFWB Radio)

Committees will be confronted with a number of seemingly conflicting uses and users as they sort through years of accumulated problems in VHF bands. One guiding principal that has helped many committees is the order of priorities outlined by the FCC. The transmission of remote pickup program material for broadcast, either live or delayed, takes precedence over other permissible uses. There is no reason to believe that the existing order of priorities will change.

VHF and UHF remote pickup with usable audio frequency response to 15 kHz is available with a variety of equipment. In many regions, interference from adjacent channels licensed to other services makes such operation difficult. A strong adjacent channel signal can "capture" an FM receiver, pulling the discriminator away from the desired signal. As channel use builds in a region, broadband white noise rises, making life difficult for wideband receivers.

Some equipment marketed for broadcast use was not designed for today's levels of channel congestion and sometimes makes the problem appear worse than it really is. Sometimes adding cavity filters to receivers helps. Sometimes relocating the receiver and antenna to a "quiet" location is the answer.

With the advent of solid state finals in transmitters, the need for cavity filters on all transmitter outputs has increased. Odd order harmonic products are a characteristic of solid state finals. Older vacuum tube equipment produced even order products as a rule. Good engineering practice now dictates using cavity filters between the transmitter and antenna, especially at common sites.

In the case of repeaters, good practice indicates installing a ferrite circulator and an appropriate reject load to reduce the possibility of unwanted mixing. With repeater operation now possible on Part 74 VHF channels, and the already high level of VHF activity in a number of radio services, committees have a responsibility to make everyone aware of these considerations.

Broadband white noise at common sites is now being viewed as much of a culprit to degraded receiver performance as spurious emissions. As the number of transmitters at a site increases, the noise level at the site increases. This noise desensitizes all receivers at the site. If a user is operating a receiver at a common site used for high power paging transmitters that are on the air most of the time, the receiver may be trying to listen in a channel less than 1 MHz away from a 250 watt transmitter with a gain antenna. The resultant 1000 watts (ERP) can cause problems for even the best equipment. Committees can educate members on this subject as well.

Committees can educate members on the pitfalls of common sites, and work with site managers to let them know of licensee concerns. There is a trend in many markets toward reengineering common sites using transmitter and receiver combiners, and physical separation of transmit and receive antennas. These changes can improve the transmit and receive performance at most sites. Changes like this are expensive. A committee can educate users on the benefits of such projects, and help generate support to make them happen.

Many committees accomplish educational and informational goals by setting aside time during monthly meetings. They invite manufacturers and distributors to put on educational programs. These range from how to use a spectrum analyzer, to how to engineer a receiver or transmitter combiner.

The two blocks of UHF channels available to broadcast licensees are separated by 5 MHz. This is adequate for repeater operations, and many licensees in markets with hilly or mountainous terrain have employed this type of system to allow field units to communicate with the base no matter where they are. Repeater operation has the benefit of being truly wireless, since remote base systems usually depend on telephone company local channels for control and audio.

Unfortunately, repeater operation requires two channels. The high level of repeater use in Southern California was one of the driving forces that led the SCFCC to request a waiver from the FCC to split the 50 kHz Group N1 channels into more 25 kHz channels, and the two 100 kHz Group S channels into four 50 kHz R channels.

Spectrum efficiency in the UHF bands by splitting channels is becoming an accepted mode of operation in other markets. Since it is possible to derive audio response beyond 5 kHz from a 25 kHz narrowband FM channel, many radio stations who want better audio quality for news reports can get it without using a 50 kHz R channel, provided the receiver used is well into full quieting. Committees can work with their members to make sure everyone is using the least amount of bandwidth consistent with needs.

Similarly, a station engaged in voice dispatch does not need a 50 kHz N1 channel. A 25 kHz N2 channel is more than adequate for this use. Responsible committees can help assure that use is matched to bandwidth. Narrowband operation using 5 kHz channels is only possible in the Part 74 VHF channels with ACSB equipment. ACSB equipment for UHF is not available as of this writing. Manufacturers of VHF ACSB equipment now on the market say that it is being developed.

Committees can sometimes arrange sharing of channels between compatible users. This can even involve several licensees operating a community repeater system. This choice not only helps

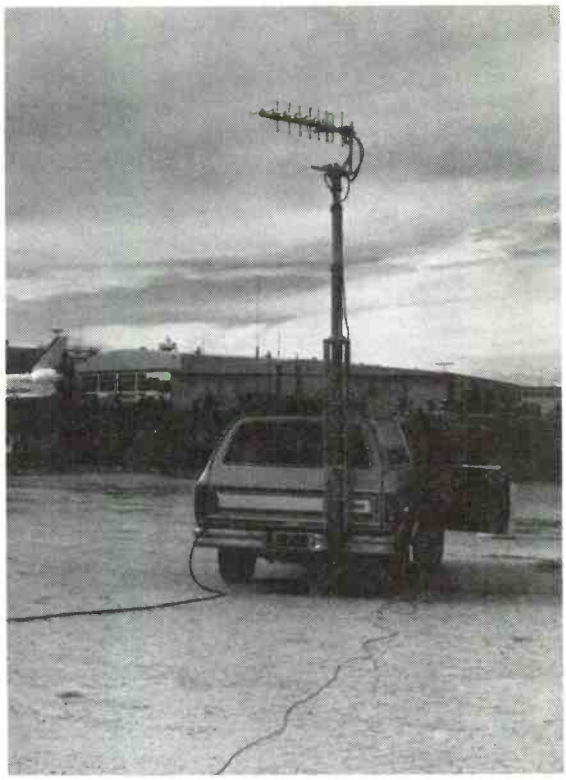


Fig. 2. The KFWB 4-wheel-drive mobile unit/repeater station features a verstile 40-foot pneumatic mast. (Photos taken by KFWB, Los Angeles. Supplied courtesy of *Broadcast Engineering* magazine.)

enhance spectrum efficiency, but may mean small stations can become part of a larger system they could not otherwise afford.

When new users are looking for Part 74 aural communications, there are some things a committee can do to ease the process along:

1. Make sure the potential user understands he must be a Part 73 licensee, or a Network (as defined in Part 74) to qualify for Part 74 channels.
2. Make sure he knows the committee really exists to help accommodate new users in bands already crowded—not to keep new users out.
3. Ask him to explain his needs during an open committee meeting, and publish what is said in the newsletter so everyone concerned can be aware of what is going on. It may be that someone at the meeting might make a suggestion to the potential user that could improve his system, or even accomodate his needs by some other means. For instance, cellular mobile telephones might be all someone needs to do ENG microwave setup if there are no dispatch channels left in a market.
4. The committee may "recommend" certain frequencies. At this point, it is up to the potential licensee to contact each co-channel and adjacent channel occupant and complete the transaction. It is NOT the responsibility of the committee to do this.
5. In the event the parties reach an impasse regarding an issue, the committee can and should act as a mediating force. Usually a compromise can be arranged.

In a congested RF environment, there is always the possibility of adjacent channel interference. Mobiles operating in the field can find themselves next to other mobiles transmitting on an adjacent channel. If this channel happens to be on the repeater output of the first station, the person in the mobile cannot communicate with its base while the other mobile has its transmitter on. If this is a chronic problem, one station may find it desirable to change frequencies. No amount of coordination will ever solve all of these problems.

There is at least one operating practice a committee can promote that will help: Make it a standard in the market for each licensee to use his appropriate station identification and unit designator call sign. Not only is this in compliance with FCC Rules, but call signs make it easier to track down interference problems that will inevitably arise.

AURAL STL CONSIDERATIONS

The FCC has now supplemented the existing 950 MHz Aural STL band with additional channels in the 18 GHz band. While of questionable value in markets that experience appreciable snowfall, this new band does offer the benefits that will come about from digital audio techniques impossible at 950 MHz because of limited bandwidth. This new band is viable according to a General Telephone paper presented during the 1984 NAB Convention for paths up to ten miles.

At this writing, the FCC has not decided what will happen with licensees in the 942-947 MHz "grandfathered" portion of the band. With new services such as AM stereo and enhanced services such as FM SCA, more and more stations will want to install their own wireless STL systems. This situation presents an ongoing problem for licensees and frequency committees alike.

In 1979 the SCFCC held a symposium for Aural STL licensees and equipment manufacturers in Los Angeles. Its purpose was to develop guidelines for the design, installation, and operation of Aural 950 MHz systems:

1. A list of stations using the band is required. The list should state the following items:
   A. Transmitter coordinates in degrees, minutes, and seconds

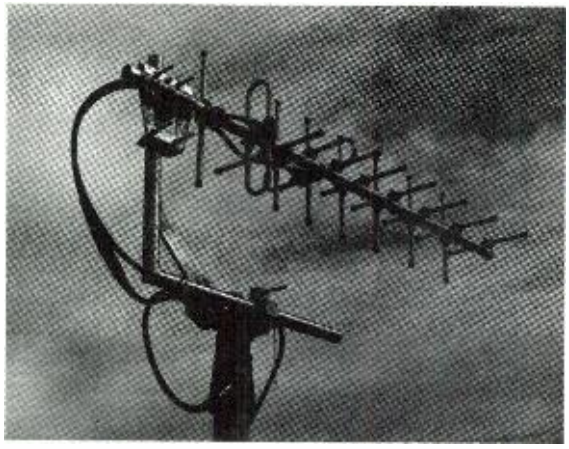


Fig. 3. Close-up of the cross-polarized yagi transmitting antenna used on the KFWB mobile unit/repeater station (Photos taken by KFWB, Los Angeles. Supplied courtesy of *Broadcast Engineering* magazine).

B. Receiver coordinates in degrees, minutes, and seconds
C. Frequencies used
D. System type (Composite, Dual, Mono)
E. Manufacturers and model numbers of receivers, transmitters, antennas, and feedline.
F. Transmitter antenna azimuth
G. Receiver antenna azimuth
H. Antenna polarization for each transmit link
I. Transmitter Power Output (TPO)
J. Effective Radiated Power (ERP) in dBm
K. Power available to the receiver in dBm
L. Path length

2. All systems should be designed with a known signal level at the receive site. The use of obstructed paths should be avoided since protection for stations attempting such paths is difficult to achieve.
3. Systems operating into the same site should, wherever possible, attempt to operate into the site at the same signal level.
4. Systems should be designed for an adequate but not excessive fade margin (approximately 30 dB in most cases). The transmitter power output should be reduced as much as possible to comply with this goal. It is recognized in some cases TPO will have to be raised for an increased fade margin to override interference.
5. Systems should be designed using antenna manufacturer's radiation pattern envelopes for their antennas at all points. All paths should be assumed to be line-of-sight in initial calculations.
6. Antenna beamwidth should be as narrow as possible. Six foot solid dishes are highly desirable. Although Paraflector (C) type antennas are acceptable for vertical polarization beam control, four foot dishes, miniflectors, and yagi antennas should be avoided.
7. Frequency tolerance for all systems should be .001%, not the presently allowable tolerance of .005% for monaural systems.
8. Dual systems should use the same polarization for each link to make channel reuse more possible for other paths. It is recognized that not all equipment is capable of accomplishing this as a goal. Stations should not arbitrarily change polarization without a thorough engineering study and necessary notification of co-channel and adjacent channel licensees.
9. There should be an external modulation limiting device ahead of all STL transmitters to limit transmitted bandwidth through the link since some STL transmitters do not incorporate internal limiting and can deviate beyond channel limits. The limiter should be frequency sensitive. If limiting cannot be installed, modulation levels should be reduced to prevent overdeviation. Cross polarization is NOT an acceptable means to accomplish this protection.
10. A bandpass filter and circulator should be used with any system likely to produce spurious emissions. This would include all transmitters operating at common radio sites, all varactor systems, and all transmitters combined into a common antenna. In the latter case, a hybrid alone is insufficient. There must be greater that 70 dB isolation, transmitter-to-transmitter. A table of proposed acceptable interference ratios was also discussed at the symposium and has been used as a guide in Southern California and several other regions:

There are non-RF alternatives available for STL systems. Laser links are feasible for very short distances where there is little likelihood of any interruption of the line-of-sight path.

Many stations still rely on program channels leased from their local telephone company. For short distances that do not involve very many telephone exchanges, this may still represent the best solution for some stations. This may be true especially in markets that have reached STL saturation.

Microwave STL's should be promoted for stations needing the extra quality and/or reliability these systems can provide if they are designed and coordinated properly. Licensees wishing to design new systems may balk at the rather strict design parameters outlined in this section. For instance,

TABLE 2. Interference Ratios Expressed in Decibels

	Co-Channel		Offset + or — 100-150 kHz		
	Composite Or Mono To Composite	Dual To Dual Or Composite Or Mono To Mono	Mono To Dual Or Dual To Mono	Composite To Dual	Dual To Composite
Current Equipment	55	45	40	50	55
Short Term Goal	50	40	35	45	50
Ultimate Goal	45	35	30	40	45

	Composite				Dual/Mono			
	350-400 kHz	500-700 kHz	1 MHz-3 MHz	3 MHz-10 MHz	200-300 kHz	500 kHz-1 MHz	1 MHz-3 MHz	3 MHz-10 MHz
Current Equipment	0	0	10	30	10	20	30	40
Short Term Goal	10	15	30	50	20	30	40	60
Ultimate Goal	25	40	60	80	40	50	60	80

six foot solid design parameters may be "overkill" for certain applications. Committees might remind their members that if the majority of the STL's in a market are engineered for efficient spectrum use, more users can be accommodated in the band, they will enjoy greater immunity from interference, and the reliability of their paths will be maximized.

TV MICROWAVE CONSIDERATIONS

Television has come to rely on either their own or common carrier microwave links to interconnect their studios with their transmitters and to facilitate live remote broadcasts. Rules governing links operated by broadcasters are found in Part 74 of the FCC Regulations and cover frequencies from 2, 7 and 13 GHz bands, and also shared frequencies in the 18, 21, 23, and 39 GHz bands.

Microwave transmissions can accommodate one or more subcarriers imbedded in the video signal to carry mono or stereo television sound, aural service for a co-owned AM or FM station, program cuing, telemetry, or a combination of these elements. In congested markets there is a trend to use the lowest possible subcarrier frequency combinations to keep occupied bandwidth as low as possible.

In major markets the number of stations engaged in field operations exceeds the number of available channels. While spectrum is available in the 2, 2.5, 7, 13, 18, 23 and GHz bands at this time, many stations and coordinating committees in these major markets have opted to make 2 GHz the primary band for ENG. However, this band will have some level of STL and ICR activity for the foreseeable future due to its long haul propagation characteristics.

The trend to using 2 GHz for ENG with its better propagation characteristics at 2 GHz as a choice over the other bands means stations have to install fewer ENG receive locations in their service area. Path lengths up to 50 miles can be operated reliably and under optimum conditions, including low humidity, path lengths up to 100 miles may be possible. Since it is not cost effective to equip a field truck and several ENG receive sites for multiple band operation, 2 GHz seems to have been the logical choice.

What this has meant in many markets is intense competition for the seven primary 2 GHz channels (1.9 through 2.1 GHz) and for the three channels at 2.4 GHz These are not available for broadcast use in some markets, and are shared

with other users in markets where they are available. This factor has contributed to the rise in frequency coordinating committee formation and activity.

Stations having 2 GHz STL's have been, for the most part, open to suggestions to relocate to 7 or 13 GHz in some cases for several reasons. First, they may themselves be involved in 2 GHz ENG. Second, a fixed link in this band has a high potential risk of interference from mobile operations. Since modern TV ENG portable equipment is frequency agile, and non-technical personnel are more involved in field operations, this is a very real risk.

Coordination for ENG is being done more and more on a "real time" basis. Coverage of breaking news cannot be planned. Coupled with the limited number of 2 GHz channels, the entire subject of 2 GHz band usage and will be a controversial topic in more and more markets.

The 1984 Olympics in Los Angeles proved to be a testing ground for ideas that have been proposed and tried in several markets. The 2 GHz Microwave Subcommittee formed under the auspices of the World Broadcasters RF Committee came up with a number of recommendations and set several goals. The broadcasters of Los Angeles followed many of these recommendations and met most of the goals. The Olympics stand as a very successful page in the history of broadcast frequency coordination. Coordination of ABC's 2 GHz operations in a band that already had more users than channels was the greatest challenge the broadcasters in the market had to face.

Suggested Operational Guidelines for TV ENG Operations

1. Form a Microwave Subcommittee. Compile a list of persons responsible for ENG technical and operational decisions at each station. This list should contain telephone numbers good 24 hours a day, should be circulated to all stations involved in ENG operations, and should be updated as needed.

Fig. 4. The KIRO-TV Chopper Seven helicopter is used for live news broadcasts and as a repeater station when needed for live ground shots. (Photos taken by KIRO-TV, Seattle, WA. Supplied courtesy of *Broadcast Engineering* magazine.)

2. The Microwave Subcommittee should be a forum to devise a Home Channel Plan for the region. The purpose of this plan is to give each user a primary channel for his operation. Alternate polarization is assigned to each channel. Split channel operation should be the long range goal for the market. Every user is furnished with a copy of this plan for reference.

3. As part of this plan, each user should set a goal to become frequency, polarization, and power agile.

4. Once the Home Channel Plan has been worked out, a method of coordinating this plan in real time is needed. WEBE in Washington pioneered a hard wired ring down network between ENG control points. The SCFCC expanded on this idea and put into operation an ACSB VHF community repeater with base stations located at the control point of each ENG licensee. This ACSB system was a key part of the coordination plan for the 1984 Olympics.

5. Each licensee should set a goal to equip his ENG operation at the following level:
   A. Mobile transmitters should be frequency agile.
   B. Each transmitter shall have continuously variable control of output power.
   C. Each mobile truck should ideally be equipped with an antenna with excellent sidelobe supression of the "Silhouette" (C) type.
   D. Each mobile truck should be capable of changing the polarity of their feed.
   E. Each truck should have a means of identifying its test bars, and ideally be able to identify its transmissions in the vertical interval. If this latter type of equipment is employed, the ID is viewed by unlocking the vertical hold control of a video monitor. (This signal must be stripped by a processing amplifier prior to on-air broadcast!)

6. Each licensee should refrain from using audio subcarriers higher than 4.8 MHz (For programs requiring dual subcarrier audio, success has been reported using 4.6 and 4.8 MHz subcarriers together.)

7. Truck crews are instructed to never light up until they receive permission from their control point, even on their home channel.

8. Truck crews should receive careful instruction on polarity settings, using only enough power for the path involved, and in the overall operational agreements with other stations engaged in ENG activity.
9. Stations should install antennas with maximum directivity at their receive locations. Preamplifiers, and channel filters that can be switched in and out of the signal path should be employed to take best advantage of the Home Channel Plan.
10. Stations normally stay on their home channel. They use the ENG control point communication system to request different channels for extra activity, to eliminate inevitable adjacent channel interference during some operations, or for paths that conflict on their home channel with Inter City Relay (ICR) links, or STL's. The request is made of the station who is assigned the desired channel as its Home Channel.

THE BENEFITS OF COORDINATION FOR MICROWAVE USERS

The 7 GHz Band

The 6.875 to 7.125 GHz band of ten channels is typically used for STL's and ICR's. Some use for remote pickup (RPU) has taken place and it has proven to be very satisfactory.

The bulk of all STL's throughout the country are in this band. There is some shared activity possible in this band with common carriers in the 6.425 and 6.525 GHz range.

The 13 GHz Band

The 12.7 to 13.25 GHz band with 44 channels (including offsets) is used also for ICR and STL activity. It is also being used more and more for low power "window" microwave to relay signals from isolated cameras in and out of the studio. (Fig. 1) This band is shared with the cable television relay service (CARS) and with private operational fixed service users on a co-equal basis. The chief liability of this band (and any microwave band at approximately 8 GHz or higher) is degradation due to rain and snow attenuation. Careful engineering is required to insure uninterrupted service, particularly for fixed links.

General Equipment Considerations

Visual microwave transmitter power in the broadcast auxiliary service runs from about 0.1 through a maximum of 20 watts. Antennas for fixed paths are generally parabolic, or in some extreme cases of the "horn" type to concentrate power at a distant receiver and to recover as much of the power as possible. The use of highly directional antennas is required in the ICR and STL service to permit geographic reuse of frequencies. Horizontal, vertical, or circular polarization is used to permit further reuse, and to eliminate ghosting interference from adjacent channels, particularly in RPU service. Circular polarization in particular is helpful in reducing ghosting on relays blocked by obstructions. These obstructions may cause polarity changes that negate benefits of simple vertical or horizontal polarization.

Temporary Operation for TV Microwave RPU

As in the aural services, temporary operation away from a station's service area without a special license is permitted for up to 720 hours or 30 days per year under Part 74.24 of the Rules. As mentioned earlier in this chapter, the Coordinator Listing compiled and maintained by the SBE can make coordination for this type of operation less painful. The coordination burden is still on the licensee who is visiting not to cause interference to the local stations. During this type of operation, the visitor uses his broadcast on-air call sign, not their Part 74 call sign. This rule is primarily designed to cover special events and should not be substituted for filing licenses. While coordinating committees do their best, for temporary operations, having a license insures co-equal status.

Microwave Licensing Considerations

Form 313 is used to apply. Instructions are included with blank forms. A license is always required for an STL or ICR, and implies careful engineering and coordination. The FCC currently issues a "one step" Construction Permit (CP) and license. Further information on the design of microwave links can be found in "Engineering Considerations for Microwave Communications" published by GTE Lenkurt, Incorporated, Copyright 1975.

The Benefits of Coordination for Microwave Licensees

As in the case of all Part 74 coordination, committees exist to help new and existing licensees share very limited amounts of spectrum. The move to frequency agility has made real time coordination possible for mobile operations. It mandates cooperation and sharing. In return, it allows licensees to operate their field ENG equipment and STL's with reduced risk of interference.

INTERFERENCE AND THE PART 74 LICENSEE

Interference to a Part 74 licensee's operations may come from almost any source of RF one cares to mention. Radiation from unshielded computer cables has interfered with wireless microphone operation, for instance. On channel interference from other broadcasters can be thought of as a problem that can be solved by additional attempts at coordination, followed, if necessary, by mediation by a neutral party.

Locating the source of spurious emissions can be a real challenge. The committee can offer some advice and support when a suspected case of interference from an out-of-channel source is reported. Quite often, other stations in the market can make spectrum analyzers available to eliminate the possibility of a mixing product that is actually generated in the front end of the receiver due to an overload condition. This type of problem is common for both voice and video equipment.

Older solid state receivers are sometimes quite prone to front end overload. When an overload-prone receiver is operating at a common site with an appreciable amount of adjacent channel activity, the receiver may be rendered useless. Filtering and attenuator pads can sometimes be suggested as cures. Video microwave receivers operating with preamplifiers can overload easily as a result of proper adjacent channel operation. In such cases, a suggestion to provide a bypass switch is in order.

Committees should encourage licensees to use call letters and unit identifiers for all voice transmissions. All video ENG trucks should be able to transmit bars with ID, and ideally should be able to place ID in the vertical interval as well for identification during program transmission.

Tracking unidentified interference is not unlike detective work. For video, tuning through the on-air signals may provide a clue. If bars with no ID are seen at an ENG receive location, triangulation may be possible if the interference can be seen by two other locations equipped with steerable dishes. Trucks have been identified by reading street signs that appear in shots. Talent on other stations can sometimes be a good means of identification.

Interference to aural links can be very challenging to trace. If call letters are not being used, anything heard then becomes a clue. If a street address is mentioned, a newsroom "criss-cross" telephone directory can be used to find a telephone number at or near the address. A call to the number identifying yourself, your reason for calling, and if a taxicab or delivery truck has been there (or will be there) often works wonders.

Land mobile transmitters are sometimes designed so the final has power applied to it at all times. Any instability in the final can start it oscillating. These transmitters can sometimes migrate through many megaHertz of spectrum, almost at random. When their exciters are keyed, they return to their proper channel. Sometimes only a spectrum analyzer and a lot of patience can trace this type of problem.

Inexpensive direction finding equipment is available for VHF and UHF tracking. Some units work with any hand-held portable. For unmodulated carriers and other types of interference that are present for long periods of time, direction finding can be a very effective (though time consuming and expensive) process.

If the licensee(s) involved, even with committee guidance, are unable to locate the interference, a call to the FCC may be in order. You will be asked for all pertinent information, such as time the interference occurs, its nature, duration, and any other details you might have learned. They generally will not take interference complaints unless you can supply this information. Remember that coordinating committees and their members are never to act as police in such matters.

Curing Interference

Dealing with the broad topic of interference cures is beyond the scope of this chapter. When committees are working to solve such problems, creativity is definitely an asset. For instance, in a case where an aural STL on an adjacent channel on a parallel path was causing interference, the cure that was tried and worked involved installing a larger dish at the transmitter. The dish was aimed slightly off azimuth from its receiver so that the receive site being interfered with appeared in a deep null of the interfering transmit antenna.

SETTING UP A COMMITTEE: A CASE STUDY

This chapter has outlined many topics Part 74 licensees should take into consideration in their day-to-day operations in coordinated and uncoordinated environments. At this point it might be useful to look at a case study of how one market dealt with its particular set of circumstances. The market selected for this analysis is Phoenix, Arizona.

Frequency coordinating in Arizona dates back to the early 1970's when the Society of Broadcast Engineers (SBE) began to keep track on a formal basis of Part 74 license assignments in the

Phoenix area. In the late 1970's, it became apparent that frequency coordination was more than a one man job.

Lists were being updated annually, but changes were occurring weekly. Within the Phoenix market, most broadcasters were making the transition to 950 MHz microwave Aural STL operation for obvious reasons. Soon, all the frequencies in the band were in use. Out of band channels were sought. It was clear channel sharing would be impossible without detailed and accurate information.

To add to the drama, new TV stations were coming on line in the market. They had needs for studio transmitter links (STL's); transmitter studio links (TSL's) for video relay and telemetry return; channels for electronic news gathering (ENG); plus Intercity Relay (ICR) links for network affiliates and cable companies.

The situation was complicated by the proximity of the Tucson market. Phoenix's South Mountain transmitter sites have a line of sight relationship to the primary TV transmission location of the Tucson market, Mt. Bigelow, located 100 miles Southeast. The potential for mutual interference was present.

These are the circumstances under which the Arizona Frequency Coordinating Committee was formed. Organization was provided for the committee by Chapter 9 of the SBE, and funding by the Arizona Broadcasters Association. The organizational structure was patterned after the Southern California Coordinating Committee.

Officer selection is based on function and availability, but Board nominations take geographic considerations into account to insure all areas of the state are represented, as well as all types of users. Board members from television, AM, FM, and cable, are nominated and elected on that basis.

The multi-market coordination process involves the use of two main coordination contacts working with a single database. For practical reasons, a separate coordinator exists for Tucson and Southerna Arizona, and one in Phoenix for Phoenix, Central, and Northern Arizona.

The philosophy governing the Coordinating Committee is one of *facilitating* coordination. It does not act as a consulting service. It does promote spectrum management and spectrum efficiency by fostering user-to-user dialogue, providing accurate record keeping, and insuring prompt dissemination of information.

The data is compiled in Phoenix on an Apple II Plus computer with dual disc drives, running a multisort database management system. This allows the integration of data for the extensive broadcast and cable use of the shared CARS band.

The coordinators rotate updated computer diskettes monthly, and share data by telephone weekly. Change in the diskettes are only made by the database manager. This is a designated duty of the Secretary-Treasurer of the AFCC. Focusing entry responsibility on one individual protects the database from the "too many cooks" syndrome.

Mailing and duplication costs are deferred by small classified ads in the AFCC Newsletter which is published monthly. We send copies of out newsletter to key personnel at the Federal Communications Commission as well as to all broadcasters and cable companies in Arizona. We also exchange newsletters with several other coordinating committees.

When asked for information, the AFCC manager gives the potential applicant data on other users of the frequency of interest. The party making the query is then expected to contact cochannel and adjacent channel users as appropriate to determine if specific objections to sharing exist. The database manager will point out possible problems, and may suggest an alternative frequency if the primary channel suggested cannot be coordinated. If the potential user is at a loss to determine a frequency that suits his needs and causes no interference, the database manager assists in selecting one.

Users of A, B, and D band microwave channels send a letter to the Committee informing it of their plans to use a specific frequency, with copies of the letter to all other users of the band in the region. The Committee publishes the data in the master list and the Newsletter. Specific objections are discussed by the users at the AFCC meeting, or on a one-on-one basis between users.

FCC releases and BROADCASTING magazine are scanned regularly to determine any new or potential licensees who may begin to operate in the state. The new broadcaster is sent a letter about the AFCC, and stressing the importance of frequency coordination. This letter also gives details on contacts to accomplish coordination.

All broadcasters and cablecasters in the state are updated on available coordination information on a monthly basis. Meetings are held ten times a year in Phoenix to provide a regular forum for the discussion of issues related to coordination and interference, or coordination problems that have arisen since the last meeting. The month of the NAB convention and December are the dark months for meetings.

Annual elections are held for the officers and the board. No limits to tenure of service are employed. In accordance with the bylaws, nominations are tendered at the November meeting and elections are held in January. With the concurence of a majority of the membership,

the Committee may comment to the FCC on matters directly or indirectly related to Part 74.

OPERATION GOLDEN RULE

The SBE National Coordinating Committee has an ongoing educational program on coordination named Operation Golden Rule. Its purpose is to make non-engineering broadcast management aware of the vital importance of coordination to their operations, and to promote the simple but effective idea that the original Golden Rule expresses the best ideals of coordination.

The theory behind this approach is simple. Since so many routine operations are now accomplished by non-technical personnel, and the usual top management at stations is non-technical, we must raise awareness concerning coordination, or our best technical efforts may be meaningless.

GOALS OF THE SBE NATIONAL FREQUENCY COORDINATING COMMITTEE

1. To identify persons willing to act as local data base administrators in light of the FCC's rewrite of Part 74.24 of the Rules. (The Commission requested persons wishing to act as coordinators make themselves known so licensees could utilize the 30 day/720 hour rule effectively, and operate without causing interference to licensees in the area they are visiting.)
2. To publish a listing of these individuals and circulate it widely throughout the Industry to supplement the FCC's stated goal under 74.24.
3. To facilitate exchange of ideas among regional coordinating bodies.
4. To ascertain problems pertaining to coordination and work to solve them.
5. To increase awareness in non-engineering management of the importance of frequency coordination as an essential "back stage" activity to all of broadcasting through an informational campaign, OPERATION GOLDEN RULE.

So far, the SBE NFCC has identified over 80 individuals throughout the 50 states, and Puerto Rico who have volunteered for this important work. It has worked with entities such as the National Political Frequency Coordinating Committee and the World Broadcasters RF Committee on various aspects of successful coordination for the political conventions and the Olympics. The NFCC has supplied Comments to the FCC on important Industry issues such as the microwave Docket where we helped make the case that the 2 and 7 GHz. TV ENG bands should not be opened to non-broadcast licensees and the channel splitting docket that we hope will allow more efficient use of the very limited number of voice channels in Part 74.

Through space in management oriented publications such as *Broadcasting*, appearances before Industry management groups, the GOLDEN RULE effort has helped promote cooperation at all levels within Part 74 activity.

The SBE considers frequency coordination to be a key Chapter activity in regions where no other body exists to facilitate licensee-to-licensee contact regarding Part 74.

MORE INFORMATION

For more information on Operation Golden Rule, an up to date list of coordinators, or additional questions on coordinating committees, contact the Society of Broadcast Engineers, P.O. Box 50844, Indianapolis, Indiana 46250.

CHAPTER 17
MINNEAPOLIS/ST. PAUL
SOCIETY OF BROADCAST ENGINEERS

RPU, STL, TSL AND OTHER AUXILIARY BROADCAST SERVICES FREQUENCY COORDINATION PROJECT REPORT FORM

Station Call or Corporate Name: _____
Street Address: _____
City: _____ State: _____ Zip: _____
Contact Person: _____ Title: _____
Phone Number: _____ Extension: _____

Please answer the following questions as accurately as possible. If you are unsure of some information, try to locate that information on your FCC Instrument of Authorization, or leave it blank. If you have more than one service to report, please photocopy this form as many times as you need, or call any member of the Committee for more.

1	TYPE OF SERVICE (Circle one): REMOTE PICKUP STUDIO-TRANSMITTER LINK TRANSMITTER-STUDIO LINK AUXILLIARY OTHER			
2	CALL SIGN OF SERVICE:			
3	OPERATING FREQUENCY:		FREQUENCY #2 (If so equipped):	
4	TYPE OF EMISSION:			
5	CONFIGURATION (Circle one): MONAURAL	DUAL MONAURAL	STEREO (Composite)	
6	TRANSMITTER OUTPUT POWER:		Circle one: WATTS	dBm
		TRANSMITTER	**RECEIVER**	
7	LOCATION: North Latitude: West Longitude:	° ′ ″ ° ′ ″	° ′ ″ ° ′ ″	
8	TYPE OF ANTENNA/dB GAIN/°AZIMUTH:			
9	POLARIZATION (Circle one):	Horizontal Veritcal CP	Horizontal Vertical CP	
10	ANTENNA HEIGHT ABOVE GROUND:	feet	feet	
11	GROUND HEIGHT ABOVE MEAN SEA LEVEL:	feet	feet	

12 DESCRIBE ANY SPECIAL CONDITIONS OR ADDITIONAL INFORMATION:

Now just fold and mail! THANK YOU!

Form FCPR-1-83

Sample database questionnaire submitted by SBE Chapter 17.

ARIZONA FREQUENCY COORDINATING COMMITTEE
LISTING OF BROADCASTING/CABLE DATA BY FREQUENCY-D1
AS OF: JAN FEB MAR APR MAY JUN JLY SEP OCT NOV DEC 1984

FREQUENCY (MHZ)	FCC ID EMISSION	LICENSEE/ID FREQUENCY USE DATE E/U	RECEIVER COORDINATES REMARKS 1	TRANSMITTER COORDINATES REMARKS 2	D/ND AZIMUTH	POLAR POWER (W)	REC #
450.450	WBJ-981 100F3	KTSP-TV, CH 10, PHOENIX RPU-BASE STATION U 11/11/83	N 33 20 02 W 112 03 42	N 33 20 02 W 112 03 42	—ND— N/A	VERT. 75.0	145
450.450	WHE-761 25F3	KVOA-TV, CH 4, TUCSON AUTOMATIC RELAY STATION U 05/19/83	N 32 24 56 W 110 42 49	N 32 24 56 W 110 42 49	—N— N/A	VERT. 75.0	146
450.4875	WQA-984 16F3	KNIX-AM/FM, TEMPE AUTOMATIC RELAY STATION U 03/21/83	N 33 19 58 W 112 03 53	N 33 19 58 W 112 03 53	—ND— N/A	VERT. 90.0	147
450.500							148
450.5125	KIW-877 25F3	KGUN-TV, CH 9, TUCSON AUTOMATIC RELAY STATION U 05/19/83	N 32 12 48 W 111 00 20	N 32 12 48 W 111 00 20	—ND— N/A	VERT. 75.0	149
450.550	APPLIED	KDTU-TV, Ch 18, TUCSON AUTOMATIC RELAY STATION E 03/17/84					150
450.550	KON-241 50F3	KHYT-AM, TUCSON AUTOMATIC RELAY STATION U 05/19/83	N 32 10 46 W 110 54 55	N 32 10 46 W 110 54 55	—ND— N/A	VERT. 100.0	151
450.550	KBH-744 50F3	KOY-AM, PHOENIX AUTOMATIC RELAY STATION U 01/07/83	N 33 27 30 W 112 04 24	N 33 20 06 W 112 03 39	—ND— N/A	VERT. 75.0	152
450.5875	KIV-89 25F3	KGUN-TV, CH 9, TUCSON RPU-BASE STATION U 05/19/83	N 32 14 49 W 110 58 38	N 32 14 49 W 110 58 38	—ND— N/A	VERT. 25.0	153

Sample database printout for the 450 mHz band.

1.4

Consultant Services: When and How to Use Them

Alan E. Gearing, P.E.
John F. X. Browne, P.E.
Association of Federal Communications Consulting Engineers
Washington, DC

The dictionary defines a consultant as a person who gives expert or professional advice. Our complex, technologically oriented society has created the need for experts who advise on subjects requiring specialized knowledge and experience.

Broadcast applicants and licensees employ the services of consultants to assist with various aspects of the conduct of their business such as engineering, finance, legal, marketing, personnel, and programming areas. The need for these services may arise for many reasons including the unavailability of staff, the need for expertise not found in-house, or the need for additional manpower to ensure timely completion of a project. Broadcasters selecting technical consultants may be unfamiliar with the variety of services normally offered, or with the procedures for selecting and engaging such a consultant which are most likely to result in a successful relationship.

The extent of services offered by consultants ranges from evaluation and recommendation, to supervision of installation, to complete turnkey responsibilities. The types of consultants range from those handling transmission and general broadcast engineering matters to those specializing in narrowly defined areas. Examples of the latter include experts in broadcast building design and acoustics, tower design and maintenance, and telephone system planning.

The tables at the end of this chapter contain a partial listing of the types of services provided. Table 1 includes services applicable to all types of broadcast facilities. Services specific to AM broadcast stations are listed in Table 2, and Table 3 lists services mainly applicable to FM and TV broadcast stations.

Many consultants offer services of the types listed in the tables for other communications activities in which some broadcasters may also be involved, such as:

- Instructional Television Fixed Service Systems
- Multichannel Multipoint Distribution Sytems
- Satellite Up Link, Down Link, and Space Facilities
- Microwave Relay Systems
- Paging Systems
- Land Mobile Systems
- Cellular Radio Systems
- International Broadcast (Shortwave) Facilities
- Subcarrier Services
- LPTV and Translator Systems
- Remote Pickup and other Auxiliary Systems
- Fiber Optic Systems

Some of the activities engaged in by consultants may affect the public in matters of health, safety, and welfare. Therefore, various means have been used to provide some assurance to the public that practitioners have at least threshold qualifica-

tions. For example, the states and some professional organizations have established minimum qualifications for persons acting in certain professional capacities including the practice of engineering. All fifty states and the District of Columbia have engineering registration laws.

The practice of broadcast and telecommunications consulting engineering is, with few exceptions, a professional field in which most states require the practitioner to be registered as a Professional Engineer, or "PE". In most cases in fact, registration is required in order legally to represent oneself as a consulting *engineer* or as providing professional engineering services. At the present time the Federal Communications Commission does not require that filings submitted by applicants and licensees be prepared by a registered Professional Engineer.

Professional Engineers are registered or licensed through a process involving verification of educational credentials (e.g., a degree in engineering or related science), the attainment of specific engineering experience (usually a minimum of four years, post graduation) plus the passing of an examination gauging the applicant's mastery of engineering fundamentals and his or her specific field of engineering practice (usually a two-day, 16-hour written exam).

The services listed in the Tables at the end of this chapter include both those which fall within the realm of the Professional Engineer and those which may not require such certification. While the guidelines for selecting a consultant, contained in this chapter, refer to the Professional Engineer or consulting engineer, they can, and should, be used as a general guide in the selection of any type of consultant service.

Professional Engineers usually subscribe to a code-of-ethics such as those adopted by the National Society of Professional Engineers (NSPE) and the Association of Federal Communications Consulting Engineers (AFCCE). Many engineering societies representing the various engineering disciplines also support ethical codes for their members.

These codes require a standard of professional conduct which govern the consultant's activites and his relationship with clients in areas such as:

- Advertising
- Solicitation of clients
- Conflicts of interest
- Confidentiality of client activities
- Practice in field of expertise
- Use of the work of other engineers

Copies of these representative codes of ethics may be obtained free of charge from the:

National Society of Professional Engineers
2029 K Street, NW
Washington, D.C. 20006

and the:

Association of Federal Communications Consulting Engineers
P.O. Box 19333
20th St. Station
Washington, D.C. 20036

The selection of a consulting engineer does not have to be a confusing formal process. Initial contacts with prospective consulting engineers are often made by referral from communications attorneys or on the recommendations of other broadcasters. Additionally, "professional cards" in trade publications or referrals by engineering societies are sources of listings on professional practitioners.

When selecting a consulting engineer the broadcaster should discuss the following topics with the potential consultant:

- professional qualifications and registrations
- knowledge of FCC Rules and Regulations and international agreements
- expertise in the particular area of interest
- recent experience
- availability of professional staff, time and facilities
- estimated time for completion
- estimated fees or fee structure

Since individual requirements vary, the above list may not be all inclusive. As a general rule, the qualifying items may be considered to be listed in descending order of importance in the selection process. Selecting a consultant primarily on a "low bid" basis is usually not in the best interests of the broadcaster.

Once a consulting engineer has been selected for a specific project an agreement regarding the scope of work, timetables and fees is normally executed. In its simplest form this may merely be an exchange of informal letters; on complex projects, particularly those involving large scale construction, there may be a need for formalized contractual documents.

To assist the consulting engineer in the performance of his work, the client should provide any and all background material as well as earlier engineering documentation that may have been developed on the project. It is important that the client recognize that the use of such information is at the discretion of the consultant, and that a fee quoted on the basis of the validity and applicability of such data to a new project may have

to be adjusted if the data are found to be unsuitable or inaccurate. In some contexts, such as filings with the FCC, the consultant must attest to the accuracy of the data being presented and, therefore, he must have a high level of confidence in data which he did not personally generate in order to incorporate it. There may also be legal or ethical problems associated with incorporating the engineering work product of other engineers, especially that prepared by non-registered or unqualified practitioners.

Changes in technical details which may appear to be minor to the client often have major impact on the work completed by the consulting engineer. A transmitter site relocation of only a mile, for example, may involve recomputation of service areas, operating parameters, interference protections or separations, or aeronautical impact. For these reasons the client should attempt to finalize such details—with guidance from the consulting engineer—as early as possible, but especially before authorizing the completion of final reports or applications.

In many cases FCC applications must be filed before certain dates which are established by processing procedures or mandated in FCC docket actions. Since the preparation of these filings in a professional manner can require a rather lengthy time frame, the client should give the consulting engineer sufficient advance notice of such filing deadlines.

In the absence of formal arrangements to the contrary, consulting engineers do not generally assume the responsibility of monitoring FCC actions in behalf of present or former clients, to note activities (such as competitive filings, notices, or grants) which could have an impact on a client's existing or proposed facility. Such monitoring is often performed by the station's legal counsel and is also available directly from some of the computer database firms serving the broadcast industry. One way in which consulting engineers do provide such monitoring, relative to potential engineering impact, is through retainer agreements in which the client employs the consultant's services under an ongoing arrangement. The agreement usually specifies the level of services, such as FCC monitoring, that will be provided and the method of reporting to be used. In some cases, such agreements also specify that the consultant will make available a specified minimum amount of staff time which may be used over the course of the agreement to respond to the client's needs as they arise.

The client should have an understanding with the consultant regarding ownership of documentation produced by the consultant. It is common practice for the consulting engineer to retain all rights to files, drawings, reports, and other work products. The consultant grants to the client permission to use such data for specified FCC filings and for retention as part of the station's files. Normally, the data cannot be transferred to another party, or copied and used as part of another filing, or incorporated as part of a design for another project or facility without the express consent of all parties.

When a consulting engineer is engaged there should be a clear understanding between the parties as to the scope of work and responsibilities of each, particularly if the client (broadcaster) desires to perform part of the engineering work in-house or plans to employ other consultants for portions of the project. There is a great potential for both duplicative efforts and omissions in these arrangements when areas of responsibility are not clearly defined. While the initial objective may have been to minimize the consulting engineer's time (and fees) the result could very well be the opposite.

There are some consultants offering services which are oriented to field projects, such as equipment installation, construction, and measurements. These persons or firms operate as extensions of the broadcaster's staff and usually can bring a wealth of practical experience and additional manpower that the broadcaster may not have in-house. Professional engineering certifications may not be required for these services, but the possession of an appropriate FCC Commercial Operator's license may be required if transmitter related services are performed. Any measurements made by these consultants, which will ultimately be used in connection with FCC filings, should be collected, assembled, and presented (including certifications) in an acceptable form. Coordination of these activities with the station's consulting engineer may be desirable. References concerning the qualifications and capabilities of such consultants may be obtained form the station's consulting engineer or the other referral sources listed earlier.

CONSULTING SERVICES

The following tables show the types of technical consulting services available to broadcasters from various sources.

Table 1: Services Applicable to All Types of Broadcast Facilities

- Allocation studies to determine the feasibility of establishing new stations at specified communities.
- Allocation studies to determine the feasibility of improving existing facilities.

- Determination of appropriate areas where transmitting facilities may be located.
- Preparation of specifications for transmitting systems.
- Transmitter plant design and construction.
- Evaluation and recommendation of equipment for studios, newsrooms, remotes, automation.
- Studio design and construction including proper acoustics, sound proofing, lighting, heating and air conditioning.
- Design and installation of in-house telephone systems.
- Preparation of specifications for computer systems and their installation and maintenance.
- Antenna tower planning, including placement of antennas, intermodulation studies, and multicoupler and filter requirements to avoid interference.
- Tower design, erection, and maintenance.
- Structural analysis of towers and antennas.
- Design and installation of equipment for lightning protection.
- Evaluation of manufacturer's equipment bids.
- Electromagnetic interference studies to determine whether or not a proposed new or improved facility would cause interference to an existing station or to another proposed new or improved facility.
- Electromagnetic radiation hazard analyses.
- Environmental impact studies.
- Population and area service analyses.
- Determination of existing and proposed services in a particular area.
- Preparation of engineering portions of applications to the FCC for construction permits and licenses.
- Consideration of air hazard aspects, and preparation of notice to FAA, of proposed construction.
- Review of engineering proposals by other stations or applicants.
- Preparation of engineering in support of petitions to deny, or replies to petitions to deny.
- Provision of expert testimony in hearings or court proceedings.
- Field review of station facilities to determine compliance with FCC Rules, and to determine the general condition of station facilities.
- Measurement and adjustment of transmission systems to establish proper operation and compliance with FCC Rules.
- Appraisals of facilities for buyers, sellers, and brokers.
- Development of operational and monitoring procedures, including specification of test equipment.
- Analysis and design of special-purpose antennas, waveguides, transmission lines, cavity resonators, and other electromagnetic devices.
- Training of technical personnel.

Table 2: Services Applicable to AM Broadcast Stations

- Measurements of RF field strength relative to allocation matters.
- Design of directional antenna systems.
- Design of phasing and coupling equipment for directional antenna systems.
- Adjustment of directional antenna systems (proof of performance).
- Investigation of effects of reradiating obstacles (buildings, power lines, water towers, utility poles, irregular terrain, nearby antennas and arrays) upon antenna performance.
- Design of special filters or detuning networks which may be required.
- Investigation of electromagnetic effects of guy wires upon AM broadcast antennas and arrays.

Table 3: Services Applicable to FM and TV Broadcast Stations

- Study of feasibility of adding allotments to FCC Table of Allotments.
- Preparation of engineering support for petition for rulemaking.
- Review of engineering aspects of comments and providing engineering support for reply comments.
- Study of and recommendations for optimum height, power, location, and vertical and horizontal radiation pattern characteristics.
- Propagation studies, including use of alternate models and taking into account actual terrain features.
- Field strength and signal quality surveys of existing facilities.
- Prepartion of specifications for antenna systems including review of manufacturer's range tests results.
- Investigation of electromagnetic effects of support towers and guy wires upon TV and FM broadcast antenna.

1.5

Frequency Allocations for Broadcasting and the Broadcast Auxiliary Services

Michael C. Rau
Staff Engineer
Department of Science and Technology
National Association of Broadcasters
Washington, D.C.

INTRODUCTION

This chapter provides a summary and overview of frequency allocations available for AM, FM and TV broadcast services and the assorted radio services ("auxiliary" broadcast services) that support broadcasting operations. The study of frequency allocations should begin with an understanding of the decision-making process that results in a particular frequency band being allocated for a particular purpose. Such decisions are complex; they not only involve fundamental decisions as to *location* of the service in the frequency spectrum, but also decisions as to channelization, power and antenna limitations, and technical standards which define and prevent mutual interference. These decisions are different for each broadcasting service, a reflection of the fact that each service developed independently from the others and therefore each possesses unique service and interference objectives.

Rather than delve extensively into the history behind each broadcasting allocation, only the current state of frequency allocations is presented together with expectations for the future. We begin with a short discussion on the mechanisms of frequency allocations decisions.

HOW IS SPECTRUM ALLOCATED?

It is a fundamental characteristic of radio wave propagation that radio waves ignore political or geographic boundaries where such boundaries are encountered. Principally for this reason, the regulation, decision-making and consideration of matters concerning the radio frequency spectrum are *federal* rather than *local* interests. Radio waves frequently cross state lines. Regulation of the radio spectrum began within the U.S. Department of Commerce's Interstate Commerce Commission (ICC) in the early 1920s, the same government agency that later came to regulate interstate trucking and "common carriage". The ICC granted the first AM broadcasting licenses. By 1927, the number of AM stations had increased to 733 and over six million radio receivers had been manufactured. However, the specific choice of location, power, and operating frequency, had, until this time, been left largely to the discretion of the broadcaster. As a result, chaos generally prevailed and interference became widespread. The federal government, therefore, formed the Federal Radio Commission in 1927. This was replaced by the Federal Communications Commission (FCC), formed pursuant to the Communications Act of 1934. From then on, and continuing today, prospective broadcast licensees *apply* for and are *granted* a *license* to operate on a particular frequency with a particular power at a specified location. The FCC is said to *allocate* radio frequencies which it *licenses* for use on a non-interference basis by license applicants.

Radio waves also traverse *international* political and geographic boundaries. International fre-

quency allocations decisions are made by the International Telecommunications Union (ITU), an arm of the United Nations with headquarters in Geneva, Switzerland. The ITU, like the UN, is a consortium among governments whose purpose is to propose, develop, revise and administer worldwide frequency allocation plans. Cooperation among nations is essential if interference is to be avoided and use of the spectrum maximized. There are at present over 150 member nations of the ITU. The ITU divides the world into three Regions. Region 1 is Europe and Africa; Region 2 is North and South America; and Region 3 consists of Asia and Australia. Unlike the FCC, the ITU does not directly license prospective radio operators; however, it does keep a master register of radio stations worldwide. The agency responsible for this activity is a subsidiary of the ITU, the International Frequency Registration Board (IFRB). Periodically, the FCC notifies the IFRB of the new stations or modifications in existing stations it has licensed. Other ITU member countries perform the same task.

The process for making decisions on worldwide allocations for radio services is done through international conferences called World Administrative Radio Conferences, or WARCs. The WARCs entertain proposals from member countries for worldwide frequency allocations. Through a process of give and take, decisions are made to allocate spectrum. These conferences take place at roughly twenty year intervals; the last WARC took place in 1979, and considered over 15,000 individual proposals dealing with numerous aspects of world telecommunications. The ITU also convenes Regional Administrative Radio Conferences, or RARCs, that consider allocations for each of the three ITU regions, as well as lists of planned assignments and technical standards. Typically, a RARC will develop lists of planned and assigned radio stations as well as standardized technical interference criteria used to resolve disputes among nations and enable nations to license individual stations on a non-interference basis.

Technical input for WARCs and RARCs comes from the International Radio Consultative Committee (CCIR). The CCIR considers technical matters necessary to the transmission of information by radio wave. A sister technical committee, the CCITT, considers information transmission by wire.

The CCIR is an international committee operating under the aegis of the ITU. Every four years, the CCIR publishes a revised version of its "green books," collections of technical information which can be used to plan and implement systems of broadcast allocations. The CCIR conducts technical investigations into matters such as radio wave propagation, receiver criteria, and new communications technologies. United States input to the CCIR is administered through the Department of State, Office of International Communications Policy. Participation on CCIR committees is open to the public.

Decisions on allocations matters that are international in nature are made at WARCs with more specific technical parameters subsequently developed at RARCs. The WARC and RARC decisions, however, are left to individual nations to implement. In the U.S., the FCC and National Telecommunications and Information Administration (NTIA) are responsible for implementing international agreements to which the U.S. has assented. For the most part, international decisions only affect AM broadcasting. Since FM and TV propagation are limited to their immediate geographic areas, there is little need to seek international guidelines for FM and TV allocations, except in border areas. Still, international agreement on technical transmission standards is essential if world-wide free-flow of communications is to be guaranteed.

Radio frequency allocations occur as a result of a series of complex decisions. On the first, most basic level, large blocks of frequencies are allocated on a worldwide basis by the ITU WARC and RARC process. Exactly *which* blocks of frequencies are allocated to what particular services is determined by evaluating the many specific proposals submitted to the WARC for each frequency band. Technical input is garnered from propagation studies and engineering analysis conducted and submitted through the CCIR committee process. While blocks of frequencies are allocated worldwide, member nations retain flexibility to modify the allocation domestically so long as the nation is not in contravention with its international agreements. In the U.S., the FCC begins to implement the allocations in response to domestic needs and priorities. See Fig. 1 for a portrayal of the international allocations process.

The FCC does not need the ITU's blessing to allocate frequencies; it can also begin allocations proceedings on its own motion or in response to requests from the public, and, in fact, this is a task the Commission frequently performs. The FCC has wide latitude in specifying operational frequencies for the services it regulates. The agency can begin allocations proceedings on its own motion or in response to an industry petition for rule making. See Fig. 2 for the FCC's allocations process. The rulemaking procedure at the FCC is a complex subject in its own right. In brief, the Commission is under an obligation to provide an opportunity for the public to comment on its proposed rule changes *before* making the rule change. To do this, the FCC issues a *Notice of Proposed Rule Making* upon which members

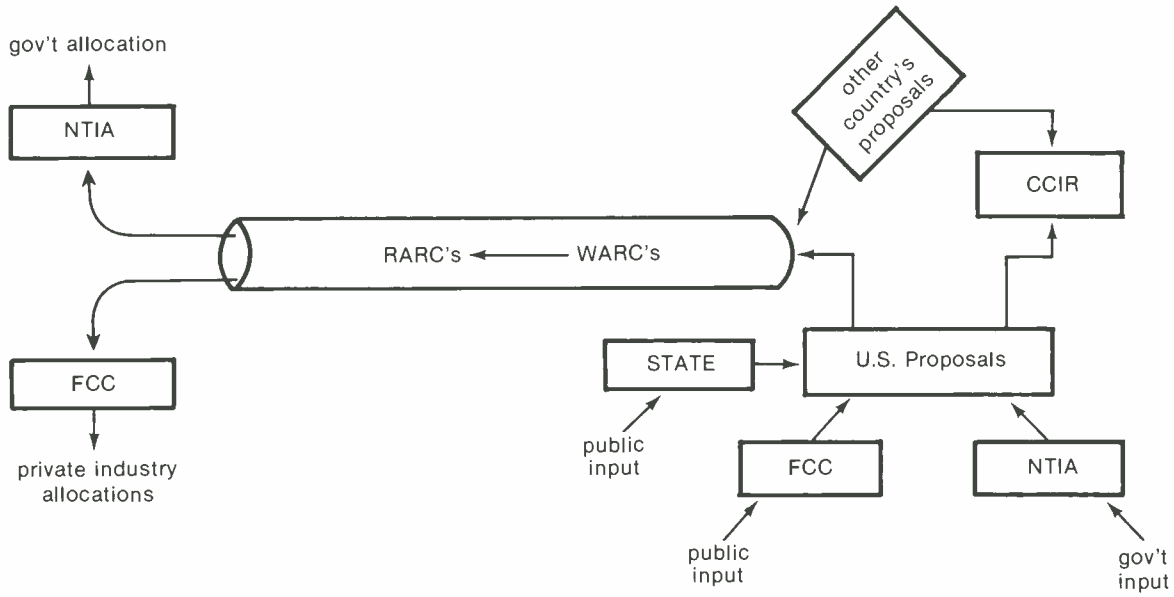


Fig. 1. The international allocations pipeline.

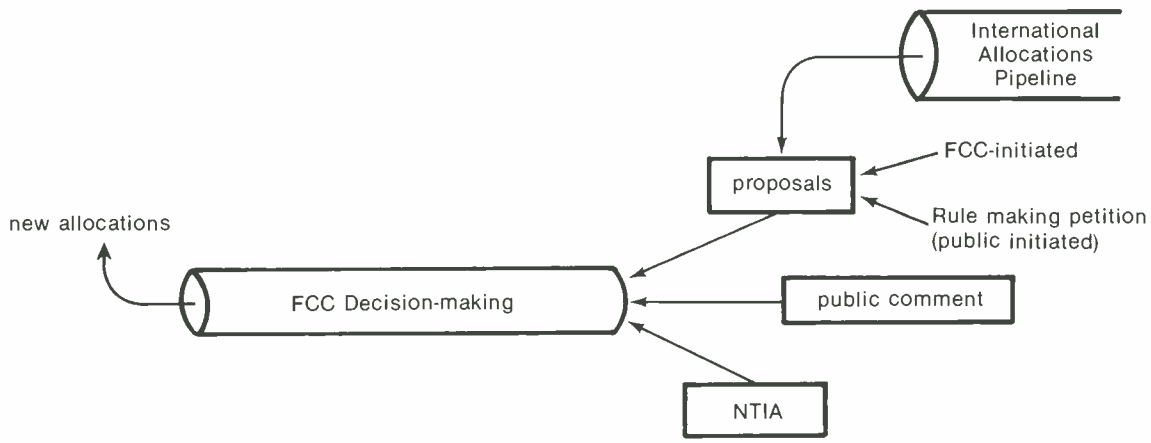


Fig. 2. The domestic allocations pipeline.

of the public can comment.There is also an opportunity for public commenters to reply to the comments of other parties. After the Commission receives comments on its *Notice*, it goes ahead and decides to either adopt its proposals or adopt slightly different proposals on the basis of the submitted comments. Sometimes the FCC's initial proposals are not adopted at all. The nature of the Commission's rule making process is described in greater detail on pages 1.1-7 to 1.1-10.

Many FCC proceedings are controversial in nature, allocations proceedings especially so. The reason is that a particular communications industry's livelihood depends in part on how much spectrum it is allocated. The FCC's allocations decisions frequently are political decisions where several industries in effect compete for a limited amount of spectrum. Or, if spectrum at a particular frequency band is relatively uncrowded, the FCC may propose to authorize sharing of this spectrum with other users. No communications

industry likes to share spectrum with a possibly dissimilar service because of the possibility of interference and the difficulty of coordinating frequency use. Because of these factors, FCC allocations proceedings consume a great deal of time and energy of the organizations, like NAB, and industries, like broadcasting, that participate in them.

From time to time there have been alternative methods proposed for allocating spectrum. These ideas usually envision the removal of the FCC as the arbiter of mutually exclusive requests for spectrum and, in its place, substituting marketplace forces where, it is contended, spectrum would be allocated to the most economically efficient user. The Commission's role would be reduced to a technical "traffic cop" of the airwaves. However intellectually appealing these ideas may be, there is considerable inertia in the present system which would have to be overcome if the current rule making procedure is to be changed.

AM BROADCASTING FREQUENCY ALLOCATIONS

It is ironic that the oldest form of broadcasting, Amplitude Modulation, remains, after many years, technologically so complex. Neither in FM or TV broadcasting do we find allocations criteria that are so complex; AM remains the most difficult allocations system to grasp quickly and easily.

The basic band plan is shown in Fig. 3. There are 107 channels each 10 kHz wide. Over 4800 commercial and non-commercial AM stations occupy these frequencies with primary powers ranging from 250 watts to 50 kilowatts. Half of all AM stations use multi-tower directional antennas to control radiation in certain directions, for the purpose of controlling interference and maximizing radio service. About half of all AM stations operate only during the day. At night, propagation considerations preclude many "daytimers" from operating fulltime on a non-interference basis under the FCC's current technical standards.

The details and methodology for allocating AM radio stations as well as basic design specifications for AM directional antennas is incorporated within FCC Rules, Parts 73.14 to 73.190, one of the largest sections of FCC Rules pertaining to broadcasting. A reader who is interested in further details of AM allocations criteria is referred to the relevant sections of the FCC's rules.

A brief allocations history of AM broadcasting may help to understand the current system. On April 16, 1960, the North American Regional Broadcast Agreement (NARBA) became effective in the United States. NARBA was an agreement among the U.S., Canada, Mexico, Cuba, the Bahamas, and certain other Caribbean countries. The NARBA was necessary principally because nighttime propagation on the AM broadcast band would cause interference to neighboring countries unless mutual allocations criteria and related technical standards were agreed upon and adhered to by parties to the agreement. In brief, NARBA provided for a partitioning of AM broadcast channels into three classes. The first of these are the so-called "clear" channels, on which a single high-power station was to enjoy primary access to its frequency. Clear channel stations provide service, both day and night, over wide areas, even the entire U.S. NARBA provided for 60 clear channels out of the 107 total available frequencies. Each NARBA country received a "priority" on certain clear channel frequencies. NARBA countries without a priority could still allocate radio stations provided that these stations protect the wide-area service of the dominant station in the country with NARBA priority. The clear channels were divided among the NARBA countries with the U.S. receiving a major portion of available priorities. A clear channel station operates with 50 kW night and day and is generally non-directional.

The second class of channels are the 41 regional channels. Unlike clear channels, there is no priority on any particular regional frequency; rather, all countries share these frequencies equally. The technical standards developed for regional channels allowed for (and depended upon) the design of directional antennas to protect existing stations operating on the band. Regional stations are presently limited to 5 kW day and night, often use directional antennas, and may operate daytime only. These stations may also operate with different powers day and night and perhaps with different antennas.

NG128: The AM carrier may be used to transmit subsidiary signals for utility board management and other purposes.

Note 1: 1605-1705 kHz is to become available for AM Broadcasting following completion of a 1986 and 1987 Regional Administrative Radio Conference ("RARC") as well as applicable FCC proceedings.

Note 2: Channel bandwidth is 10 kHz.

Fig. 3. AM broadcast frequency allocations: 535-1705 kHz.

The third class of channels are the six local channels. On these frequencies, nearly all stations are entitled to operate with a uniform 1000 watts daytime and 1000 watts at night with non-directional antennas.

A station that operates on a clear channel was considered a clear channel station if the station was accorded Class 1 or dominant status on its frequency. Similarly, regional stations operated on regional channels and local stations operate on local channels. Each class of station engenders its own particular set of allocations criteria and technical standards. Intermixture of station classes on the various frequencies was in general not permitted; there were, however, different *types* of operations on clear and regional channels, in particular: on the clear channels, daytime-only stations were permitted which did not cause daytime interference with the clear channel station on the frequency. Daytimers are permitted on the regional channels but are not found on local channels. And some clear channel frequencies have dual priorities and are therefore shared.

But NARBA is now obsolete; although many of the agreements continue to underlie the U.S. system of AM allocations. In 1981, a Region 2 RARC was held in Rio de Janeiro which developed a plan for further broadcasting use of the AM spectrum. The NARBA classification system was modified to allow any class of station to operate on any AM frequency and receive protection from interference. The proposed AM station need only comply with applicable interference protection criteria for its class of station.

Today, the clear channels are being broken down to permit the authorization of additional stations. Clear channel stations now are protected only for approximately 750 miles at night.

As of this writing, the AM band is scheduled to be "expanded" from 1605 to 1705 kHz. A RARC will convene in 1986 and again in 1988 to develop a plan for broadcasting use of this spectrum. This RARC will require a vast amount of necessary technical work. Much of this work is now being performed at the FCC.

FM BROADCASTING ALLOCATIONS

FM Broadcast Allocations are quite different from AM. It is much more a strictly domestic U.S. matter and less of an international matter; there have been no RARCs dedicated exclusively to FM matters. While U.S.-Canadian and U.S.-Mexican bilateral agreements remain necessary, they exist primarily to equitably allocate permissible FM broadcast locations on either side of the border and to agree on applicable transmission standards. Technical standards are also agreed upon in order to insure system compatibility.

The basic FM band plan is shown in Fig. 4. FM broadcasting uses frequencies from 88 MHz to 108 MHz. There are 100 available channels each 200 kHz wide. Most non-commercial broadcasting is concentrated at 88-92 MHz (20 channels) with the rest of the band used for commercial purposes.

Commercial FM allocations have recently undergone a significant change. In June 1983, the FCC terminated a lengthy Rule Making proceeding which modified the domestic allocations criteria for FM broadcasting. The title of this proceeding was BC Docket No. 80-90; "Modification of FM broadcast station rules to increase the availability of commercial FM assignments". Prior to Docket 80-90, the FCC authorized three classes of FM stations. Class A stations were designated to operate on 20 exclusive channels. They have a service radius of approximately 15 miles, operate with a maximum height-above-average-terrain (HAAT) of 300 feet, and use a maximum effective radiated power (ERP) of 3 kW. Class B or C stations operate on the remaining 60 channels. Whether a station is designated Class B or C depends on where in the U.S. it is located. Class B stations have approximate service areas of 40 miles and are located in FCC Zones I and I-A. Zone I is the northeast U.S. extending south to the Virginia-North Carolina border and west to the Mississippi River. Zone I-A is a portion of southern California, plus Puerto Rico and the Virgin Islands. Class B stations operate at a maximum ERP of 50 kW at 500 feet HAAT. Class C stations have the largest FM facilities authorized by the FCC and Class C stations can operate with up to 100 kW at 2000 feet

Allocations Notes:

NG 2: Facsimile stations may be authorized at 88-108 MHz.

NG 128: Permits use of FM baseband for subsidizing communications purposes.

NG 129: In Alaska, 88-100 MHz is also allocated to the fixed service on a secondary basis.

US 93: 108 MHz may be used for VOR test facilities on a non-interference basis to FM Broadcasting.

Fig. 4. FM broadcast frequency allocations: 88-108 MHz.

HAAT, for service areas of approximately 57 miles. Class C stations operate in FCC Zone II (the rest of the U.S. that is not Zone I or Zone I-A). FM stations that elect to operate at a HAAT above maximum are required to reduce their ERP to keep their designated coverage areas within the FCC's prescribed limits.

The use of FM channels is governed by the FM "Table of Assignments" found in Section 73.202 of the FCC's rules. The table lists all communities in which FM stations are operating, or may operate, and the channel on which they must transmit. The placement of FM radio stations is initially determined by applicable technical standards. For FM, these standards are the required minimum distance separations between, for example, two co-channel FM transmitter sites. First, second, and third adjacent channel mileage separations are also specified.

In 1983, however, much of the pre-existing FM allocations criteria such as station classes, permitted zones, and mileage separations were changed with the new rules adopted in Docket 80-90. Without changing the basic Table of Assignments concept, Docket 80-90 amended the Commission's rules to:

1. Allow Class A stations on Class B or C channels;
2. Create a new type of Class B FM station, Class B1. This class is allowed to operate in Zones I and I-A. With an expected service area of 28 miles, a permitted maximum ERP of 25 kW at 100 meters (328 feet HAAT); and
3. Create two new types of Class C stations, Class C1 and Class C2 to operate in Zone II. Class C1 stations have an expected service area of 45 miles with an authorized maximum ERP

Station Classes

Station Class	Maximum Facilities kW & m. (ft.)	Permitted Zone	Service Radius km. (mi.)	Field Strength mV/m (dBu)
A	3 & 100 (328)	1&2	24 (15)	1.0 (60)
B1	25 & 100 (328)	1	45 (28)	.7 (57)
B	50 & 150 (492)	1	64 (40)	.5 (54)
C2	50 & 150 (492)	2	52 (32)	1.0 (60)
C1	100 & 300 (984)	2	72 (45)	1.0 (60)
C	100 & 600 (1968)	2	92 (57)	1.0 (60)

MINIMUM DISTANCE SEPARATION REQUIREMENTS in kilometers (miles)

Relation	Co-channel	200 kHz	400/600 kHz	10.6/10.8 MHz
A to A	105 (65)	64 (40)	27 (17)	8 (5)
A to B1	138 (86)	88 (55)	48 (30)	16 (10)
A to B	163 (101)	105 (65)	69 (43)	16 (10)
A to C2	163 (101)	105 (65)	55 (34)	16 (10)
A to C1	196 (122)	129 (80)	74 (46)	32 (20)
A to C	222 (138)	169 (105)	105 (65)	32 (20)
B1 to B1	175 (109)	114 (71)	50 (31)	24 (15)
B1 to B	211 (131)	145 (90)	71 (44)	24 (15)
B1 to C2	200 (124)	134 (83)	56 (35)	24 (15)
B1 to C1	233 (145)	161 (100)	77 (48)	40 (25)
B1 to C	259 (161)	193 (120)	105 (65)	40 (25)
B to B	241 (105)	169 (105)	74 (46)	24 (15)
B to C2	241 (150)	169 (105)	74 (46)	24 (15)
B to C1	270 (168)	195 (121)	79 (49)	40 (25)
B to C	274 (170)	217 (135)	105 (65)	40 (25)
C2 to C2	190 (118)	130 (81)	58 (36)	24 (15)
C2 to C1	224 (139)	158 (98)	79 (49)	40 (25)
C2 to C	249 (155)	188 (117)	105 (65)	40 (25)
C1 to C1	245 (152)	177 (110)	82 (51)	48 (30)
C1 to C	270 (168)	209 (130)	105 (65)	48 (30)
C to C	290 (180)	241 (150)	105 (65)	48 (30)

Fig. 5. FM allocations technical standards.

of 100 kW at 300 meters (984 ft.) HAAT. The service area of a Class C2 station will be 32 miles with an authorized maximum power of 50 kW ERP at 150 meters (492 ft. HAAT). FM allocations standards are summarized in Fig. 5.

Further, Docket 80-90 provided that *existing* Class B or C FM stations *not* operating with maximum facilities will be required to upgrade their facilities within 3 years, (March 1, 1987) or be reclassified to a lower class based on their existing facilities.

After the FM allocations rules were changed in Docket 80-90, it was necessary for the Commission to establish procedures which would allow applicants for new FM stations to take advantage of the new rules. Since the FM Table of Assignments concept was preserved, any new FM allocations that became available through Docket 80-90's rule changes had to be incorporated in the FM Table. The Commission believed that a flood of such petitions to amend the Table would descend unless amending the Table could be done in an organized, step by step fashion. Accordingly, using the FCC's computer resources, the Commission elected to propose a mass modification of the FM Table, using expressions of interest in new radio stations it had solicited from interested parties several years earlier. Initially, approximately 700 locations were proposed. It is expected that the process of proposing new allocations, allowing for public comment, and, finally, accepting applications will continue for some time.

Further changes in FM allocations are not envisioned in the near future, at least until we see the result of Docket 80-90.

TELEVISION BROADCASTING ALLOCATIONS

There are several different bands used for broadcast television stations. The low-VHF band comprises TV channels 2 to 4 (54 MHz to 72 MHz) and channels 5 and 6 (76 MHz to 88 MHz). The high-VHF band comprises TV channels 7 through 13 (174 MHz to 216 MHz). The UHF band is comprised of TV channels 14 through 69 (470 MHz through 806 MHz). Technical standards for TV stations are given in Fig. 6. A diagram of frequency allocations is given in Fig. 7.

Like the case for FM broadcasting, full power TV allocations are governed by a Table of Frequency Assignments located in Part 73.606 of the FCC Rules. Requests for modification of the Table are made by petitioning the FCC; such requests must comply with applicable mileage separation criteria which serve to prevent mutual interference. Generally speaking, few, if any, VHF allotments are available. There are, however, a number of vacant UHF channels that remain scattered throughout the U.S. Low Power Television Stations (LPTV) are not allocated according to a predetermined table. Rather, these stations operate on a strictly secondary, non-interference basis with full power TV stations

Channel	Maximum Visual Effective Radiated Loss	Grade A (dBu)	Grade B (dBu)
2-6	20 dBk (100 kW)	68	47
7-13	25 dBk (316 kW)	71	56
14-69	37 dBk (5000 kW)*	74	64

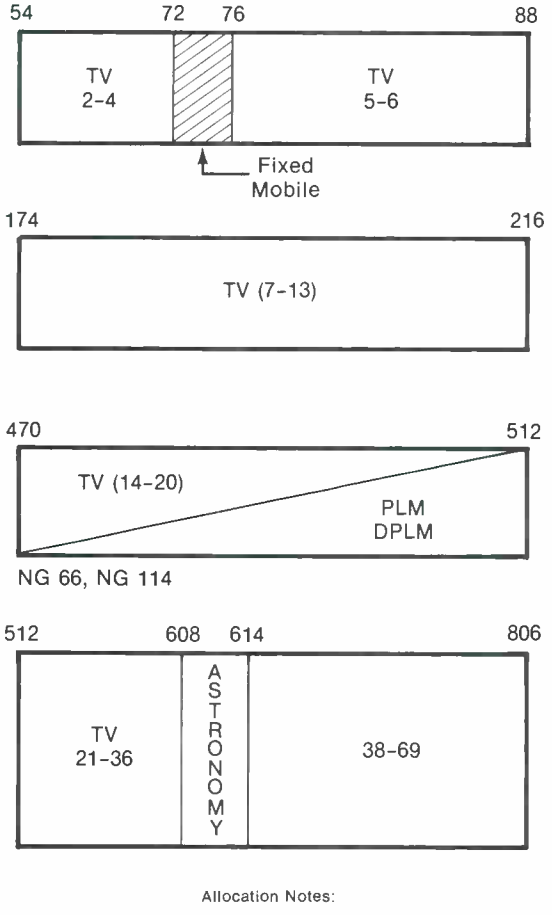
* 30 dBk within 250 miles of the U.S./Canadian Border.

Basic Mileage Separations*

	— Co-Channel			
	Channels	Channels	Adj. Channel	
	2-13	14-69	2-13	14-64
Zone 1	170	155	60	55
Zone 2	190	175	60	55
Zone 3	220	205	60	55

* There are other "taboos" which may or may not preclude a particular television station from operating in a particular location. See FCC Sec. 73.698.

Fig. 6. Television broadcast allocations technical standards.



Allocation Notes:

NG 66: Permits PLM sharing with UHF-TV in certain markets.

NG 114: Ch. 17 is allocated to certain PLM services along the Gulf Coast offshore of Louisiana.

Fig. 7. Television broadcast frequency allocations.

wherever they can be located. Technical standards governing the establishment of LPTV stations are given in subpart G of part 74 of the FCC's Rules.

Aside from establishment of the LPTV service, there has been little change in the allocation of television broadcast stations over the past several years. The last major change was the reallocation of channels 70 through 83 from TV to the Land Mobile radio services in the early 1970s. At that time, sharing of UHF channels 14-20 with land mobile radio services became permitted in certain markets. Such efforts to achieve reallocation of UHF spectrum continue and must be studied carefully by broadcasters.

In August 1984, for example, the Los Angeles County Sheriff petitioned the FCC to reallocate channel 19 in Los Angeles for land mobile communications. Many studies have been conducted which portray the land mobile industry as one suffering from severe spectrum congestion and hence requiring additional spectrum. Public safety land mobile agencies claim that reallocation of additional spectrum would assist their communications capability to the extent of saving lives and property. On the other hand, a FCC Field Operations Bureau study, completed in the summer of 1984, indicates that many of the available land mobile channels in Los Angeles are lightly loaded, if they are used at all. And several organizational and technology implementation studies (the *Hatfield Reports*) have shown that the Los Angeles County Sheriff can meet his existing needs as well as plan for future growth by strategically employing modern narrowband (Amplitude Compandored Single Sideband or ACSB) communications systems. On still another hand, in 1983 the FCC completed a broad-based study evaluating land mobile's need for additional spectrum; this report concludes that additional spectrum is necessary by the year 1990 and that a likely source lies in the domain of UHF Television: generally the first place land mobile's industries look to expand their use of frequencies.

Even further, in June of 1985 the FCC proposed reallocation of certain UHF channels in eight of our largest markets. A technical advisory committee consisting of broadcast and land mobile representatives has been formed to address the complex technical questions.

In any event, the debate goes on and there will undoubtably be further studies and additional rhetoric. One indicator of the seriousness of this matter is that the Commission's *Notice of Proposed Rule Making* responding to the L.A. Sheriff's request for channel 19 spectrum in Los Angeles mysteriously raised the spectre of modifying the license of the channel 18 adjacent TV station, which, by operating at full power, might preclude the sheriff's use of channel 19. It will be interesting to see how TV-Land Mobile allocations in Los Angeles are changed, if they are at all, in the near future.

AUXILIARY BROADCAST SERVICES

Broadcasters use auxiliary broadcast services for a multitude of essential purposes. With recent deregulation, the number of potential uses is growing rapidly. Yet, while there has been steady growth in the number of AM, FM and TV stations, there has not been a corresponding growth in the allocated frequencies for auxiliary services; in many broadcast markets, these frequencies are congested and the prospect for further growth is unlikely, if not impossible; at least with current technical standards. Pressure from competing radio services, such as private, land mobile, government, cable and other services, makes it unlikely that, in the future, additional spectrum for auxiliary services will be allocated.

Still, in many small to medium markets, demand for auxiliary facilities is less and plenty of auxiliary spectrum is available for radio and TV broadcasters.

It is imperative that broadcasters make efficient use of the spectrum we have now. To do this, it is first necessary to understand what spectrum is allocated and available and how it is used; what portion of available spectrum is at present most controversial and why; the extent that cost efficient technology can alleviate existing spectrum shortages and assist broadcasters; and recent FCC rule changes of a procedural or policy nature that impact on auxiliary spectrum use.

Radio Broadcasting Auxiliary Allocations

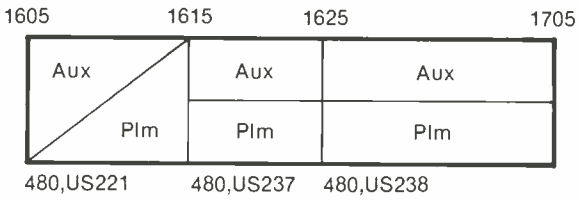
Radio stations use auxiliary broadcast facilities for studio-to-transmitter links (STLs), remote pickup units (RPUs) and on occasion, intercity relay links (ICRs). STLs carry the live on-the-air programming, remote metering, control telemetry, and any subsidiary communications from the studio location to the actual broadcast transmitting facility. STL stations are operational whenever the broadcast station is on the air, often for a full 24 hours. RPUs are mobile or portable facilities that are also used to transmit live on-the-air programming from a temporary remote location, such as a shopping center or football game, to the station's studio facilities for taping, for later rebroadcast, or for on-the-scene-reports incorporated into the actual on-going live broadcast. Radio stations typically have several RPUs that may be licensed to one or more frequencies. ICR stations are used to circumvent obstacles in an otherwise clear path from the studio to the transmitter. ICRs aid the broadcaster's capability to relay programming from studio location to transmitter site, even though the terrain and buildings in between do not allow a clear path. In these cases, the ICR generally is located on the highest point on the path between studio and transmitter. Typically, ICRs transmit on different frequencies than they receive; however, recently the Commission has authorized use of microwave "boosters" which receive and retransmit on the same frequency. Because STLs, RPUs and ICR stations frequently, if not always, carry live on-the-air programming, they must be protected from undesired interference from other telecommunications allocations which may be sharing their frequencies or operating in adjacent spectrum. Absent such protection, interference received by operating STL stations can impair programming intended for reception by the general public. Moreover, any interference or interruption to the STL transmission, or RPU or ICR transmission, can be immediately present on the actual broadcast and would therefore be present everywhere within the broadcast station's service area. In the case of STLs, proper operation is so critical to the technical integrity of the broadcast, that many stations purchase and erect hot stand-by STL stations which immediately begin transmitting (on the same frequency) if the main STL fails.

In November 1984, the FCC significantly revised its radio broadcast auxiliary frequency allocations to permit the *optional* use of narrow band technologies in the Broadcast Remote Pickup Service. The Commission's goal was to foster spectrum efficiency in a flexible manner; broadcasters and equipment manufacturers who wanted to operate narrowband equipment, the Commission believed, should not be precluded from doing so by rigid FCC rules.

In December 1984, the FCC allocated additional spectrum for radio STLs and ICRs. In brief, the new spectrum is expected to relieve much of the congestion at STL frequencies in many markets as well as provide for future growth. Additionally, spectrum at 18 GHz is now available for aural STL purposes.

Here is a brief summary of existing and new frequency allocations for radio broadcast auxiliary services.

1. ***1605-1705 kHz:*** There are three channels in the band available for mobile remote pickup broadcast stations: 1606, 1622 and 1646 kHz. At 1606 kHz, use is subject to the condition that no harmful interference is caused to the reception of AM stations operating on 1600 kHz. Maximum operating power for these frequencies, like other auxiliary bands, is limited to that power. The entire band, is subject to

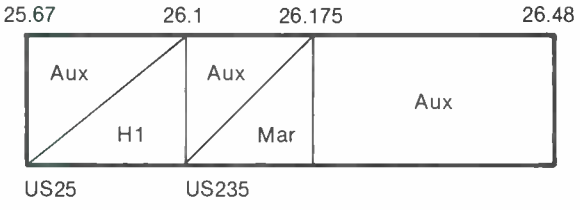


Allocation Notes:

480: Use of 1605-1705 kHz is subject to a 1986 and 1987 RARC (AM Broadcast Band Expansion.)
US221: Use of 1605-1615 kHz is limited to distribution of Traveler's Information stations ("TIS"), operating at 1610 kHz.
US237, US238: At 1615-1625 kHz, Radiolocation services are primary until the 1985 RARC.

Available Frequencies: 1606, 1622, and 1646 kHz, subject to operation on a non-interference basis with other services.
Bandwidth is 10 kHz.

Fig. 8. Radio broadcast auxiliary services: 1605-1705 kHz.



Allocation Notes:

US25: No interference to high-frequency broadcasting.
US235: These frequencies have yet to be implemented by the Maritime Mobile Services and their use may be modified by future RARCs.

Available Frequencies:
1. 25.87, 25.91, 25.95, 25.99, 26.03. Maximum bandwidth is 40 kHz.

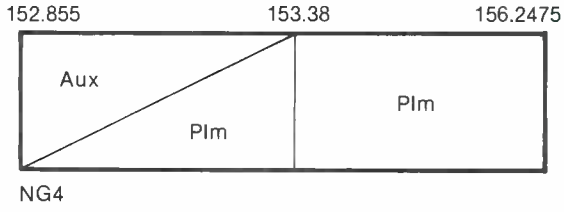
2. 26.07,26.09,26.11,26.13,26.15,26.17,26.21,26.23,26.25,26.27,26.29, 26.31,26.33,26.35,26.37,26.39,26.41,26.43,26.45, and 26.47 MHz.

Fig. 9. Radio broadcast auxiliary services: 25.67-26.48 MHz.

modification at a 1986 Regional Administrative Radio Conference (RARC), which will consider the establishment of technical standards for AM broadcasting at 1605-1705 kHz. Also, at 1610 kHz, many local government entities operate Travelers' Information Stations (TIS). See Fig. 8 for a summary.

2. ***25.67-26.48 MHz:*** There a total of 25 frequencies available in this band for use by remote pickup broadcast stations. All are subject to the condition that no interference is caused to high frequency broadcasting, primarily at night. Some of these frequencies are shared with the Maritime Mobile Services; but, as yet, this service has not been implemented. These frequencies are also subject to other fixed station uses which may be established at future RARCs. Bandwidth is 20 kHz except at 25.87-26.03 MHz were the allowable bandwidth is 40 kHz. See Fig. 9 for a summary of allocations at these frequencies.

3. ***153 and 161 MHz***: In November 1984, the FCC split available spectrum into 5 kHz segments beginning at 152.8575 MHz and ending at 153.362 MHz. These segments may be stacked to form a channel which may be assigned for use by broadcast remote pickup stations. Frequencies are allocated provided no interference is caused to other services. Also, many frequencies will not be licensed to network entities, and will not be authorized to new stations for use on board aircraft. Similarly, the frequencies at 160.8625-161.3975 MHz and 161.6275-161.7725 have been split into 5 kHz segments and are also available for stacking. The maximum authorized bandwidth is 30 kHz. The first set of frequencies are only



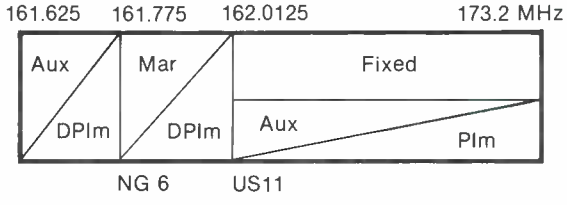
Allocation Note:

NG4: Limits available frequencies to 152.84—153.38 MHz

Available Frequencies:

152.8575—153.362 MHz. (at intervals of .005 MHz "stackable" to a maximum authorized bandwidth of 30 kHz.) Provided no interference is caused to PLM services; not licensed to network entities; and not licensed for use on aircraft.

Fig. 10. Radio broadcast auxiliary services: 152.855—156.2475.



Allocation Notes:

US11: Available Frequencies are limited to 166.25 and 170.15 MHz in certain areas.
NG 6: Some DPLM services may operate between 159.51 and 161.79 MHz, but cannot interfere with AUX services. New DPLM services will not be authorized.

Available Frequencies:

1. 161.6275—161.7725 MHz; (available at .005 MHz intervals "stackable" to a maximum authorized bandwidth of 30 kHz.) Not available to "network entities".

2. 160.8625—161.3975 MHz; (available only in Puerto Rico and the Virgin Islands. Available at .005 MHz intervals "stackable" to a maximum authorized bandwidth of 30 kHz.)

3. 166.25 and 170.15 MHz; see FCC Rules Sec. 74.402(e)(8). Maximum channel bandwidth is 25 kHz.

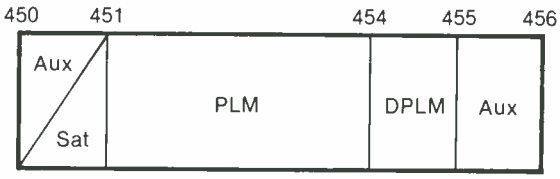
Fig. 11. Radio broadcast auxiliary services: 161.625—173.2 MHz.

available for assignment in Puerto Rico or the Virgin Islands, and may be shared with certain Land Mobile Services; the second set of frequencies are not available in Puerto Rico and the Virgin Islands, but may be shared in certain areas with Land Mobile radio services. See Figs. 10 and 11 for a summary of the band plan at these frequencies. Broadcasters contemplating operation in this band are urged to consult the latest FCC rules. This particular band seems to be susceptible to quick change in applicable regulations.

4. *450 MHz and 455 MHz*: Frequencies in the UHF band have also been split and are available for stacking. Operating frequencies occur every 5 kHz from 450.0275 MHz to 450.6225 MHz and from 455.0275 to 455.6225 MHz. Maximum authorized bandwidth is 50 kHz. However, some segments in this frequency band are partitioned into 25 kHz segments which also may be stacked to form a wider channel. These segments are shown in Fig. 12.
5. *942-952 MHz:* In the past, this spectrum has been quite controversial for radio broadcasters. Prior to November 1984, only half —947-952 MHz—was actually allocated for radio STLs on a primary basis. The lower half, 942-947 MHz, belonged to a land mobile reserve pool of frequencies that had yet to be implemented by that service.

In the early 1970s as part of a massive restructuring of radio spectrum to accommodate the long term needs of the land mobile services, available STL spectrum was halved from 942-952 MHz to 947-952 MHz. STLs that operated there at that time continue to do so today; they are permitted continued renewal of their licenses pending a decision as to their disposition through a future FCC Rule Making proceeding. That rule making proceeding began on June 23, 1982 when the FCC adopted *Notice of Proposed Rule Making* in General Docket No. 82-335. The Commission brought together a number of different proposals for the disposition of STLs operating below 947 MHz that had accumulated during the ten years or so since the band was halved. In 1976, NAB petitioned the FCC to reallocate 942-947 MHz for all STL stations on a primary basis. Another petition, filed by Moseley Associates, a manufacturer of STLs, proposed permitting broadcast STLs to operate on a secondary non-interfering basis within unassigned UHF television channels. Docket 82-335 also included a tentative decision in two previous FCC proposals (1) to allow STL stations to operate in the band 2150-2160 MHz; and (2) to allow STL stations to operate at 2110-2113 MHz. Both of these proposals envisioned sharing spectrum with other fixed users; the Commission suggested that the latter two of these proposals be abandoned, chiefly because spectrum congestion precluded extensive STL frequency/path availabilities.

But the essence of Docket 82-335 proposed to permit STLs to access spectrum at 2130-2150 MHz and 2180-2200 MHz. Broadcasters now operating STLs below 947 MHz would be required to move to the new frequencies within five years of the adoption of rules in this proceeding.



668
US87

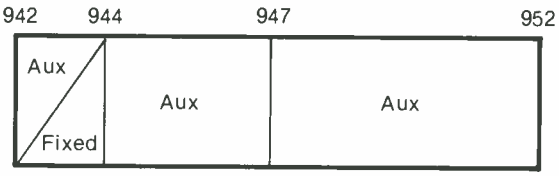
Allocation Notes:

668: 449.75—450.25 MHz may be used for the space operation service.
US87: 449.5—450.5 MHz may be used for "space telecommand" purposes by Govt.

Available Frequencies:

1. 450.0275—450.6225 MHz; 455.0275—455.6225 MHz. (at .005 MHz intervals; can be "stacked" to form channels up to 50 kHz wide)
2. 450.6375—450.8375 MHz; 455.6375—455.8375 MHz. (at .025 MHz intervals; can be "stacked" to form channels up to 50 kHz wide).
3. 450.900, 450.950; 455.900; and 455.950 MHz. 100 kHz maximum bandwidth.

Fig. 12. Radio broadcast auxiliary services: 450-456 MHz.



Allocation Notes:

1. Licensed STL's at 942-944 MHz may remain and are protected from interference STL's operating pursuant to special temporary authority must relocate within five years.

Available Frequencies:

1. 944-952 MHz at .5 MHz intervals subject to local frequency coordination.

Additional Notes:

1. The FCC is expected to begin in early 1985 a "spectrum efficiency proceeding" which may result in optional bandwidth reductions.
2. Additional STL frequencies at 2130-2150 MHz and 2180-2200 MHz may be available in congested areas.

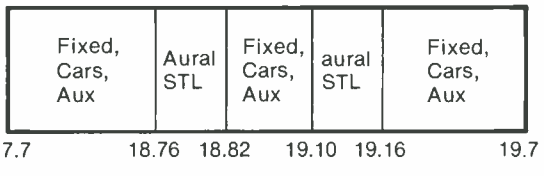
Fig. 13. Radio broadcast auxiliary services: 942-952 MHz.

In December 1984, the FCC resolved Docket 82-335 and reallocated an additional 3 MHz at 944-947 MHz for STL and ICR use on a primary, exclusive basis. Existing *licensed* STL facilities are entitled to remain where they are and will be protected from interference. STL

facilities operating pursuant to a Special Temporary Authority (STA) and *below* 944 MHz are required to change operating frequency to one that is above 944 MHz by November 1989. Further, an allocation at 2130-2150 MHz and 2180-2200 MHz will be available as an escape valve in the event of congestion at 944-952 MHz. See Fig. 13 for the current band plan.

On October 31, 1985, the Commission revised the channelization and bandwidth criteria of the aural STL band, 944-952 MHz (MM Docket No. 85-36). The new rules "split" the existing 500 kHz channels into 25 kHz "segments" which can be "stacked" to form channels of varying bandwidths. The Commission also adopted RF bandwidth "criteria" for aural STL operation: 300 kHz for FM stereo stations using subcarriers, 200 kHz for AM stations and the existing 500 kHz bandwidth as a "wideband" criterion.

6. ***18.76-19.160 GHz***: As a result of a recent FCC microwave utilization proceeding (Docket 82-334), some spectrum was allocated for Radio Fixed STLs and ICRs at 18 GHz. STLs may operate at 18.76-18.82 GHz and 19.10-19.160 GHz on 12 two-way channels, each 5 MHz wide. These frequencies are shared on a co-primary basis with stations in the point-to-point microwave services licensed under Parts 21, 78 and 94 of the Commission's Rules. Applicants may use either a two-way link or one frequency of a frequency pair for a one-way link, and may employ analog (FM) modulation or digital modulation, subject to a number of specific emissions limitations designed to help prevent adjacent channel interference. See Fig. 14 for a detailed band plan.



Television Use: Available bandwidths use 6 MHz, 10 MHz, 20 MHz, 40 MHz, and 80 MHz. Each bandwidth has its own channel plan. *See* Sec. 74.601(i) of the Commission's Rules.

Radio Use: STL's and other Fixed links are permitted at 18.76-18.82 GHz and 19.10-19.16 GHz width SMHz channels. *See* Sec. 74.502(b).

Note: *All* broadcast use of these frequencies is subject to the Frequency coordination requirements of FCC Rule Part 21.100(d).

Fig. 14. 17.7—19.7 GHz

Frequency Coordination at 18 GHz is subject to FCC Rule 21.100(d), a firmly rigorous coordination scheme. The reader is referred to this Rule if 18 GHz operation is contemplated.

7. ***23 GHz Operations.*** Although not strictly a "Broadcast Auxiliary" frequency band, 23 GHz is, nonetheless, available to broadcasters for STL intercity uses. Depending upon the rate of precipitation, the line-of-sight path lengths can be up to five miles or possibly more.

Further, 23 GHz is relatively uninhabited and there is almost no frequency coordination required. Eligible frequencies are 21.8-22.4 and 23.0-23.6 GHz. Applications and instructions are available from the FCC, Land Mobile and Microwave Division. Suitable equipment is available from popular microwave equipment manufacturers.

Auxiliary Broadcast Allocations: Television Broadcasting

Television broadcasters use auxiliary broadcast spectrum for many of the same reasons that radio broadcasters do. The most popular uses include television STLs and Electronic News Gathering (ENG). Additionally, television stations frequently employ intercity relay links when news events require mobile coverage. Typically, an ICR is located at a strategic high place within the station's city of license. Then, the mobile ENG equipment directs their transmissions to the relay point instead of the station itself. The relay station improves the station's capability to gather live news by extending the area within which ENG transmissions can be received.

On balance, the spectrum allocated for television auxiliary services is significantly more competitive than spectrum allocated for radio broadcasting services. Network entities often travel extensively and can compete with local broadcasters for available frequencies, resulting in an enhanced potential for spectrum congestion. Further, the variety of different activities that television broadcasters undertake usually requires more complex auxiliary systems than is the case in the radio industry. Also, most of the auxiliary spectrum allocated for television broadcasters is located above 1 GHz, popular spectrum used by private and common-carrier communications services.

There are three principal bands used for television broadcast auxiliary services: 1990-2500 MHz (the 2 GHz band), 6425-7125 MHz (the 7 GHz band), and 12.7-13.25 GHz (the 13 GHz band).

1. ***The 2 GHz Band:*** While the 2 GHz band extends from 1990-2500 MHz, only 1990-2110

and 2400-2500 MHz is available for television broadcasters who wish to own and operate their own auxiliary news gathering services. There are seven channels at 1990-2110 MHz. There are few potential interfering services that also operate at these frequencies. Recently, however, the Commission has proposed to allow Cable TV networks and certain cable systems to access 2 GHz channels. Unless mutual efforts to coordinate frequencies are successful, this "sharing" of spectrum, if adopted by the Commission, may lead to increased interference.

Other sources of interference include certain earth-to-space and space-to-earth transmissions on 2025-2110 MHz and at certain locations on 1990-2120 MHz. Also, there may be government-operated earth exploration satellite services at 2106.4 MHz. At certain geographical sites in the United States, space research radio services are authorized on a co-equal basis with auxiliary broadcasters at 2025-2035 MHz. Fortunately, all of these services operate on a non-interfering basis with television auxiliary broadcasters. There are three channels available at 2400-2500 MHz. One of these channels, the uppermost one (channel 10) is currently being sought for reallocation by a new radiodetermination satellite service, called *Geostar*, that would use channel 10 as part of a larger allocation for a satellite downlink in their system.

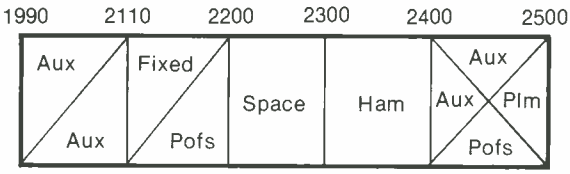
The 2 GHz band is used for both fixed STL uses and mobile ENG applications on a co-equal basis by television broadcasters. To date, local frequency coordinating committees have done an admirable job of ensuring that both these fixed and mobile users of 2 GHz coordinate their use of these frequencies. See Fig. 15 for a complete band plan.

On October 31, 1985, the Commission changed the channelization of the 2 GHz band. The existing 17 and 18 MHz "wideband" channels were "split" into 250 kHz "segments," which can be "stacked" to form channels of varying bandwidths. The Commission's rationale for this rule revision is to offer broadcasters "increased flexibility in system development and implementation."

Coupled with the proposals contained in Docket 82-334 (see below), microwave operations at 2 GHz may become significantly more complicated despite Commission assertions of "increased flexibility". We should find out in 1986 and 1987.

2. ***The 7 GHz Band:*** There are four channels available between 6425 and 6525 MHz and ten channels available between 6875 and 7125 MHz. Like the 2 GHz band, both fixed and mobile operations are permitted on a co-equal basis. A standard satellite service time signal operates at 6427 MHz; and, occasionally, passive microwave sensor measurements are taken at 6425-7025 MHz. At 6425-6525 MHz, ENG stations operate on a secondary basis. Between 6875 and 7125, TV relay stations can operate on a secondary basis. These frequencies are primarily available for television broadcasters who wish to own and operate their own auxiliary services. There are other frequencies available for common carrier entities that wish to sell or lease their services to broadcasters. Although the communications provided by a broadcaster who owns his auxiliary service and the common carrier entity who leases or sells the same service are identical, they currently occupy different portions of the spectrum. See Fig. 16 for a complete band plan.

Like the 2 GHz band, in October 1985, the Commission changed the 7 GHz band channelization. Wideband channels were "split"



Allocation Notes:

US90: There may be earth-to-space and space-to-earth transmissions authorized on a non-interfering basis at 2025-2110 MHz.
US111: There may be government space research earth stations authorized on a non-interfering basis at certain locations at 1990-2120 MHz.
US219: There may be government earth exploration satellite services at 2106 MHz.
US222: At certain U.S. sites, certain space research radio services are authorized on a co-equal basis at 2025-2035 MHz.
NG118: TV translator relay stations may operate on a secondary basis at these frequencies.
US41: Government radio location service at 2450-2500 MHz can operate on a non-interference basis with non-government services.
752: All radio services must accept interference from industrial, scientific and medical equipment operating at 2450 MHz.

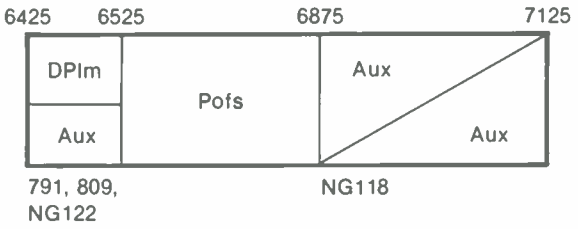
Available Frequencies:

1. 1990-2008, 2008-2025, 2025-2042, 2042-2059, 2059-2076, 2076-2093, and 2093-2110 MHz. Bandwidth is 17 MHz.

2. 2450-2467, 2467-2484, 2484-2500 MHz. Bandwidth is 17 MHz.

Notes:
1. Channels are split into 250 kHz segments, stackable into channels of wider bandwidths.
2. Docket 82-334 may alter various requirements for use of this band.

Fig. 15. Television broadcast auxiliary services: 1990-2500 MHz.



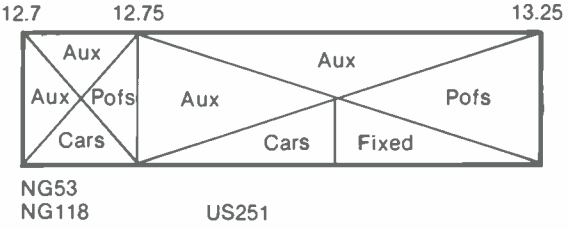
Allocation Notes:

791: 6426 MHz is a "standard" satellite service time signal.
809: "Passive" microwave sensor measurements at 6425-7025 MHz.
NG122: TV Pickup stations may operate at 6425-6525 MHz on a secondary basis.
NG118: TV translator relay stations may operate at 6875-7125 MHz on a secondary basis.

Available Frequencies:

1. 6425-6450, 6450-6475, 6475-6500, 6500-6525 MHz. Bandwidth is 25 MHz.
2. 6875-6900, 6900-6925, 6925-6950, 6950-6975, 6975-7000, 7000-7025, 7025-7050, 7050-7075, 7075-7100, and 7100-7125. Bandwidth is 25 MHz.
3. Channels are split into 250 kHz segments, stackable into channels of wider bandwidths.
4. Docket 82-334 may alter various requirements for use of this band.

Fig. 16. Television broadcast auxiliary service: 6425—7125 MHz



Allocation Notes:

NG53: TV pickup and CARS pickup are co-equal at 12.7-13.15 GHz. At 13.15 GHz, are co-equal and exclusive within 50 km of the top 100 markets.
NG118: TV translator relay stations may operate on a secondary basis.
US251: Space research at 12.75-13.25 GHz only at Goldstone, CA.

Available Frequencies:

1. 12700-12725, 12725-12750, 12750-12775, 12775-12800 12800-12825, 12825-12850, 12850-12875, 12875-12900 12900-12925, 12925-12950, 12950-12975, 12975-13000 13000-13025, 13025-13050, 13050-13075, 13075-13100 13100-13125, 13125-13150, 13150-13175, 13175-13200 13200-13225, 13225-13250 MHz.

2. 12.7125-12.7375, 12.7375-12.7625, 12.7625-12.7875, 12.7875-12.8125 12.8125-12.8375, 12.8375-12.8625, 12.8625-12.8875, 12.8875-12.9125 12.9125-12.9375, 12.9375-12.9625, 12.9625-12.9875, 12.9875-13.0125 13.0125-13.0375, 13.0375-13.0625, 13.0625-13.0875, 13.0875-13.1125 13.1125-13.1375, 13.1375-13.1625, 13.1625-13.1875, 13.1875-13.2125, 13.2125-13.2375 MHz.

Fig. 17. Radio broadcast auxiliary services: 12.7-13.25 GHz.

into 250 kHz "segments" which can be "stacked" to form channels of varying bandwidths. The proposals being considered in Docket 82-334 may significantly change the manner in which our industry uses this band (see below).

3. *The 13 GHz Band:* The 13 GHz band is without question becoming increasingly congested. In addition to television broadcasters, Cable Television Relay Systems (CARS) use these frequencies as do Private Operational Fixed Service users (POFS). Thirteen GHz can support both mobile and fixed operations; however, mobile ENG is nearly always operated on a secondary basis to fixed service users. This spectrum is also highly controversial—as explained in detail below. A current plan is shown in Fig. 17.

At 13 GHz:

- Private operational fixed service users displaced from 12 GHz may operate on the frequencies 12.7-13.20 GHz, on a co-primary basis with existing fixed users of that band,
- Mobile ENG units may operate on the secondary basis to fixed users on the frequencies 12.7-13.20 GHz, except that, on the frequencies 13.15-13.20 GHz, within 50 kilometers of the top 100 television markets, they are co-primary with CARS and ENG; and
- Mobile ENG units may operate on a co-primary basis with existing fixed users on the frequencies 13.20-13.25 GHz.

On November 27, 1985, the Commission released a *Second Notice of Proposed Rule Making* in Gen. Docket No. 82-334. The new proposal offers many of the same concepts used in the First *Notice*: minimum path length requirements, antenna performance standards, and further sharing of 2 GHz and 7 GHz by other users.

The Commission's new proposal would permit Cable TV Networks and local CATV operators to have "equal access" to the 2 and 7 GHz microwave bands, for *mobile use only*, such as ENG operations. Moreover, the Commission would impose *minimum path lengths and antenna sizes* for *new fixed* microwave links or major changes in existing links in areas where there is frequency congestion. Finally, the Commission has offered the use of the 6.4 GHz band, now used sparingly by common carriers, to broadcasters and others. Broadcasters currently have access to this band on a secondary basis, but its use must be formally coordinated which has proved to be time consuming. Use of 6.4 GHz would be limited to "portable" use only, rather than mobile or ENG use. Substantial lead time would be necessary before a broadcaster could use these frequencies.

The Commission will decide in 1986 whether or not to adopt its proposals.

Future Changes

The foremost pending proceeding is General Docket No. 82-334. This rulemaking began in early 1982, and seeks to establish a spectrum utilization policy for the fixed and mobile services use of certain bands between 947 MHz and 40 GHz. The proposals espoused by the FCC in the original *Notice of Proposed Rule Making* could, if implemented, have a disastrous effect on television broadcast auxiliary frequency use. In brief, the FCC proposed to displace present occupants of what is now the direct broadcast satellite (DBS) downlink band, 12.2-12.7 GHz, to bands that included those allotted for television broadcast auxiliary services (TV ENG and STL at 2, 7 and 13 GHz). Not only would sharing be permitted but, for the first time, the FCC would impose technical standards it believes would improve spectrum efficiency. These proposed standards include required minimum path lengths for transmission on each microwave band, minimum antenna suppression standards, a new channeling plan for the 2 GHz band and revised frequency coordination procedures.

In September 1983, the FCC adopted a favorable *First Report and Order* in Docket 82-334. The FCC, for the time being, preserved the integrity of 2 and 7 GHz, and allowed only limited sharing at 13 GHz and opened up the 18 GHz band to all. At that time, no action was taken on other technical proposals such as minimum path length requirements.

CONCLUSION

The figures contained in this chapter of the handbook present the broadcast auxiliary spectrum as presented by the FCC's *Second Report and Order* in General Docket No. 80-739: domestic implementation of the Final Acts of the 1979 World Administrative Radio Conference (1979 WARC) as modified by subsequent FCC orders.

If a given portion of spectrum is divided horizontally, the upper service is primary and the lower service is secondary. If, on the other hand, a portion of spectrum is divided diagonally, both services enjoy co-equal status. If an identical service appears twice in the same frequency portion, then, for this service, both fixed and mobile services are permitted.

Note the allocation footnotes for each spectrum portion. These are located in Section 2.100 to 2.108 of the Commission's Rules. Here are the relevant terms:

POFS = Private Operational Fixed Service
AUX = Auxiliary Broadcast Service
MAR = Maritime Mobile
PLM = Private Land Mobile
DPLM = Private Land Mobile (common-carrier)
HF = High frequency broadcasting
HAM = Amateur Radio
FIXED = Fixed microwave services (private or common carrier)
SAT = Satellite uplink or downlink.

1.6

Source Guide: Broadcast Standards and Information

INTRODUCTION

The purpose of this chapter is to provide an easily accessible guide to organizations whose activities affect the work of broadcast engineers. This includes government agencies, trade and professional associations, and private companies.

There is also a list of abbreviations and acronyms.

The information here has been compiled from various sources by David Bialik of NAB. Accuracy and currency cannot be guaranteed; please contact listed organizations directly for more information.

FEDERAL GOVERNMENT

Department of Agriculture

14th and Independence Avenue, S.W.
Washington, DC 20250
(202) 447-2791

The Department of Agriculture (USDA) Forest Service oversees the use of 190 million acres of land under the domain of the National Forest System. More often than not, the use of a mountain top transmitter site is controlled by the Forest Service. Land use permits are obtained from the Forest Supervisor for the particular forest of interest who has detailed policy directives for permissible uses and fee structures of forest land.

Department of Commerce

National Bureau of Standards

Gaithersburg, MD 20899
(202) 921-1000

The National Bureau of Standards of the Department of Commerce has been authorized by Congress to undertake the following functions: "The custody, maintenance, and development of the national standards of measurements and the provisions of means and methods for making measurements consistent with those standards, including the comparison of standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions, with the standards adopted or recognized by the Government."

Time and Frequency Division

The Time and Frequency Division, located in Boulder, Colorado, is that part of the National Bureau of Standards that carries out the above functions related to time and frequency. This division is responsible for distributing the standards and for finding new and improved methods of dissemination. The dissemination services for time and frequency are presently available from stations WWV and WWVB in Fort Collins, Colorado, and from WWVH in Kauai, Hawaii. In addition, services using network television and satellite signals are also available. Correspondence

pertaining to station operations may be addressed to:

Engineer-in-Charge
NBS Radio Stations WWV and WWVB
2000 East County Road 58
Fort Collins, CO 80524
(303) 484-2372

or,

Engineer-in-Charge
NBS Radio Station WWVH
P.O. Box 417
Kekaha, Kauai, HI 96752
(808) 335-4361

National Telecommunications and Information Administration

14th St. and Constitution Avenue N.W.
Washington, DC 20230
(202) 377-1551

The National Telecommunications and Information Administration develops telecommunications policy for the executive branch; manages federal use of radio spectrum; conducts technical research on radiowave transmissions and other aspects of telecommunications; serves as information source for federal and state agencies on the efficient use of telecommunications resources.

Department of the Interior

The Bureau of Land Management of the Department of Interior oversees the use of 360 million acres of "public domain" lands, those lands not under the domain of the USDA Forest Service. Broadcaster use of these lands for transmitter sites is coordinated by the State Director of the Bureau of Land Management.

Topographic Maps

Topographic maps usually used in prediction of coverage and other engineering studies requiring accurate information about the position and elevation of terrain features may be obtained from the U. S. Geological Survey (USGS), a bureau of the U. S. Department of the Interior. Standard topographic quadrangles on a scale of 1:24,000 (7.5 minutes) or 1:62,500 (15 minutes) are usually used, but other scale maps are available. To order free map indexes or to purchase maps, contact one of the following offices.

For areas east of the Mississippi River (including Minnesota, Puerto Rico, and the Virgin Islands:

Eastern Distribution Branch
U.S. Geological Survey
1200 S. Eads Street
Arlington, VA 22202

For areas west of the Mississippi River (including Alaska, Hawaii, Louisiana, Guam, and Samoa:

Western Distribution Branch
U.S. Geological Survey
Box 25286, Federal Center
Denver, CO 80225

Department of Labor

200 Constitution Ave., N.W.
Washington, DC 20210
(202) 523-6666

Broadcast engineers should be aware that two federal laws, the Fair Labor Standards Act and the Occupational Safety and Health Act, empower the Department of Labor (DOL) to regulate work place safety standards and wages and hours of employment of broadcast employees. Occupational safety standards are enforced by OSHA, the Occupational Safety and Health Administration of DOL, while the minimum wage and hours of employment are enforced by DOL's Wage and Hour Division.

Applicability of OSHA and Wage and Hour Division regulations depend upon many factors such as the station's geographic location, the number of station employees and the type of work they perform; so, broadcast engineers should consult their station's attorney to determine what regulations apply to them and how to abide by them.

Department of Transportation

Federal Aviation Administration

400 7th Street, S.W.
Washington, DC 20590
(202) 426-4000

When construction of a new broadcast tower, or a change in height of a existing tower, is proposed, the Federal Aviation Administration (FAA) becomes involved to study the potential impact that the proposed structure may have on navigable airspace. Broadcasters are required to notify the FAA of proposed new or modified tower structures. The FAA than applies its obstruction standards (Part 77 of the FAA Rules) to determine whether or not the tower constitutes a hazard to navigable airspace. Broadcasters may need to accommodate an adverse finding by the FAA with a modified tower location and or tower height. FAA clearance of a proposed tower specifies the lighting and marking requirement, which are then included on the FCC construction permit. See Part 17 of the FCC Rules and Section 2 of this *Handbook*.

Environmental Protection Agency

401 M Street, S.W.
Washington, DC 20460
(202) 382-2090

When broadcasters construct station facilities such as antenna towers or large satellite earth stations they should be aware that these activities may fall under the scope of the National Environmental Protection Act (NEPA). NEPA grants the Environmental Protection Agency (EPA) authority to regulate activities which may affect the "quality of the human environment." The FCC cooperates with EPA in enforcing provisions of NEPA that relate to telecommunication licensees.

The FCC monitors construction of telecommunications facilities and requires information about the operation of transmitters and other broadcast equipment. For example, the FCC, with the assistance of EPA, monitors the level of employee and general public exposure to nonionizing radiation emitted from the equipment. Generally, licensees who propose to construct such facilities must file studies of the potential environmental consequences with the FCC and may be required to take steps to minimize possible environmental hazards.

Federal Communications Commission

1919 M St. N.W.
Washington, DC 20554

For information on the Federal Communications Commission refer to chapters 1.1 and 1.2.

Every station should have an up-to-date copy of the FCC's broadcast rules. There are two ways to obtain them:

1. Order a set of the Code of Federal Regulations (CFR) issued annually by the U.S. Government Printing Office. Call them at (202) 783-3238 and order "47 CFR Parts 0-19" for the Tower Regulations in part 17 and "47 CFR Parts 70-79" for the Broadcast Rules Part 73 and Broadcast Auxiliary Rules Part 74.

The CFRs may also be ordered by writing the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

2. For a continuously updated subscription, call the Rules Service Company at (301) 424-9402. Parts 17,73 and 74 in loose-leaf (updated quarterly) form. Or write them at 7658 Standish Place, Suite 106, Rockville, MD 20855.

National Labor Relations Board

1717 Pennsylvania Avenue, N.W.
Washington, DC 20570
(202) 254-9044

Broadcast engineers should also be aware that the National Labor Relations Act (NRLA) protects the right of station employees to bargain collectively with management over the "terms and condition of employment." The National Labor Relations Board (NLRB), an independent federal agency, was established to enforce the right of workers to organize and engage in " concerted activity." As with the DOL regulations, the extent of these rights depends upon many factors such as the type and the number of employees involved.

STATE AND LOCAL GOVERNMENTS

A number of aspects of a broadcast engineer's job are affected or controlled by state or local governmental bodies. It is important for the engineer to have some familiarity with the laws, codes and zoning ordinances governing such matters as building construction, electrical wiring, and fire safety. Many such considerations are, or should be, obvious, but some are not and others are often overlooked. Furthermore, regulations may vary from one community to another, even within the same state or county.

While there are model national codes, these codes may or may not be adopted by a state or local government. If adopted, there may be some changes from the national model. The only way to determine definitely is to check with the local agency or agencies having jurisdiction over the matter in question. For more information on state or local regulations see the following:

The station's local lawyer,

The local business licensing office,

Building inspector, fire marshall,

A licensed local contractor who does the type of work in question.

TRADE ASSOCIATIONS

Association of Federal Communications Consulting Engineers (AFCCE)

The AFCCE is a professional association of communications engineers practicing before the Federal Communications Commission. Engineering for broadcast stations in the AM, FM and TV services, for microwave, cellular radio, and paging systems, and for satellite facilities are some of the areas in which AFCCE members offer their professional services. Full members of the AFCCE are registered Professional Engineers in the jurisdictions wherein they practice.

Association of Maximum Service Telecasters (MST)

1735 DeSales Street, N.W. Suite 400
Washington, DC 20036
(202) 347-5412

The purpose of MST is to assure the maintenance and development of an effective nationwide system of free over-the-air television based on local broadcast stations providing service of high technical quality. MST seeks to meet both present and future needs of developing an effective nationwide VHF and UHF system; to provide free over-the-air broadcasting; to develop local stations to reflect the needs and interests of local communities; to safeguard against broadcast of only a few purely national voices; to protect against interference and degradation of the public's broadcast service. MST develops and preserves opportunities for local stations to use new technologies.

Advanced Television Systems Committee (ATSC)

1771 N Street, N.W.
Washington, DC 20036
(202) 429-5345

The Advanced Television Systems Committee (ATSC) was established in 1983 to develop and coordinate voluntary national technical standards for advanced television systems, and to recommend to the U.S. Department of State positions for the United States within international standards organizations such as the International Radio Consultative Committee (CCIR).

The ATSC is composed of fifty member companies, all of which are major factors within the United States television industry. These members include broadcast networks and stations, cable television companies, program producers, professional and consumer equipment manufacturers, and satellite communications companies.

Electronic Industries Association (EIA)

2001 Eye Street, N.W.
Washington, DC 20006
(202) 457-4900

The Electronic Industries Association is a trade association representing the manufacturers of telecommunications, industrial and consumer equipment; components (parts, tubes and solid state products); equipment and systems for the government. Their engineering activity includes the publication of voluntary standards. Those of interest to broadcasters are TV test charts and standards covering transmitters, towers, microwave transmission systems and tape cartridges. The standards work is primarily done in the Broadcast Television Systems Committee and engineering committees of the Telecommunications Group: the catalog of standards and engineering publications may be obtained from:

Standards Sales Department
Electronic Industries Association
2001 Eye Street, N.W.
Washington, DC 20006
(202) 457-4966

A selection of EIA voluntary standards of interest to broadcast engineers is given below along with the date of acceptance or reaffirmation. Interested readers should contact EIA for a current listing and price list.

RS-189-A Encoded Color Bar Signal. 1976

RS-200-A Circular Waveguides. 1975

RS-211-D Processed Analog Disc Records and Reproducing Equipment. 1981

RS-215 Basic Requirements for Broadcast Microphone Cables. 1958

RS-219 Audio Facilities for Radio Broadcasting. 1959

RS-221-A Polarity or Phase of Microphones for Broadcasting, Recording and Sound Reinforcement. 1979

RS-222-C Structural Standards for Steel Antenna Towers and Antenna Supporting Structures. 1976

RS-224 Magnetic Recording Tapes. 1959

RS-225 Rigid Coaxial Transmission Lines. 1975

RS-232-C Interface between Data Terminal Equipment and Data Communication Equipment Employing Serial Binary Data Exchange. 1981

RS-238-B Standards for Stylus Tips Used for Disc Phonograph Reproducing. 1981

RS-240 Electrical Performance Standards for Television Broadcast Transmitters, Channels 2-6, 7-13, 14-83. 1961

RS-250-B Electrical Performance Standards for Television Relay Facilities. 1977

RS-258 Semi-flexible Air Dielectric Coaxial Cables and Connectors. 1962

RS-261-B Rectangular Waveguides. 1979

RS-264 Magnetic Recording Tape Cartridge Dimensions. 1962

RS-288 Audio Magnetic Playback Characteristic at 7½ IPS. 1963

RS-295 Disc Recording Characteristic. 1973

RS-297-A Cable Connectors for Audio Facilities for Radio Broadcasting. 1970

RS-386 Recommended Measurement Method for Phonograph Rumble. 1978

RS-455 Standard Test Procedures for Fiber Optic Fibers, Cables, Transducers, Connecting and Terminating Devices. 1980

RS-462 Electrical Performance Standards for Television Broadcast Demodulators. 1979

TR-101-A Electrical Performance Standards for Standard Broadcast Transmitters. 1948

TR-107 Electrical Performance Standards for FM Broadcast Transmitters. 1949

TR-117 Antennas and Combinations of Antennas for FM Broadcasting Stations. 1949

National Association of Broadcasters (NAB)

1771 N Street, N. W.
Washington, DC 20036
(202) 429-5300

The NAB represents the broadcasting industry before Congress, the courts, regulatory agencies, at the White House and before the general public. They serve a membership of over 4,000 radio and 880 television stations including all the major networks.

The Science and Technology department provides technical support to other NAB departments, prepares engineering statements and presentations for comment on FCC-related issues, and provides technical services to members. Their services include the monthly *Engineering Report, Equipment Clearinghouse* which lists used equipment for sale, plus special engineering bulletins, studies, conferences and meetings. The department also participates in industry standards committee activities and conducts special projects and investigations.

NAB Direct Dial Reference List (All numbers are Area Code 202 except toll-free as noted)

Employment/Minority Services 429-5497
Government Relations 429-5301
Government Relations Hotline .(800) 424-8806
Legal 429-5430
Library and Information Center 429-5490
President's Office 429-5444
Radio 429-5420
Radio Membership 429-5400
Research and Planning 429-5380
Science and Technology 429-5346
TV/TV Membership 429-5362
Billing .....(800) 626-5542
Publications .....(800) 368-5644
Insurance Information .....(800) 368-5644

Engineering Publications of the National Association of Broadcasters

- *AM Technical Improvement Bibliography*
- *Earth Station Planning*
- *Broadcast Engineering Conference Proceedings* (Published annually at the Conference; current year and back issues for some years available.)
- *NAB Standard Magnetic Tape (Reel to Reel) Recordings and Reproductions*
- *NAB Standard Audio Cassette Recordings and Reproductions*
- *NAB Standard Cartridge Tape Recordings and Reproductions*
- *NAB Standard Disc Recordings and Reproductions*
- *NAB Test Record*
- *AM Ground Wave Field Strength vs Distance Graphs* (metric complete set)
- *AM Ground Wave Field Strength vs Distance* (metric graph paper)

National Cable Television Association (NCTA)

1724 Massachusetts Avenue N.W.
Washington, D.C. 20036
(202) 775-3550

The National Cable Television Association (NCTA) is the major trade association for the cable industry. They represent the cable television industry before Congress and Federal Agencies, in the courts and before state regulatory agencies. Members comprise over 400 cable operating companies and over 600 equipment manufacturers, programmers and service companies.

PROFESSIONAL ASSOCIATIONS

Institute of Electrical and Electronic Engineers (IEEE)

Broadcast Technology Society

Institute of Electrical and Electronic Engineers
345 East 47th Street
New York, NY 10017
(212) 705-7900

Members of the IEEE include engineers and scientists in electrical engineering, electronics, and allied fields as well as over 30,000 students. The IEEE holds numerous meetings and special technical conferences, conducts lecture courses at the local level on topics of current engineering and scientific interest, assists student groups, and awards medals, prizes, and scholarships for outstanding technical achievement. They also sup-

port the Engineering Societies' Library in New York City with other groups.

The boards include Awards, Educational Activities, Publications, Regional Activities, Technical Activities, U.S. Activities Board. Societies of interest to broadcasters include Acoustics, Speech and Signal Processing; Aerospace and Electronic Systems, Antennas and Propagation, Broadcast, Cable and Consumer Electronics, Circuits and Systems, Communications Computer Control Systems, Education, Electrical Insulation, Electromagnetic Compatibility; Electron Devices; Industrial Electronics; Instrumentation and Measurement, Microwave Theory and Techniques, Power Engineering, Professional Communications.

Publications of the IEEE include the *Proceedings*, monthly; *Spectrum*, monthly; *Directory*, annually; Standards, irregular; the Societies and Councils publish 42 journals, 8 magazines, and 125 conference proceedings.

IEEE publishes a number of voluntary standards and practices affecting broadcasting. A few of those are listed below. For a current listing and prices, contact IEEE.

152 Recommended Practice for Volume Measurements of Electrical Speech and Program Waves. 1971 (Ask about revision with PPM.)

153 Standard Definitions of Terms Relating to Television. 1979

202 Standards on Television: Methods of Measurement of Aspect Ratio and Geometric Distortion. 1972

205 Standards on Television: Measurement of Luminance Signal Levels. 1972

206 Standards on Television: Measurement of Differential Gain and Differential Phase. 1978

208 Standards on Video Techniques: Measurement of Resolution of Camera Systems, 1961. 1978

511 Standard on Video Signal Transmission: Measurement of Linear Waveform Distortion. 1979

Society of Broadcast Engineers, Inc. (SBE)

7002 Graham Rd., Suite 118
Indianapolis, IN 46220
(317) 842-0836

The Society of Broadcast Engineers, Inc. (SBE) encourages the professional development of its members who include broadcast engineers, students, and broadcast professionals in closely allied fields. It also provides information exchange.

The SBE administers a certification program, recognizing four levels of engineering achievement.

1. Broadcast Technologist
   This certification can be obtained in either two ways:
   By achieving a passing grade on the proficiency examination. There is no experience requirement to be eligible for the examination.
   By holders of a valid FCC First Class (not general) Operator license with either two years of continuous satisfactory service in broadcast engineering prior to the date of application, or a total of three out of last five years of satisfactory service in broadcasting.
2. Broadcast Engineer
   The candidate must have had five years of suitable experience in broadcast engineering, and achieve a passing grade on the proficiency examination.
3. Senior Broadcast Engineer
   The candidate must have had ten years of responsible experience in broadcast engineering, and achieve a passing grade on the proficiency examination.
4. Twenty Year Certification
   The candidate must have had twenty years of professional broadcast engineering experience. Also, the candidate must be recommended by a certified Senior Broadcast Engineer, have at least one additional reference from a certified Senior Broadcast Engineer, and a reference from at least one person who has supervised his or her work.

For more information on Certification you can write:

Certification Secretary
Society of Broadcast Engineers
P.O. Box 50844
Indianapolis, IN 46220
(317) 842-0836

For information on the SBE Frequency Coordination Program see section 1.3. of this *Handbook*.

Society of Motion Picture and Television Engineers (SMPTE)

826 Scarsdale Avenue,
Scarsdale, NY 10583
(914) 472-6606

The membership of SMPTE is comprised of professional engineers and technicians in motion pictures, television, and allied arts and sciences. The society advances engineering technology, disseminates scientific information, and sponsors lectures, exhibitions, and conferences to advance the theory and practice of engineering. They also develop standards for motion pictures, television, and optical and magnetic recording and sponsor standards promulgated by the American National

Standards Institute. For copies of SMPTE standards contact their standards subscription service.

SMPTE also makes available visual and sound test films for use as standardized measuring tools and organizes and sponsors technical courses at universities on such subjects as sound techniques, laboratory processing, and film handling for television station technicians. The society presents eight annual awards for outstanding contribution to motion pictures and television.

SMPTE Committees include: Audio Recording and Reproduction Technology; Educational, Industrial and Consumer Film Technology and Applications; Film Technology; Laboratory Services Technology; Theatrical Projection Technology and Applications; Video Recording and reproduction Technology. Publications of the society include the *Journal* and various standards, recommended practices and engineering guidelines.

RELATED ORGANIZATIONS

American National Standards Institute (ANSI)

655 15th Street, N.W., Suite 300
Washington, DC 20005
(202) 639-4090

Members include industrial firms, trade associations, technical societies, labor organizations, consumer organizations, and government agencies. ANSI serves as the clearinghouse for nationally-coordinated voluntary safety, engineering and industrial standards. The institute gives status as American National Standards to standards developed by agreement from all groups concerned, in such areas as: definitions, terminology, symbols and abbreviations; materials, performance characteristics, procedure and methods of rating, methods of testing and analysis; size, weight, volume, and rating; practice, safety, health, and building construction. They also provide information on foreign standards and represent United States' interests in international standardization work. The ANSI committee is Certification. The Councils are: Company Member, Consumer, Executive Standards, International Standards, Organizational Member. Publications of the institute are the *Reporter*, biweekly; *Standards Action*, biweekly; *Catalog of Standards*, published annually.

American Radio Relay League (ARRL)

225 Main Street
Newington, CT 06111
(203) 666-1541

Members are licensed amateur radio operators in the U.S. and Canada and others interested in amateur radio, communication, and experimentation. The league operates a nationwide message handling network, the National Traffic System, with members serving as official relay stations, observers, phone stations, emergency coordinators, experimental stations, and bulletin stations. They operate an experimental equipment laboratory and maintain the Museum of Amateur Radio. They also sponsor contests and present awards for operating proficiency. ARRL serves as secretariat for International Amateur Radio Union. Publications include *QST*, monthly and *Radio Amateur's Handbook*, annually as well as special booklets for beginners and others on antennas and mobile and radio fundamentals.

Association for Broadcast Engineering Standards (ABES)

2000 M St., N.W., Suite 600
Washington, DC 20036
(202) 331-0606

An independent, nongovermental, voluntary organization of licensees and permittees of U.S. radio broadcast stations "united to assist the appropriate government authorities and the industry in assuring optimum radio service for the people of the United States and to follow the intent of Congress in the Communications Act of 1934, as amended." Objectives include: "rejecting and opposing proposals which would decrease, impair, or destroy the radio service now available to the American people; and supporting the adoption of legislature and Federal Communications Commission policies that encourage sound technical standards upon which optimum radio service may be obtained." Analyzes proposed broadcast legislation, FCC proposals for rule making, and industry proposals filed with the FCC that will, directly or indirectly, affect the public interest in optimum radio service. The association formulates and conducts short and long range programs of technical research to assist governmental and industrial groups in maintaining sound technical standards.

Audio Engineering Society (AES)

60 East 42nd Street, Room 449,
New York, NY 10017
(212) 661-8528

Members include engineers, administrators, and technicians who design or operate recording and reproducing equipment for radio, television, motion picture and recording studios, or who produce, install, and operate disc, magnetic tape, and sound amplifying equipment; educators who use recording in teaching, or who teach acoustics, electronics, and other sciences basic to the record-

ing and reproducing of sound; administrators, sales engineers, and technicians in the sound industry and related fields.

Broadcast Education Association (BEA)

National Association of Broadcasters
1771 N Street, N.W.
Washington, DC 20036
(202) 429-5355

Primarily directed by those in the academic community, its orientation is toward exploring new trends, ideas, and opportunities in broadcasting. Publishes *Journal of Broadcasting and Electronic Media* and *Feedback*. They also administer the Patterson Radio Scholarship and the Harold E. Fellows Memorial Scholarship.

Illumination Engineering Society of North America (IES)

345 E. 47th St.
New York, NY 10017
(212) 705-7926

This is a technical society whose members include engineers, architects, designers, educators, students, contractors, distributors, utility personnel, scientists, and manufacturers dealing with the art or science of illumination. They provide assistance with technical problems, reference help, and speakers. They maintain liaison with schools and colleges and offer basic and advanced IES Lighting Courses through local sections and in cooperation with other organizations.

Underwriters Laboratories (UL)

333 Pfingsten Rd.
Northbrook, IL 60062
(312) 272-8800

A testing laboratory that maintains additional laboratories in Melville, NY, Santa Clara, CA, and Tampa, FL. "By scientific investigation, study, experiments and tests to determine the relation of various materials, devices, products, equipment, constructions, methods and systems to hazards appurtenant thereto or to the use thereof affecting life and property, and to ascertain, define and publish standards, classifications, and specifications for materials, devices, products, equipment, construction, methods, and systems affecting such hazards, and other information tending to reduce loss of life and property from such hazards."

BROADCAST ENGINEERING AND RELATED PERIODICALS

ABU (Asian Pacific Broadcast Union) Review

NHK Broadcasting Centre
2-2-1 Jinnan
Shibuyaku
Tokyo, Japan

Audio

1515 Broadway
New York, NY 10036

BM/E (Broadcast Management/Engineering)

295 Madison Avenue
New York, NY 10017
(212) 685-5320

BM/E's World Broadcast News

295 Madison Avenue
New York, NY 10017

Broadcast Engineering

P.O. Box 12901
Overland Park, KS 66212
(913) 888-4664

EBU (European Broadcast Union) Review

Brussels edition
European Broadcasting Union Technical Centre
Avenue Albert Lancaster 32
B-1180 Brussels, Belgium

Electronic Media

Crain Communications Inc.
740 North Rush Street
Chicago, Il 60611

Electronic News

Fairchild Publications
7 East 12th Street
New York, NY 10003

Proceedings of the IEEE

Institute of Electrical & Electronics Engineers
345 E. 47th Street
New York, NY 10017
(212) 705-7900

IEEE Transactions on Broadcasting

Institute of Electrical & Electronics Engineers
345 E. 47th Street
New York, NY 10017
(212) 705-7900

Journal Of The Audio Engineering Society

60 East 42nd Street
New York, NY 10165
(212) 661-2355

Microwaves and RF
10 Mullholland Drive
Hasbrouck Heights, NJ 07604
(201) 393-6000

Pro Sound News
220 Westbury Avenue
Carle Place, NY 11514

QST
225 Main Street
Newington, CT 06111

Radio-Electronics
200 Park Avenue South
New York, NY 10003
(212) 777-6400

Radio World
5827 Columbia Pike, Suite 310
Falls Church, VA 22041

Recording Engineer/Producer
Gallay Communications Inc.
1850 Whitley Suite 220
Hollywood, CA 90028

SMPTE Journal
Society of Motion Picture and Television Engineers
862 Scarsdale Avenue
Scarsdale, NY 10583

Studio Sound and Broadcast Engineering
Link House
Dingwall Avenue
Croydon CR9 2TA, Great Britain

Television Broadcast
Globecom Publishing Limited
4551 W. 107th Street, Suite 210
Overland Park, KS 66207

TV Digest
475 Fifth Avenue
New York, NY 10017
212-686-5410

TV/Broadcast Communications
4551 W. 107th Street, Suite 210
Overland Park, KS 66207
(913) 642-6611

Television Technology
5827 Columbia Pike, Suite 310
Falls Church, VA 22041
(703) 998-7600

Video Systems
P.O. Box 12901
Overland Park, KS 66212
(913) 888-4664

BROADCAST ABBREVIATION REFERENCE LIST

(Compiled by John Reiser, Mass Media Bureau, FCC.)

AA	Average Audience
ABES	Association for Broadcast Engineering Standards
ACC	Automatic Chrominance (or Contrast) Control
ACE	American Cinema Editors
ACSB	Amplitude Compandored Sideband
ACTS	All-Channel Television Society
ACTS	Association of Cable Television Suppliers
ACTVA	American Community TV Association
ACU	Antenna Coupling Unit
ADC	Analog-to-Digital Converter
ADS	Alpha Delta Sigma (Advertising Fraternity)
AER	Alpha Epislon Rho—College Broadcast Fraternity
AES	Audio Engineering Society
AF	Audio Frequency
AFC	Automatic Frequency Control
AFCCE	Association of Federal Communications Consulting Engineers
AFN	Armed Forces Network
AFRTS	American Forces Radio & Television Service
AFT	Automatic Fine Tuning
AFTRA	American Federation of Television & Radio Artists
AFTRCC	Aerospace Flight Test Radio Coordinating Council
AGC	Automatic Gain Control
AID	Arbitron Information on Demand
AIM	Accuracy in Media
AITS	Association of Independent Television Stations
ALC	Automatic Level Control
ALJ	Administrative Law Judge
ALPTVA	American Low Power TV Association
AMOL	Automated Measurement of Lineup
AMST	Association of Maximum Service Telecasters
ANSI	American National Standards Institute
AOR	All Over the Road (undefined program format)
AOR	Album Oriented Rock (program format)
APA	Administrative Procedures Act
APL	Average Picture Level
ARCH	Automatic Remote Cassette Handler

ASC	American Society of Cinematographers
ASCAP	American Society of Composers Authors and Publishers
ATFP	Alliance of Television & Film Producers
ATS	Applications Technology Satellite
ATS	Automatic Transmission System
ATSC	Advanced Television Systems Committee
ATU	Antenna Tuning Unit
AWG	American Wire Gauge
AWRT	American Women in Radio & Television
BBC	British Broadcasting Corporation
BEA	Broadcast Education Association
BET	Black Entertainment Television
BFM	Broadcast Financial Management Association
BIAC	Broadcast Interassociation Council
BIB	Board for International Broadcasting
BICIAP	Broadcasting Industry Council to Improve American Productivity
BMI	Broadcast Music Incorporated
BOC	Bell Operating Company
BRC	Broadcast Rating Council—See EMRC
C/CS	County Coverage Service
CAB	Canadian Association of Broadcasters
CAMS	Cable Audience Measurement Study
CARS	Community Antenna Relay Service
CATA	Community Antenna Television Association
CBA	Community Broadcasters Association
CBC	Canadian Broadcasting Corporation
CC	Closed-Captioned
CCB	FCC Common Carrier Bureau
CCD	Charge Coupled Device Camera
CCIR	International Radio Consultative Committee
CCSB	Clear Channel Broadcasting Service
CCTA	Canadian Cable Television Association
CCTV	Closed Circuit Television
CD	Compact Disk (Audio Recordings)
CE	Chief Engineer (Chief Station Operator)
CFR	Code of Federal Regulations
CHR	Contemporary Hit Radio (Format)
CHUT	Cable Households Using Television
CIRT	Mexican Association of Broadcasters
CLI	Cumulative Leakage Index
CODEC	Coder, Decoder (digital)
CONTAM	Committee on Nationwide Television Audience Measurement
CP	Construction Permit
CPB	Corporation for Public Broadcasting
CPCS	Common Program Control Station for EBS
CRT	Copyright Royalty Tribunal
CRT	Cathode Ray Tube (video monitor)
CRTC	Canadian Radio Television & Telecommunications Commission
CS	Close Shot (in video or film production)
CTAM	Cable Television Administration & Marketing Society
CTS	Communications Technology Satellite
CU	Close Up Shot (in video or film production)
CUB	Council for UHF Broadcasters
CUME	Cumulative Audience
CWA	Communications Workers of America
DA	Directional Antenna
DA	Distribution Amplifier
DAC	Digital-to-Audio Converter
DAF	Demographic Adjustment Factor
DATS	Digital Audio Transmission Service
DB	Delayed Broadcast
DBA	Daytime Broadcasters Association
DBS	Direct Broadcast Satellite
DBSA	Direct Broadcast Satellite Association
DMA	Designated Market Area
DRAW	Direct Read After Write (Optical Data Disk)
DTTR	Digital Television Tape Recorder
DVE	Digital Video Effects
EAN	Emergency Action Notification
EBR	Electron Beam Recording
EBS	Emergency Broadcast System
EBU	European Broadcasting Union
ECU	Extreme Close-up Shot (in video or film production)
EEPA	Electromagnatic Energy Policy Alliance
EFP	Electronic Field Production
EIA	Electronic Industries Association
EMP	Electro-Magnetic Pulse
EMRC	Electronic Media Rating Council
ENG	Electronic News Gathering
EPA	Environmental Protection Agency
EPM	Equipment Performance Measurements
ERP	Effective Radiated Power

ETV	Educational Television
FCBA	Federal Communications Bar Association
FCC	Federal Communications Commission
FDM	Frequency Division Multiplex
FEMA	Federal Emergency Management Agency
FET	Field Effect Transistor
FMX	FM Extended-Range Transmission System
FNG	Film News Gathering
FOB	FCC Field Operations Bureau
FOIA	Freedom of Information Act
FSK	Frequency Shift Keying
GAO	General Accounting Office
GPO	Government Printing Office
HAAT	Height Above Average Terrain
HASL	Height above Mean Sea Level
HDTV	High Definition Television
HID	High Intensity Discharger (for lighting lamps)
IAAB	Inter-American Association of Broadcasters
IATSE	International Alliance of Theatrical Stage Employees
IBA	Independent Broadcasting Authority
IBEW	International Brotherhood of Electrical Workers
IBS	Intercollegiate Broadcasting System
ICPM	Incidental Carrier Phase Modulation
ICR	Inter-City Relay Station
ICTV	Independent Community Television Alliance
ID	Station Identification
IEEE	Institute of Electrical and Electronics Engineers
IFB	Interruptable Feedback (Remote Pickup System)
IFRB	International Frequency Registration Board
IHF	Institute of High Fidelity
INTELSAT	International Telecommunications Satellite Organization
INTV	Association of Independent Television Stations
IPA	Intermediate Power Amplifier
IRAC	Interdepartmental Radio Advisory Committee
IRE	Institute of Radio Engineers (now IEEE)
IRTS	International Radio and Television Society
IRTV	International Radio & Television Foundation
ISDN	Integrated Services Digital Network
ITFS	Instructional Television Fixed Service
ITNA	Independent Television News Association
ITU	International Telecommunications Union
JCIC	Joint Council on Intersocietal Coordination
LED	Light Emitting Diode
LFCC	Local Frequency Coordinating Committee
LNA	Low Noise Amplifier
LPTV	Low Power Television
LS	Long Shot (in video or film production)
MAC	Multiplex Analog Component (TV Transmission)
MCR	Master Control Room
MTS	Multi-channel Television Sound
MCU	Medium Close-Up Shot (in video or film production)
MDS	Multipoint Distribution Service
MEOV	Maximum Expected Operating Value
MERPS	Multiple Event Record & Playback System
MLS	Medium Long Shot (in video or film production)
MMB	FCC Mass Media Bureau
MMDS	Multichannel-Multipoint Distribution Service
MNA	Multi-Network Area
MO&O	Memorandum Opinion and Order
MOP	Minute of Program
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MSO	Multiple System Operator (CATV)
MST	Association of Maximum Service Telecasters
MUSE	Multiple Sub-Nyquist Sampling Encoding (for TV)
NAB	National Association of Broadcasters
NABA	North American Broadcast Association
NABET	National Association of Broadcast Employees and Technicians
NABOB	National Association of Black-Owned Broadcasters
NABTS	North American Broadcast Teletext Standard
NAC	National Audience Composition
NAITPD	National Association of Independent TV Producers and Distributors
NAL	Notice of Apparent Liability
NAPTE	National Association of Television Program Executives
NAPTS	National Association of Public Television Stations

NARAS	National Academy of Recording Arts and Sciences
NARBA	North American Radio Broadcasting Agreement
NARTE	National Association of Radio & Television Engineers
NARUC	National Association of Regulatory Utility Commissioners
NASB	National Association of Spanish Broadcasters
NATAS	National Academy of Television Arts & Sciences
NBN	National Black Network
NCFM	Noncommercial FM
NCTA	National Cable Television Association
NEMO	Remote Broadcast—Not Emminating from Main Office
NHK	Japan Broadcasting Corporation
NIAC	National Industry Advisory Committee (EBS)
NILPTV	National Institute for Lower Power TV
NOI	Notice of Inquiry
NPACT	National Public Affairs Center for Television
NPR	National Public Radio
NPRM	Notice of Proposed Rule Making
NRB	National Religious Broadcasters
NTA	National Translator Association
NTIA	National Telecommunications and Information Administration
NTSC	National Television System Committee
OB	Outside Broadcast
OFS	Operational Fixed Service
OIRT	International Radio and Television Organization
OMD	FCC Office of Managing Director
OPP	FCC Office of Plans and Policy
OROM	Optical Read Only Memory (for data storage)
OSHA	Occupational Safety and Health Administration
OST	FCC Office of Science and Technology
PA	Power Amplifier
PAL	European Color Television System
PBS	Public Broadcasting Service
PCM	Pulse Code Modulation
PDM	Pulse Duration Modulation
PDT	Published Data Tapes
PLL	Phase Locked Loop
PLP	Presentation Level Protocol
PLT	Private Line Telecommunications Circuit
POV	Point of View (shot in video or film production)
PPM	Peak Program (level) Indicator
PRB	FCC Private Radio Bureau
PSA	Presunrise Service Authorization
PSK	Phase Shift Keying
PSRA	PreSunrise Authority
PSSA	Post Sunset Authority
PSSC	Public Service Satellite Consortium
PTAR	Prime Time Access Rule
PTV	Public Television
QPSK	Quadrature Phase Shift Keying
R&F	Reach & Frequency
RARC	Regional Administrative Radio Conference
RCC	Radio Common Carrier
RCL	Remote Control Location
RDD	Random Digital Dialing (for audience surveys)
RFA	Regulatory Flexibility Act
RFE	Radio Free Europe
RFI	Radio Frequency Interference
RFR	Radio Frequency Radiation
RGB	Red-Green-Blue Color Monitor Signal
RIAA	Recording Industry Association of America
RMS	Root Mean Square
RNA	Radio Network Association
RO	Receive-Only Earth Terminal
RP	Restricted Radiotelephone Operator Permit
RPU	Remote Pickup
RSS	Root Sum Square
RTNDA	Radio & Television News Directors Association
SAP	Second Audio Program on TV Subcarrier
SBE	Society of Broadcast Engineers
SCA	Subsidiary Communications Authority
SCPC	Single Channel per Carrier
SCTE	Society of Cable Television Engineers
SECAM	French and Russian Color Television System
SECC	State Emergency Communications Committee (for EBS)
SH	Specified Hours (Licensed hours of operation)
SIA	Storage Instantaneous Audimeter
SID	Source Identification Signal (in TV VBI)
SIU	Sets in Use
SMA	Special Market Area
SMATV	Satellite Master Antenna Television System
SMPTE	Society of Motion Picture and Television Engineers
SMSA	Standard Metropolitan Statistical Area
SNG	Satellite News Gathering

SOF	Sound on Film
SPACE	Society for Private & Commercial Earth Stations
STA	Special Temporary Authority
STC	Satellite Television Corp.
STL	Studio Transmitter Link
STV	Subscription Television
STVA	Subscription Television Association
SWARC	Satellite World Radio Conference
T/R	Transmit—Receive Earth Terminal
TARPAC	Television & Radio Political Action Committee
TARPEC	Television and Radio Political Education Committee
TASO	Television Allocations Study Organization
TBC	Time Base Corrector
THD	Total Harmonic Distortion
TIO	Television Information Office
TMC	Time Multiplex Component Video
TOC	Television Operator Council
TPO	Transmitter Power Output
TSL	Transmitter to Studio Link
TVB	Television Bureau of Advertising
TVI	Television Reception Interference
TVROTV	Receive-only Satellite Earth Terminal
UHF	Ultra High Frequency
USIA	United States Information Agency
VAR	Video to Audio Carrier Ratio
VBI	Vertical Blanking Interval
VBIC	Vertical Blanking Interval Code
VCR	Video Cassette Recorder
VHF	Very High Frequency
VIRS	Vertical Interval Reference Signal
VITC	Vertical Interval Time Code
VITS	Vertical Interval Television Signal
VOA	Voice of America
VSWR	Voltage Standing Wave Ratio
VTR	Video Tape Recorder
VU	Volume Unit (measurement of program level)
WARC	World Administrative Radio Conference
WHCAA	White House Communications Agency
WIC	Women in Cable
WICI	Women in Communications, Inc.
WPFC	World Press Freedom Committee
WST	World System Teletext

Chapter 1: Design, Erection and Maintenance of Antenna Structures
Chapter 2: Lightning Protection for Broadcast Facilities
Chapter 3: Transmission Lines
Chapter 4: AM Broadcast Antenna Systems
Chapter 5: Antennas for FM Broadcasting
Chapter 6: Antennas for Television Broadcasting
Chapter 7: Measurement of FM and TV Field Strengths
Chapter 8: AM Field Strength Measurements and Proof of Performance
Chapter 9: Radio Wave Propagation
Chapter 10: Radio and TV RF Systems

2.1

Design, Erection, and Maintenance of Antenna Structures

John Windle
Vice President, Engineering
Stainless, Inc.
North Wales, Pennsylvania

Wayne Kearsley
President and Director of Engineering
Flash Technology Corporation of America
Nashua, New Hampshire

INTRODUCTION

The purpose of this section is to provide broadcast engineers and managers information concerning the design, erection and maintenance of antenna structures. While fundamental principles of the design and behavior of these structures will be discussed, it is not intended to enable the reader to design and build his own tower, but rather to provide him with a basic understanding of these unique structures that will enable him to better plan, modify and maintain his facilities.

TOWER CHARACTERISTICS

Types

All towers may be classified in one of the two basic groups—guyed or self-supporting. As their names imply, guyed towers are those which depend upon cables running to anchors located some distances from the tower base for their structural integrity, while self-supporting towers rely solely on their own construction as a cantilivered space truss.

With only a few exceptions, the cost of the actual tower structure and foundations is considerably less for a guyed tower than for one that is self-supporting. The advantage of the self-supporting tower is the relatively small land area required. Therefore, the choice between guyed or self-supporting depends to a large degree on the availability and cost of real estate.

A self-supporting tower requires a nearly square plot of land with sides equal to 8 to 20 percent of its height.

The amount of land required for a guyed tower depends on the distance between the tower base and the guy anchors. This distance is preferably between 70 and 80 percent of the height which would require a rectangular plot having sides equal to 125 and 145 percent of the height.

Because of the great flexibility in guyed tower design, it is possible to reduce the anchor distance to as little as 35 percent of height thereby requiring a much smaller land area. However, the cost of the tower increases as the anchor distance decreases. The approximate relationship of cost to anchor distance for a representative 1200 feet television broadcast tower is shown in Fig. 1.

It is often possible to position a guyed tower on an irregularly shaped plot or to obtain long-term lease agreements or easements for guy paths and anchor locations in order to minimize the tower cost without obtaining large, rectangular land areas.

Configurations

1. ***Self-supporting Towers*** may be either square or triangular in cross section. While it is usually more economical to use a triangular cross

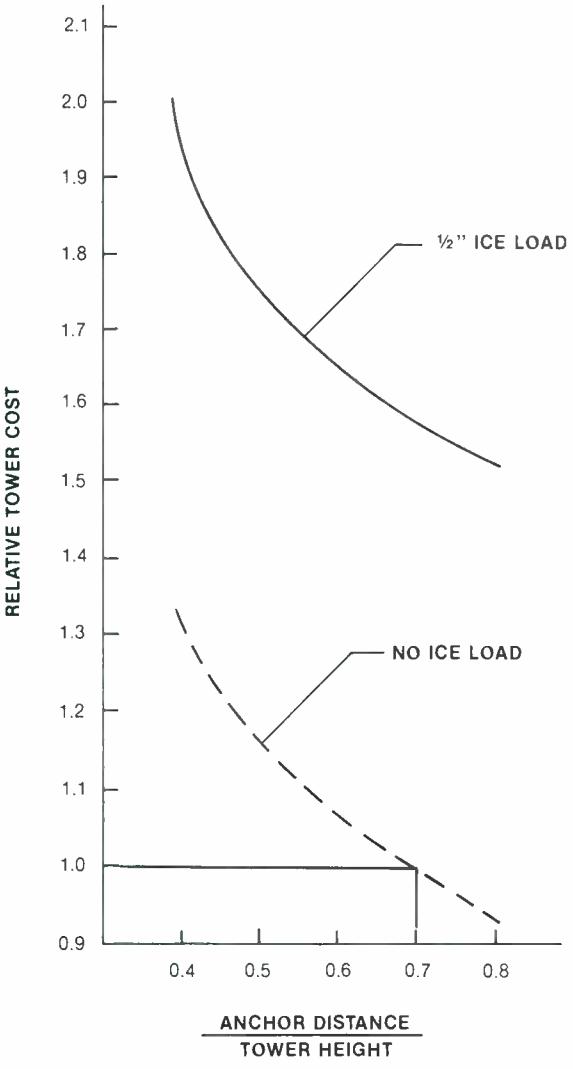


Fig. 1. Effects of anchor distance on cost of a 1200 ft. guyed TV broadcast tower.

section, there are situations where a square cross section is a better choice. The principal structural elements are the legs, the web bracing in each face, and if required for stability, horizontal diaphragm bracing. The legs are usually sloped (tapered) to provide adequate strength and stability as the height increases. The degree of slope is an option of the designer to suit the equipment supported, the required rigidity and the available land area. The slope is sometimes varied within a tower to maintain a desirable balance between the costs of leg members and bracing, or to reduce the foundation loads. Frequently the legs in the top section of the tower will be parallel to simplify the mounting of equipment.

There are several different configurations of bracing members for the individual truss panels. The choice is influenced by the width of the panel, the magnitude of the wind and ice loads imposed, the location of equipment and the required stability. Continuity in transferring the applied loads through the structure without significant eccentricity is essential regardless of the configuration used.

2. *Guyed towers* are almost always of triangular cross section although there are a few unique conditions for microwave antenna supports where a square cross section is advantageous. The principal structural elements are the legs, the web bracing in each face, and the guy support systems. Except for sections at the tower base and locations where the width changes, the legs are parallel. The width of the tower is usually constant throughout the height of the tower with the exception of sections supporting antennas requiring a specific width of support structure. The base section is often tapered to a single point to provide a pivot support to eliminate large bending and torsional moments.

   Theoretically there are an infinite number of arrangements of guy cables to support a tower. The most common arrangement is three cables spaced at 120 degrees with one attached to each leg. This is the minimum number of cables that can be used. When the tower supports equipment which imposes large twisting moments (torques), it is necessary to provide six cables at a level to maintain torsional stability. If the torque is localized, the guys at that location may be attached to triangular frames as shown in Fig. 2b. If the torques occur throughout the height, it may be desirable to double guy the tower at every level as shown in Fig. 2c.

   The number of levels of guy cables to support the tower is dependent on a number of factors including the height of the tower, width, location of equipment, and the environmental loading conditions. Because the tower is an axially compressed column, its strength is a function of its slenderness. While design codes permit slenderness ratios resulting in triangular towers having a span-to-width ratio as great as 49, it is usually economical to limit the ratio to a maximum of 30. While there is no upper limit to the number of guy levels imposed by any code, a practical limit for economical design is 10.

   The position of equipment on the tower is an important factor in determining the location of guy levels. Preferably, guy attachments should not be located within the apertures of side mounted TV and FM broadcast antennas. Equipment producing large localized wind loads, such as microwave antennas or clusters of two-way radio cabinets and antennas,

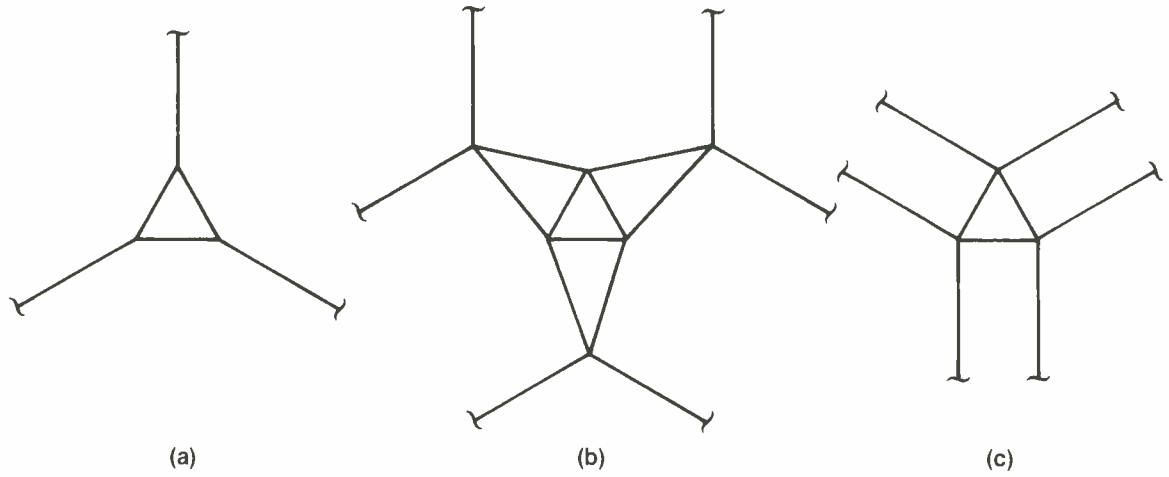


Fig. 2. Typical guy arrangements.

should not be positioned near the center of spans between guys.

If the tower will be subjected to ice loading, it is desirable to reduce the number of guy levels to minimize loads imposed on the tower by ice accumulation on the guy cables.

The number of anchors in each guy direction is dependent on several factors including the number of guy levels, the soil conditions, topography, and obstacles. As a general guideline, it is desirable to limit the number of guy levels attached to a single anchor to five. However, there is nothing absolute about this number, and other conditions may dictate using an anchor for a greater number. There are some soil conditions where it may be economical to provide two or more smaller anchors while in another instance the use of one large anchor might be desirable. If minimizing the area within which the tower would fall in the event of a collapse is a consideration, a minimum of two anchors should be used in each direction.

Where the elevations of the anchors differ from the tower base, it is desirable to vary the distance of the anchors from the tower base to maintain nearly equal initial tensions in the guy cables. Anchors higher than the tower base should be moved toward the tower; and anchors that are lower, away from the tower. The amount of movement should be specified by the designer.

Materials

1. *Tower Structures*

Nearly all broadcast towers are made from steel because it provides the most economical structure. The selection of the grade and shape of steel is obviously an important design consideration.

Steels used for towers commonly have low carbon content with yield strengths in the range of 36,000 to 60,000 psi. These materials have good ductility and are suitable for welding. Some towers have been built using higher grade materials with yield strengths up to 100,000 psi, but the savings in weight are more than offset by higher base prices and increased fabrication costs. Regardless of the grade of material, its physical and chemical properties should be certified by the producing mill to ensure that it conforms to the design requirements.

The shape of the material as well as its size and strength affects its load carrying capacity. The shape also has a significant effect on the magnitude of loads produced by wind. Design standards permit a reduced wind load on round members between 60 to 70 percent of that for flat or angular members of the same width. For this reason, solid round bars, round structural tubes and pipe are used extensively. This advantage in wind load is offset somewhat by increased fabrication costs, due to the necessity of welding plates onto them for connecting the various members.

There is no one grade or shape of material that is "best". The choice depends to a large degree on the preference of the designer and the type of fabricating facilities available.

A factor equally as important as the selection of the grade and shape of the structural steel is the design of the connections. For shop welded connections, the compatibility of the base and filler metals and required preheat temperatures must be considered. The procedures used must be qualified and the welders

certified for them. Inspection procedures should be compatible with the weld design.

Bolts for field assembly may be of various types. Usually those for the main load carrying members are high strength. If positive resistance to slippage of the connections is required, interference body, ribbed ("drive") bolts may be used.

2. *Guys*

The most common material for tower guys is galvanized steel strand. This material has excellent strength and durability. Its "structural" elongation due to the seating of the individual wires in the strand is small and can be almost entirely eliminated by prestressing the strand to 50 percent of its breaking strength at the factory. This should be done for guys on tall towers with factory connected end fittings.

For guys on AM towers, and those close to FM and TV antenna appertures, a nonconductive material is sometimes desirable. Two such materials that have been used are Kevlar rope and fiberglass rods. When using these materials, careful attention must be given to protection against corona effects, fatigue and deterioration from exposure to ultraviolet light. Also, their elongation characteristics under load must be evaluated. They require delicate handling at all times.

Just as for the tower structure, the connections for the guys are as important as the guy material itself. Some of the more common connections are as follows:

a. ***Sockets*** of forged or cast steel attached with molten zinc or epoxy resins develop the full strength of the guy. They are normally installed at the factory and proof loaded to 50 percent of the guy breaking strength. This type of fitting is most common for the larger guys used on tall towers.

b. ***Dead end grips*** are preformed wire loops in the shape of a large hairpin. The two legs of the hairpin are wrapped around the guy with its closed end forming an eye. These grips are used for guys up to one inch in diameter and usually develop their full strength. They are easily installed in the field, but the ends must be completely snapped into place and a protective device installed to prevent ice from sliding down the guy and loosening the grip.

c. ***Clips*** used to clamp the ends of guys develop 85 percent of the guys's strength when properly applied and tightened. To install them it is necessary to bend the strand back on itself to form a loop; thus their use is difficult on large cables. The saddle of U-bolt type clips must be on the load side and not the dead end which provides another potential error in their installation.

d. ***Swaged Sleeves*** develop between 85 and 100 percent of a guy's strength depending on its size and equipment used to squeeze the sleeve. These fittings are usually installed at the factory and can be proof loaded. They are advantageous for connecting closely spaced insulators where the length of dead end grips is unacceptable.

e. ***Serving*** is a connection made by rolling the individual wires of a strand back on the strand itself. This method has for the most part been replaced with dead end grips, but it is advantageous for small guys with closely spaced insulators.

3. *Insulators*

a. ***Base insulators*** for AM towers are made from porcelain with appropriate galvanized steel end fittings. For a guyed tower, one end is fitted with a rocker plate or spherical bearing joint to prevent uneven loading on the porcelain and subsequent cracking. For self-supporting towers the fittings must be designed so that the assembly can sustain either upward or downward forces while keeping the porcelain loaded in compression.

b. ***Sectionalizing insulators*** to isolate portions of a guyed tower have been made from both porcelain and fiberglass. If these insulators are designed only for the compression loads they are subjected to after installation, temporary connections, or fittings to prevent their failure under tension loads imposed during construction, must be provided.

c. ***Guy insulators*** are available in several types. To break up a cable into segments and prevent re-radiation, porcelain insulators are normally used. These insulators are a single piece of porcelain placed between interlocking loops of the guy. In this manner, the porcelain is loaded in compression, and even if it should fail, the loops remain connected providing a "fail-safe" connection. For larger size guys, the same concept is achieved by placing the porcelain within an interlocking steel frame which is in turn connected to the guy segments.

Strings of the insulators may be used to provide insulation between the guy and an AM tower. Strain insulators made of fiberglass rods or porcelain cylinders have also been used next to the tower where a higher degree of insulation is required. These insulators are loaded in tension and do not

have the "fail-safe" characteristics of the porcelain break-up insulators.

Finishes

1. *Corrosion Protection*

Steel is susceptible to deterioration from atmospheric corrosion. To prevent this, the tower members and hardware must be given a protective coating. This coating is usually zinc which has excellent resistance to corrosion, and because it is higher in the electrochemical series, it provides cathodic protection to exposed steel surfaces adjacent to it. Even though the zinc coating may be scraped or otherwise damaged, it continues to inhibit corrosion of these exposed areas, and rust will not develop beneath the zinc coat adjacent to them.

There are several methods of applying the zinc including hot dip galvanizing, flame spraying electroplating and painting. All must be applied to clean surfaces.

a. ***Hot-dip galvanizing*** consists of dipping the steel into a bath of molten zinc. A metallurgical bond develops between the steel and the zinc which adheres to it. When galvanizing tubular members, it is necessary to provide holes in both ends to ensure that the inside surfaces are coated. Careful attention must be given to the type of base and weld metals used, as well as to the welding and forming procedures used in fabrication to safeguard against possible embrittlement of the steel when galvanized. When properly applied, this process provides the most durable coating.

b. ***Flame spraying*** consists of spraying molten zinc at high pressure onto the steel surfaces. The bond in this process is mechanical rather than metallurgical. The coating produced is more porous and has less resistance to abrasion than the hot-dip galvanized coating. It cannot be used for the inside of hollow sections or other cavities where access is difficult.

c. ***Electroplating***, while suitable for small objects, does not produce a coating thick enough to withstand an aggressive environment. It is not recommended for tower parts or hardware.

d. ***Zinc Rich Paint*** consists of extremely finely divided zinc in an inorganic or organic vehicle. It is not a metal coating method, but rather a painting procedure. Its resistance to abrasion and durability are less than hot-dip galvanizing. It is, however, useful for maintenance.

2. *Aircraft Marking*

When required by the FCC construction permit, towers must be marked as a hazard to air traffic. To comply with this requirement, a tower is painted with contrasting colors of white and international orange in alternate bands. Selection of the paint materials must be compatible with surfaces to which they will be applied. There are several manufacturers who have one-coat paint systems that can be applied directly to galvanized surfaces. Like all paint procedures, clean, dry surfaces and suitable temperatures are essential to obtaining satisfactory adherence.

3. *Ice Prevention*

Recently, a coating has been developed that is intended to reduce the adherence of water to surfaces and subsequently the formation of ice on them. There is not sufficient data as yet to evaluate its effectiveness and life expectancy.

Access Facilities

A tower must have some access facilities in order to maintain it and the equipment it supports. For small towers, the bracing members of the tower itself often serve as steps or step bolts are attached to one leg or face.

1. *Ladders*

For taller broadcast towers, a fixed ladder inside the tower is desirable. OSHA Standards for these ladders require a minimum clear width between side rails of 16 inches and a maximum rung spacing of 12 inches. They also require that any continuous ladder more than 20 feet in height be equipped with a safety device. This device consists of a continuous rail, either rigid or cable, running up the center of the ladder. A clamping device attached to the climber's safety belt rides along this rail. As long as the climber is in a normal position, the clamp slides freely; if he begins to fall, a cam actuated mechanism freezes the clamp to the rail and prevents his falling.

2. *Elevators*

For tall towers supporting multiple antennas, it is often desirable to install an elevator. Most tower elevators are of the power, cable-driven type with a capacity of 500 to 750 pounds and a speed between 80 and 100 feet per minute. They consist of a driving mechanism, car, guide rails, hoist cable with supporting sheaves, tension weights, electronic controls, and a two-way communications system.

Considerable attention must be given to safety features. These should include limit

switches to prevent travel beyond the upper and lower landings on the tower, an automatic brake on the driving mechanism that is activated by any interruption in power, a mechanism to automatically clamp the car to the rails in the event of a broken hoist cable, and interlocks to prevent operation with the car gate open. It is advisable to determine what state or municipal government regulations apply and what permits, tests, and inspections are required before the tower and elevator system are designed.

The added wind and dead loads from an elevator system are substantial and must be considered in the tower design. Also, careful attention must be given to the positioning of the ladder, RF transmission lines and electrical conduits in relationship to the elevator. The ladder must be positioned so it is accessible from the elevator car and can be used for emergency descent. While the elevator hoist cables can be restrained in guides on the return side, they are free to move about under wind load on the lifting side. Therefore, the conduits and transmission lines must be protected from hoist cables striking and damaging them. If a side mounted TV or FM antenna produces a high RF field within the hoistway, protection must be provided to prevent arcing between the hoist cables, the tower structure, and other appurtenances.

3. *Transmission Line Bridges*

To allow for thermal expansion and contraction, it is necessary to locate broadcast towers some distance from the transmitter building. Unless the transmission line is going to be placed underground, it is necessary to provide a structural support for it at a height compatible with the transmitter location in the building. The top of the support can be covered with steel grating or plate to protect the lines from falling ice. The details of this structure can become quite involved for sites with multiple antennas, uneven terrain and roadways, or obstacles between the tower and building.

4. *Stairways*

The lower landing for a tall, guyed broadcast tower with an elevator is often 30 feet or more above ground level. A stairway may be desirable to permit easier access to the landing. This structure can be combined with the transmission lines support bridge. It may also be desirable to install a small capacity boom above the lower landing to lift radio cabinets or other equipment onto the landing.

ELECTRICAL SYSTEMS FOR TOWERS

Tower Lighting

Since a tower is a hazard to air navigation, the government prescribes certain warning lights to be installed on broadcast towers. In general, the lighting requirements are spelled out in a pamphlet put out by the Federal Aviation Administration (FAA) called "Standards for Marking and Lighting Obstructions to Air Navigation" (AC 70/7460-1). Prior to submission of your application for construction to the FCC, the various options for tower lighting should be carefully considered, and any preferance for an option should be requested with the application.

The various methods for marking and lighting towers are as follows:

Red Lights With Orange and White Paint

When considering red lights and paint, the height of the tower determines the number of flashing beacons and steady burning side light levels. (See FAA AC 70/7460-1). Other factors to be considered are:

1. Due to color fading, repainting may have to be done every 4 to 5 years to meet the FAA color specifications. On galvanized towers, paint peeling can become a severe problem after several years. Depending on the tower location, the cost of insurance during the repainting may become a very significant economic consideration.
2. In view of the high cost of electricity and the low efficiency of incandescent lighting, the long-term cost of power should also be considered.
3. Lamp life is dependent on many factors but is particularly sensitive to vibrations and high line voltage. The FAA recommends changing lamps when they have reached 50% of their rated life, which in a practical sense usually amounts to changing all of the lamps every 6 months.
4. The requirement of $\pm 3\%$ of nominal voltage at the lamp socket must be met by the system design. If the voltage is too low the light output falls below specifications, and if too high the lamp life is shortened. For instance, a 3% low voltage results in a 10% drop in light output, and a 3% high voltage results in a 30% reduction of the rated lamp life.
5. Although the FCC no longer requires the daily logging of tower light operation, the logging of a tower light failure is required along with notification to the FAA of the failure and the

proposed schedule for resumption of normal operation. Automatic monitoring is available in accordance with FAA requirements to alert station personnel of a flashing beacon failure as well as a side light failure. Computer compatible monitoring systems are available for use with logging systems.

Medium Intensity Electronic Lights With Orange and White Paint

FAA AC 70/7460-1 currently permits the use of medium intensity electronic lights during twilight and nighttime on painted towers over 250 feet. This type of lighting is energy efficient; power costs will typically be less than 10% of comparable red lighting systems. Although this type of lighting is especially suitable for remote locations, it has also proven economical for lighting systems on towers that use paint for daytime marking.

Refer to the previous marking method for paint considerations, and to the following marking method for the electronic light considerations.

High Intensity Electronic Lights

High intensity electronic lights may be used effectively to mark towers and eliminate the requirements for the orange and white paint. These lighting systems have three intensities for marking the structure during the day, twilight, and night. Again, the height of the tower will determine the number of high intensity light levels needed to mark the tower. (See FAA AC/70/7460-1). Effective intensity is probably the least understood term when it comes to the practical use of electronic flash equipment. The term *candella* is used as the unit of measurement, and *effective candella* is specified if the Blondel-Ray relationship has been taken into account.

The eye is able to integrate a light pulse with virtually no reciprocity failure for pulse lengths much shorter than the decay time constant for the eye which is approximately 0.2 seconds. Therefore, the eye is sensitive to the integrated value of the light pulse and not to the peak value, which for short pulses can be stated in impressively high but meaningless figures, as far as the eye is concerned.

The effective intensity can be determined from the Blondel-Ray relationship

$$I_E = \frac{I_M \times t}{0.2 + t} \text{ candella}$$

Where:

I_E = Effective Intensity
I_M = Measured Intensity in candle-seconds
t = Pulse width of the light pulse (Usually between the ⅓ amplitude points)
0.2 = the decay time constant for the eye.

For short light pulses, the effective intensity can approach 5 times that of a steady light source with the same candle-second intensity.

Other factors to be considered when using high intensity electronic lights for marking towers are:

1. With the higher efficiency optics and power converters of the electronic lights that are currently available, the 24 hour per day operating power cost can be reduced to at least one-half that of the red light nighttime operating cost.

2. The economics of electronic light operation is governed by many design factors. FAA approved systems are required to meet specific operational requirements but must only guarantee a minimum of one year life. Economical operation demands the careful consideration of the following life-determining factors:

   a. Even the best quality UV-inhibiting quartz flash tubes will have a life that will vary widely depending on the flash tube's bore size, length, operating voltage, current pulse shape, and electrode, operating temperatures. Generally speaking, larger bore flash tubes using lower voltages between 500 and 1000 volts and a power loading of less than 5 watts per square centimeter of flash tube surface area, along with good electrode cooling, should give a lamp life in excess of 5 year providing that the flash tube current wave shape has been optimized.

   b. The energy storage capacitors should be properly derated for the operational voltage to provide long life. Operational deratings for capacitors in common use during the past 10 to 20 years have shown deratings to 60% as being safe and long-lived. New technology capacitors using state of the art dielectric materials have shown derating to 80% as being safe and long-lived. Because of the significant energy levels used in these lights, energy storage capacitors using minimal derating should have built-in protection devices to minimize the possibility of overheating, rupturing and causing damage not only to themselves but to beacon interiors as well.

   c. The power transformers used in electronic lights today are typically of the constant current/voltage regulating type. This type of transformer is very efficient when used to charge capacitors and is capable of supplying a near constant current from 0 volts to full flash operating voltage on the capacitor. This type of transformer is not harmed if a flash capacitor shorts out, and is less likely to catastrophically destroy the capacitor. Another feature of this type of

transformer is its inherent immunity to voltage transients and spikes on the power line. Since the flash energy is proportional to the square of the flash voltage, capacitor safety margins are maintained and light output can be kept within the FAA specifications over the normal input power voltage fluctuations. To guard against lightning induced voltages on the tower, the breakdown voltage from the primary to case and to other windings should be designed for at least 5 kV with insulation of high enough heat rating to hold up for the desired useful life of the beacon.

d. Using up-to-date technology with properly engineered designs and low flash voltages in the 500 to 1000 volt range, recent beacon designs have been able to virtually eliminate the corrosion problems that have plagued many of the older style, high voltage designs operating in the 1.5 to 3.1 kV flash voltage range.

e. For enviromental considerations, the optical design is very important. These lights are specifically designed to alert pilots, on a collision course, of the tower's existence. Stray light reaching inhabited areas on the ground may be minimized by using louvers to block the direct radiation from the flash tube. Special optical designs using polyfocal parabolas, which provide a very sharp cut off on the bottom of the beam, may also be used to further reduce the undesirable light reaching the ground. Within ranges where the eye is able to resolve the light aperture size, a larger aperture will provide a less intense looking light, while at the same time, providing the proper far-field intensity.

f. Although the FCC no longer requires daily logging of tower light operation, the logging of a tower light failure is required along with notification to the FAA of the failure and the proposed schedule for resumption of normal operation. Automatic monitoring is available in accordance with FAA requirements to alert station personnel of a tower lighting failure. Computer compatible monitoring systems are available for use with remote logging systems.

Other Electrical Circuits

Other electrical considerations when planning a tower installation are:

a. Antenna deicing circuits should be designed to be installed in the main electrical power conduit. If a choice of deicer operating voltage is available, consider choosing the highest voltage under 600 volts in order to minimize wire size. In many cases a 208/240 volt deicer system is fed with 480 volts using a step down transformer to reduce the I^2R losses incurred in the long run feeding systems on tall towers. Deicing systems should be designed to provide no more than 5 to 10 percent voltage drop to insure the proper operation of the deicer since the available heating power is proportional to the square of the voltage. Most deicer control circuits require a shielded triplet which may also be installed in the power conduit.

b. An ac utility circuit to provide access to 120 volt power at several elevations on the tower will often save time during maintenance and repair work on the tower and associated systems.

c. Wiring for the elevator control circuits, if needed, may also be installed in the power conduit.

d. A sound-powered telephone system in a separate ½" conduit to provide communications with ground personnel from the various working platforms can likewise save time during maintenance and repairs.

e. With the recent increase in two-way communications activity, many tall tower installations have found it advantageous to provide several platforms with up to 150 amp, 120 volt service which will accomodate the full spectrum of two-way communication systems.

A separate conduit with 20 to 100 pair telephone cable is normally used to provide audio input for these systems.

DESIGN STANDARDS

Industry

The vast majority of towers in the United States have been designed in accordance with the Electronic Industries Association (EIA) Standard RS-222, *Structural Standards for Steel Antenna Towers and Antenna Supporting Structures.* This standard has been used since 1959 when it replaced the Radio-Electronic-Television Manufacturers Association (RETMA) Standard TR-116. The current revision "C" of RS-222 was issued in 1976, and a new edition is contemplated toward the end of 1985.

This standard is intended to provide *minimum* criteria for specifying and designing steel antenna towers and antenna supporting structures. Unlike general specifications and building codes it is applicable only to antenna towers and supporting structures. As such it contains criteria peculiar to these structures that are not readily available elsewhere. Therefore it is always advisable to specify that your tower must conform to this standard.

Statutory

Most municipal and state governments have statutory codes regulating the design of structures. Many of these are patterned after or include one of several model codes. The most common of these are the Building Officials and Code Administrators International (BOCA) *Basic Building Code,* The International Conference of Building Officials (ICBO) *Uniform Building Code*, and the Southern Building Code Congress (SBC) *Standard Building Code.*

These codes cover all types of structures and are directed primarily toward conventional types of buildings. As such, they do not contain all the criteria necessary to design broadcast towers. For example, none of them includes a recommended safety factor for guy cables.

Of particular concern to tower designers is their provisions for calculating wind load.

The *BOCA Code* specifies that radio and television towers be designed for wind loads in accordance with the American National Standards Institute (ANSI) Standard A.58.1, *Minimum Design Loads for Buildings and Other Structures,* which contains specific criteria for wind loads on towers.

The Uniform Building Code gives specific, but incomplete criteria for towers up to 400 feet tall, and states that taller structures be designed in accordance with "approved national standards." No further definition is given, leaving that determination to the judgement of the local building official.

Since it is necessary to comply with the applicable statutory requirements, it is important to determine what they are and include them in the specification for the tower. They can have a significant effect on the cost.

LOADS, ANALYSIS AND SAFETY FACTORS

Loads

In addition to its own dead weight and the dead weight of the appurtenances and equipment it supports, the tower must withstand the forces of nature: wind, ice, temperature changes, and earthquakes.

1. *Wind Load*

Wind produces a principal load on tower structures. For design purposes it is represented as a horizontal static force proportional to the square of the wind velocity and the size and shape of the structure and its attachments.

While all of the design standards use the same statistical data for the maximum probable wind velocity at a specific location, they use different procedures for relating the design load to that velocity. These differences are in the shape coefficients applied to the projected area of the members and in amplification factors used to account for the dynamic effects of wind gusts and the tower's response to them.

The design standards also differ in their methods of accounting for the variation of wind velocity with respect to height above ground. This relationship has been empirically determined to be exponential based on records obtained during severe storms. In this area the EIA Standard differs significantly from the others for towers greater than 650 feet in that its recommended design wind pressures are based on a constant velocity over the entire height.

Graphic examples of the differences in wind loads when using various design standards are shown in Fig. 3.

Since the wind may act from any direction, it is necessary to apply the wind loads in any horizontal direction to determine the maximum stresses produced in the structure. For a triangular tower three directions must be considered, while for a square tower two are sufficient. These are shown in Fig. 4.

In addition to this direct load in the direction of the wind (drag), there may also be a component of load perpendicular to the wind direction (lift). These lift components are calculated in a manner similar to that for drag forces using different shape coefficients that vary with respect to the angle of attack between the member's geometric axis and the wind direction. They are most significant for wind acting on guy cables, microwave antennas and rectangular waveguides.

2. *Ice Load*

Ice accumulations have two effects on a tower. The weight of the ice acts directly on the structure in the same manner as the dead weight. The ice accumulation also increases the area exposed to the wind and consequently the load produced by the wind. This increase is substantial on small components such as guy cables, tension rods, ladders, small diameter transmission lines and reflector screens for antennas. It is also possible for the ice accumulation to alter the aerodynamic shape of members thereby requiring the use of a different coefficient in calculating the wind load. An example of this would be a set of closely spaced parallel coaxial lines. Without ice they would each be considered a round cylindrical member. With accumulated ice they would

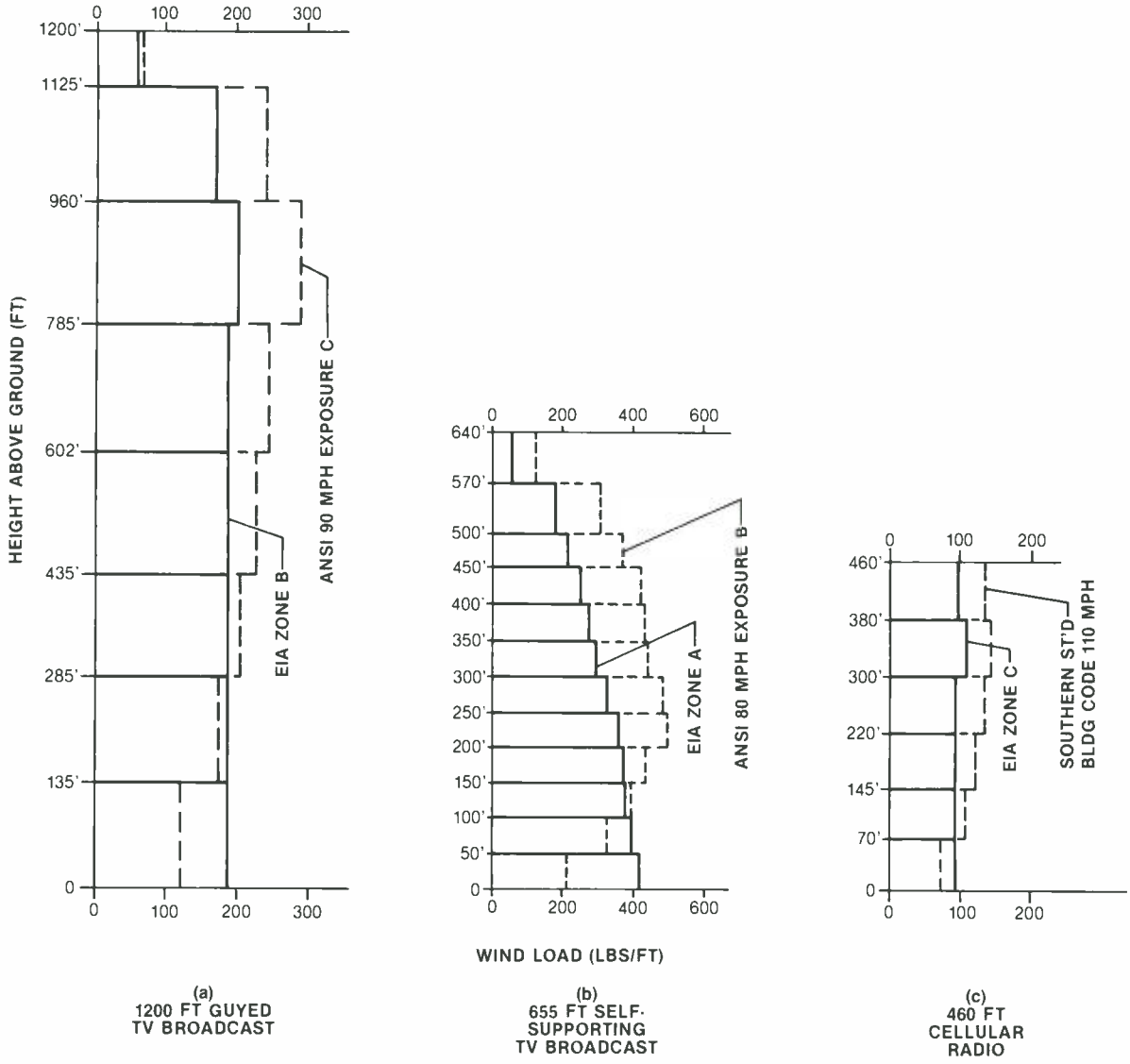


Fig. 3. Examples of wind load differences using various design standards.

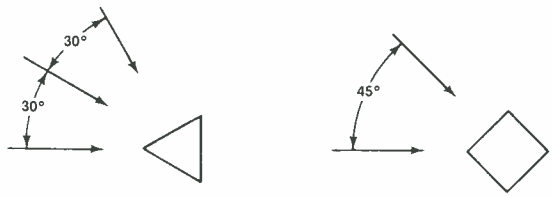


Fig. 4. Wind directions to be considered.

present a large flat area to the wind requiring a much larger coefficient.

Ice produces an entirely different stress distribution in a tower than wind so it is not reasonable to merely increase the design wind load to provide for ice accumulations. It is also a misconception that ice will break up and blow off the tower, and therefore, ice and wind need not be considered simultaneously. In areas where ice may form, it is advisable to specify an ice accumulation and a wind load to act concurrently.

While all of the design standards say that ice accumulations should be considered, none of them gives specific recommendations for the magnitude of accumulation or the wind load with which it should be considered. This is unfortunate because ice is a significant load on a tower and has been the direct cause of a number of collapses in recent years.

3. *Temperature Changes*

Changes in temperature have no significant load producing effects on self-supporting towers, but they can on guyed towers. Because of their differences in length, the guy cables

expand and contract different amounts than the tower itself and thereby require elastic deformations from stress changes. The effects are greatest for those cables having the flattest angle with the ground. While the stresses produced are considerably less than those produced by wind and ice loads, they should be considered in the design of guyed towers.

4. *Seismic Loads*

Loads due to earthquakes are considered to act horizontally and are dependent on the mass and stiffness of the tower. They are usually less than those produced by wind but are distributed in a different manner. Procedures for calculating these loads are given in some of the design standards including ANSI A58.1, but not in EIA RS222C. While a tower properly designed for wind load is usually adequate for seismic forces, they cannot be neglected in areas with frequent and intense earthquake occurrences.

Structural Models and Analysis

A self-supporting tower may be described structurally as a cantilevered space frame or truss. Although it may have many different members, it is a relatively simple structure, and the determination of the forces in the individual members due to the applied static loads is easily done using fundamental principles of structural mechanics. The potential modes of failure are buckling of individual leg or bracing members under compressive loads, and shear or tension failures of the connections.

A guyed tower is a much more complex structure than a self-supporting tower. Whereas there is only one basic path through a self-supporting tower for the loads to be transferred to the ground, there are several for a guyed tower. The distribution of the loads among these paths is dependent upon the relative stiffnesses of guy systems and the tower shaft.

Each span of the tower has a stiffness with respect to axial and shear forces and bending and torsional moments. These stiffnesses are a function of several variables including the geometric configuration, the mechanical properties and size of the individual guy cables, the amount of initial tension, the magnitude of ice load, and the magnitude and direction of wind load on the cables.

By evaluating all of these it is possible to simulate all the guys at a given level as a spring having a specific stiffness. Because of the nonlinearity of some of the relationships involved, the spring constant derived is only valid for a specific set of conditions and for a finite range of translation. Similarly a torsional spring constant can be derived. It is interdependent with the translation stiffness and is also valid for only a finite range of translation.

Another difference between a guyed and self-supporting tower is the magnitude and significance of the axial load. For a self-supporting tower this is composed only of the gravity loads from the tower, its appurtenances and any ice load. It is independent of wind load and its effects on individual member loads are relatively small. The axial load for a guyed tower includes in addition to the gravity loads, the vertical components of the tensions in the various guys. Since these tensions are directly affected by the wind loads, the axial load is now dependent upon wind load, and its effects on the individual leg members are relatively large. It also produces an additional bending moment on the tower equal to the product of the axial load and the deflection of the tower.

Despite the complexity of the relationship involved, the availability and wide spread use of digital computers permits accurate structural analysis of guyed towers. There are several different structural models that may be used.

One of the most commonly used is to idealize the tower shaft as a continuous beam-column on non-linear elastic supports (the guys) subjected to simultaneous transverse (wind and/or seismic) and axial (dead, ice and vertical components of guy tensions) loads.

The modes of failure are buckling of individual leg or bracing member under compressive loads, rupture of bracing members, guys or guy anchor arms under tensile loading, and shear or tension failures of the connections.

Dynamic Considerations

As previously mentioned, even though wind and earthquakes involve kinetic energy, their effects are simulated by equivalent static loads determined in accordance with the design standards. In recent years there have been more sophisticated efforts to investigate the actual response of tower structures to the dynamic aspects of wind gusts. A conclusion drawn from these studies is that the bending moments in the upper portions of tall guyed towers are considerably higher than those determined by the usual static analysis. Consequently the loads imposed on the vertical legs and their splice connections would be amplified beyond safe limits indicating a potential failure condition. Considering the usual fundamental periods of tall guyed towers, it appears that towers taller than 1200 to 1300 feet should be investigated dynamically as well as statically.

There are two other phenomena related to the dynamics of wind that are important in guyed

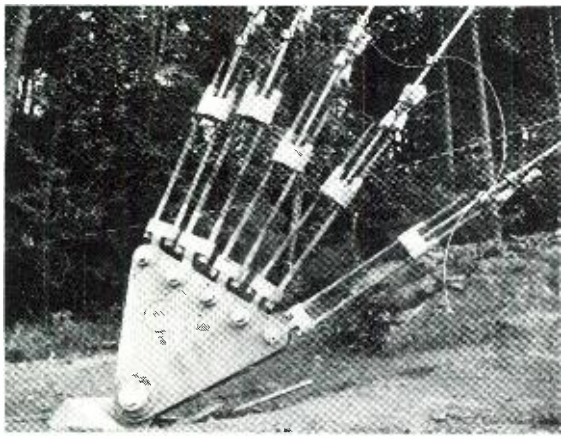


Fig. 5. Typical anchor connection with dampers to prevent aeolian vibrations.

tower design. These are aeolian vibrations and "galloping", both of which involve periodic loading.

Aeolian vibrations are low amplitude, high frequency movements which occur in the tower guy cables due to a phenomenon known as vortex shedding. If they are not suppressed through the use of dampers, they can result in destruction of the filaments in the tower lights at the least, or fatigue failure of a guy cable and collapse of the tower at the worst. Stockbridge dampers attached at one or both ends of the guy cables have proven effective in controlling these vibrations and should be considered for all tall guyed towers.

Galloping is a condition of instability involving large amplitude, low frequency movements. It is caused by the perpetual amplifications of periodic load due to the motion of the body itself. The most dramatic and well-known example of galloping is the collapse of the Tacoma Narrows suspension bridge in 1940.

For tower structures, galloping is usually associated with the guy cables on tall towers, but in at least one instance it was related to a large rectangular waveguide. There have been several different methods involving detuning and energy dissipation used for preventing galloping in guy cables that appear to be successful. In the case of the rectangular waveguide, galloping was controlled by moving the waveguide inside the tower along the centroidal axis from its original position on the outside of one face. This reduced the torsional rotation of the structure which was the source of the perpetuating force. Based on this experience it would appear prudent to always install this type of waveguide inside the tower unless adequate torsional rigidity is provided throughout the height of the tower.

Allowable Stresses and Safety Factors

Towers, like all other structures, are designed so that the maximum anticipated stresses that occur in them are less than those which would cause failure. This ratio of failure stress to maximum allowable stress is known as the safety factor. It is intended to provide for several variations from the ideal conditions assumed for design including loads greater than anticipated, imperfections in materials and tolerances in fabrication and construction.

The design standards refer to the American Institute of Steel Construction (AISC) "Specification for the Design, Fabrication and Erection of Structural Steel for Buildings," and the American Concrete Institute (ACI) "Building Code Requirements for Reinforced Concrete Structures," for the allowable stresses and safety factors to be used. Both of these specifications permit an increase in allowable stresses (or a reduction in safety factor) for stresses due to wind and seismic loads acting alone or in combination with dead and live loads above those values normally permitted for dead and live loads only. The reason for this is that maximum wind and seismic forces are infrequent and of brief duration. EIA Standard RS-222 has always prohibited use of this increase for stresses due to wind load on tower structures. Thus, while wind loads calculated according to other design standards are greater than

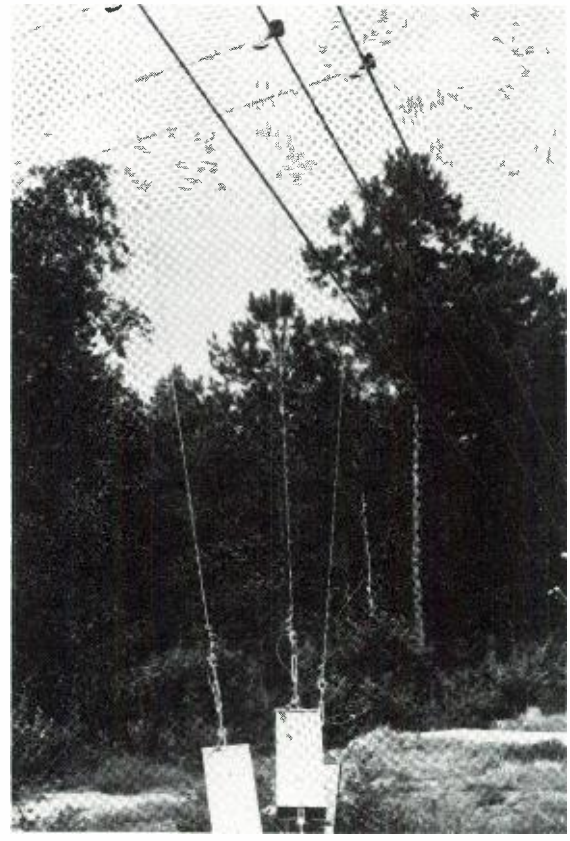


Fig. 6. Anchor connection with snubber system to prevent galloping.

those calculated according to EIA RS-222, their effects are offset by consideration of the increase in allowable stresses. This demonstrates the importance of not extracting portions of different design standards and combining them into a single specification.

EFFECTS OF ANTENNAS AND TRANSMISSION LINES

Except for AM radiators, the tower is the "necessary evil" to support the broadcast antennas and transmission lines at a suitable height above ground. Thus the effects of this equipment are of paramount importance.

Loads

Every antenna imposes a wind load and a dead load on the tower. If the antenna is mounted atop the tower, it also imposes an overturning moment, and if it is mounted off one side of the tower, it imposes a torsional moment. For TV and FM broadcast antennas and microwave antennas, these loads are relatively large, and their location has a significant effect on the placement of guy cables.

Transmission lines feeding the various antennas also impose wind and dead loads on the tower. These loads are distributed uniformly between the antenna and their entry point near the base of the tower. The total load produced by a coaxial line or a waveguide is frequently greater than that produced by the antenna itself. The shape of the transmission line influences the magnitude of the wind load, with circular or elliptical lines having loads two-thirds of those for rectangular lines with the same projected area.

It is important not to overlook the support system required for transmission lines. Some large waveguides have support systems that require nearly continuous vertical structural members that add substantial wind and dead loads. Small, flexible lines require supports at a maximum interval of three to four feet which is often less than the vertical spacing of horizontal members in the tower. Thus it may be necessary to provide an additional support structure for these lines, again adding to the total load.

Width Restrictions

Some antennas impose restrictions on the width of the supporting tower. One common example is a side mounted FM antenna requiring a maximum width of 18 to 24 inches. For antennas with more than 8 bays, this results in a very slender structure. When placed at the top of a tall guyed tower, the design of the guy system for this structure becomes extremely critical. Use of a cantilevered pole structure above the top of the main tower should be considered for these cases.

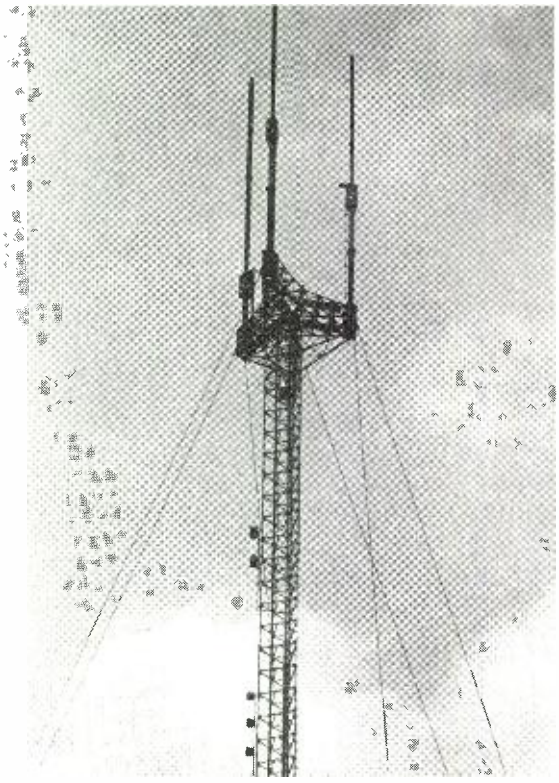


Fig. 7. Triangular multiple TV antenna support with FM antennas side mounted below.

Another example of width restriction is a panel type TV or FM antenna mounted on the faces of the tower. Here, too, it is often better to support these antennas on a cantilevered structure above the main tower rather than placing guys within the aperture of the antenna.

As previously mentioned, it is desirable to place large waveguides inside the tower near the vertical centroidal axis to prevent large torsional loads. This requires a tower having a minimum face width in the range of 7 to 8 feet to accommodate the waveguide and its supports.

Initial and Future Considerations

Because the antennas and transmission lines have such a significant effect on the tower design, it is important to consider all possible uses for a tower before it is designed. It is better to have unused capacity than to undergo expensive modifications or replacement in several years to obtain additional height or accomodate another antenna. This has become apparent in recent years with the proliferation of microwave, two-way communication, and cellular radio systems.

When providing for multiple antennas, it is important to determine not only the number and type of antennas and lines, but also their loca-

tion on the tower. The distribution of load is equally important as magnitude.

Triangular top platforms ("candelabras") to support broadcast antennas on each corner have been successfully used for many years. They have the advantage of placing all antennas at the same height. A variation of this platform to support only two antennas ("tee-bars") has also been used. Both of these systems require multiple guy cables at the top platform to provide adequate torsional stability. It is possible to design the tower for a multiple antenna support platform, but not install it until some later date.

Another arrangement of multiple antennas is "stacking", i.e., installing one antenna atop the tower and arranging others along the tower, one below the other. This arrangement can also be combined with a multiple antenna support platform.

If capacity for microwave antennas is required, it should be provided near guy levels and preferably above to minimize interference with the guy cables. The guy system and web bracing at these levels must be designed to provide adequate torsional rigidity.

Capacity for small antennas may be provided at various locations throughout the height of the tower. One arrangement for a large number of antennas is to provide a platform around the outside of the tower large enough to support the radio equipment for these antennas. The antennas can be mounted on the outside railing of the platform, thereby requiring only a short run of coax. Electrical power must be provided to the platform. This arrangement imposes a large concentrated load at the platform location with a relatively small uniform load between the tower base and the platform. If the same number of antennas were mounted along the tower and each fed by an individual coax line from the base, there would be only small concentrated loads at the antenna locations, but a relatively large uniform load due to the lines. This is an entirely different distribution of load and would have a pronounced effect on the design.

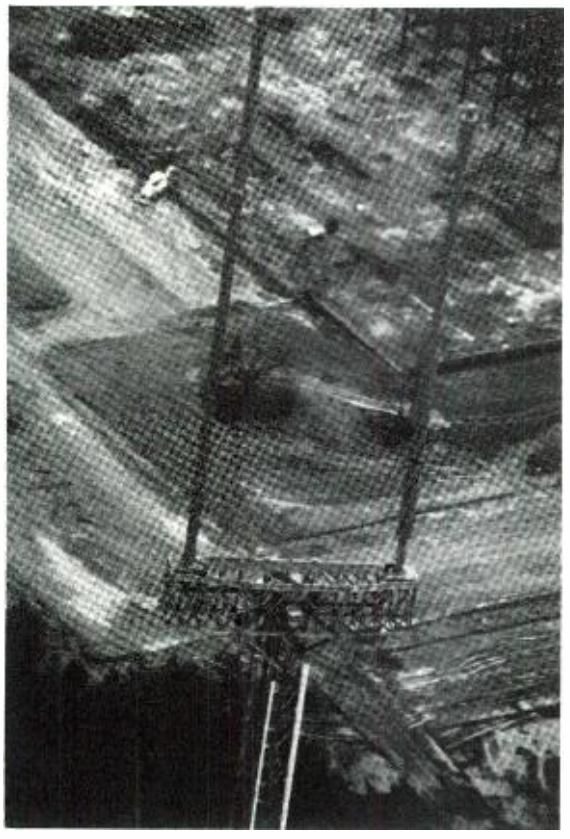


Fig. 8. Tee bar antenna support platform for two TV antennas.

Another important consideration for future antennas or height extensions is the electrical system. If an extension in height is planned, the wiring for the aircraft warning light system should be designed so that any additional lights can be connected to the system without adding or replacing wires in the existing conduit. The same holds true for any circuits required for future antennas. If the necessary wiring cannot be provided during the initial installations, capacity should be provided for additional conduits to hold the future circuits.

Replacement, Relocation or Additions to Existing Towers

Since every tower has been designed for a specified arrangement of equipment, changes should not be made without considering their effects on the structural adequacy of the tower.

Two common misconceptions related to changes in equipment are: "lower is better", and "smaller is better". Neither is necessarily correct, especially for guyed towers. Decisions based on these premises can have serious consequences.

It is much better to have a structural analysis of the tower made by a structural engineer experienced in tower design. This analysis will determine if any overstresses would occur in the tower or its foundations and what modifications and reinforcing would be required to retain the structural integrity. To make this analysis, it is necessary for the engineer to have complete data on the tower and its foundations including configuration, member sizes and material strengths. The use of presumptive values can result in an analysis with little value.

FOUNDATIONS AND ANCHORS

The component of a tower installation for which it is most difficult to predict the cost is

the foundation system. This is due to the non-homogeneous nature of soils and the uncertainty of what conditions exist below grade. Therefore, it is necessary to have an investigation made of the sub-surface soil conditions.

It is important to note that the soil design parameters given in EIA Standard RS-222-C are intended to serve only as a basis for preliminary design and estimating of foundation costs prior to obtaining specific soil data. They should not be used for the final design without verification by subsurface investigation.

Soil Investigation

The soil investigation should be made by an engineering firm which specializes in soil investigations and evaluations and is familiar with the general area of the tower site. It should consist of making a test boring at each foundation and guy anchor location, analysis of soil samples taken from the borings, determination of the structural properties of the soils, determination of ground water levels, recommendations of parameters for designing the foundations, identification of any special construction procedures required, and recommended backfill specifications. If piles or rock anchors are necessary, recommendations related to these should be provided. It should also address requirements for frost protection and bouyancy effects.

Because the loads imposed on foundations for towers are unique from those for conventional buildings in that they include large uplift and horizontal components, it is important to provide the soils engineer with the loading conditions before he makes his investigation. This will enable him to plan his work in a manner suitable for obtaining and reporting those characteristics relevant to designing for these loads.

Self-Supporting Tower Foundations

Except for relatively small towers with narrow base spreads isolated foundations at each leg are usually more economical than a single mat for all legs. These foundations may be spread footings, drilled caissons or driven piles. If sound rock is present at shallow depths it is often economical to anchor the footing to the rock. These anchors should be proof loaded to ensure their holding capacity in uplift.

Since these foundations are subjected to large uplift forces, it is important to consider bouyancy effects if ground water is present. Also, if driven or cast-in-place piles are used, they must be adequately anchored to the reinforced concrete cap.

Guyed Tower Base Foundations

These foundations may be spread footings, drilled caissons, or driven piles. Since they are subject only to downloads with relatively small horizontal forces, they require no special anchorage details for uplift unless they are placed above expansive soils. Bouyancy is usually not a problem.

Guy Anchors

Deadmen (buried reinforced concrete blocks), drilled caissons or driven piles may be used for these foundations. If sound rock is present at shallow depths it is often economical to anchor the foundation to the rock.

These foundations are subject to large horizontal forces as well as vertical uplift. Therefore, deadmen must have a large enough frontal area bearing against the soil to resist sliding; drilled caissons must have sufficient diameter and depth to prevent excessive lateral deflection; and driven piles must be sloped to prevent large lateral loads being imposed on them. Rock anchors may be installed along the slope of the resultant of the horizontal and vertical loads, or they may be installed vertically and post tensioned to clamp the concrete cap to the rock to prevent sliding. Because of the uplift forces, it is important to consider buoyancy due to ground water and to provide adequate anchorage for driven or cast-in-place piles.

Construction

Since nearly the entire foundation system will be below finished grade and not subject to later inspection, it is important to carefully monitor its construction. The following items should be verified:

1. Location and alignment of anchors in plan and elevation.
2. Condition of excavation surfaces on which concrete will be placed.
3. Position, size and grade of reinforcement steel.
4. Placement of concrete to prevent voids and air pockets.
5. Strength of concrete using test cylinders for 7 and 28 day break tests.
6. Protection of concrete against freezing during the curing period.
7. Placement and compaction of backfill.
8. Driving records and/or load tests of piles.
9. Proof loading and post-tensioning of rock anchors.

For towers with extensive foundation systems, it is advisable to retain an independent inspections service for this work. Often the firm making the subsurface soil investigation can also provide this service.

ERECTION

The erection of towers is a highly specialized field and should be done only by firms having the proper equipment and experienced rigging personnel. It is also important that the erector have adequate insurance coverage including workmen's compensation, general and automobile liability and all risk for direct damage to the tower and antennas being erected.

Owners Preparation

Prior to the arrival on site of the erection crew, the site should be made ready for work to begin. These preparations include:

1. *Access*

   Suitable access from public roads for delivery of the tower materials and erection equipment is required. While a paved roadway is not necessary, the access must be able to handle heavy trucks and construction equipment.

2. *Permits*

   All necessary building and construction permits should be obtained and posted as required. Any inspections required during construction should be noted.

3. *Clearing*

   A work area must be cleared to permit unloading, sorting, and assembling the tower. Paths from the tower base to the guy anchors must be cleared for a width adequate to permit hauling the guy cables to the anchors and pulling them to the tower. Paths must also be cleared for the hoist line from the tower base to the hoist location and for the tag line used to stabilize the loads as they are uplifted. The sizes and locations of these cleared areas should be agreed upon beforehand with the erector. A typical layout is shown in Fig. 9.

4. *Electrical Power*

   Power for operating the temporary aircraft warning lights must be available before erection begins.

Assembly

The usual procedure for erecting a guyed tower is to assemble the individual sections on the ground and then lift them one at a time as an assembled unit. For a self-supporting tower, the wider sections near the bottom of the tower are often assembled in the air as the tower is constructed.

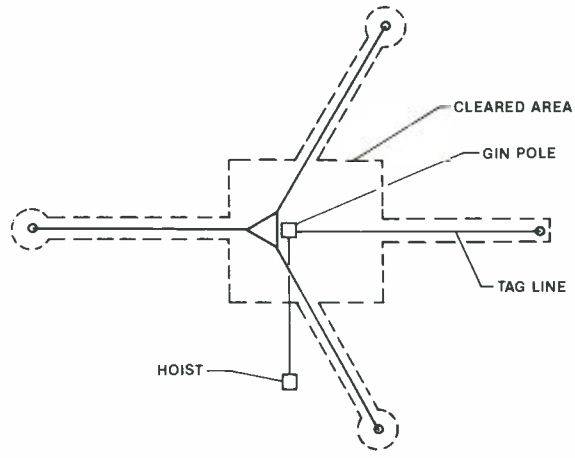


Fig. 9. Typical layout for guyed tower.

Assembly of the tower sections should be done on a level bed to ensure that they will be straight and not racked or twisted. Bolts must be properly tightened and have a locking device. For high strength galvanized bolts, tightening by the "turn-of-the-nut" method is preferable to using a calibrated torque wrench.

Stacking

For a guyed tower, the first group of three to six sections are often joined together on the ground and then lifted into place using a crane. This portion of the tower is then guyed with temporary cables, and the remaining sections are erected one at a time using a vertical boom or "gin pole". This boom is moved or "jumped," up the tower as each section is installed. This arrangement is shown in Fig. 10. Temporary guys to stabilize the tower should be used as instructed by the designer.

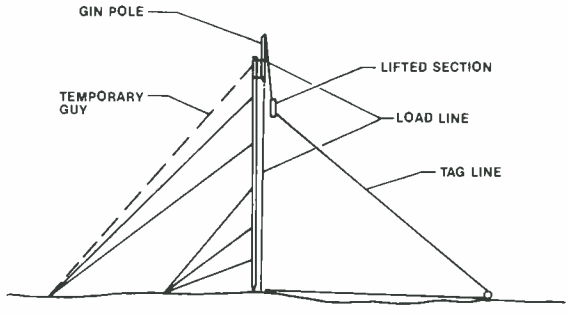


Fig. 10. Typical erection setup for guyed tower.

For a self-supporting tower, a crane is often used to lift as many of the tower sections as possible after which a gin pole is installed and used for the upper sections beyond the crane's reach.

Temporary aircraft warning lights must be installed at the top of the construction at the end of each day.

The tower should be grounded as soon as the first section is in place.

Guy Installation

When the tower reaches a guy attachment level, the cables at that level are installed. The guys in all three directions should be pulled out simultaneously to prevent any large unbalanced loads on the tower.

The tower should be checked for plumbness as each set of guys is installed and tensioned. Maintaining a plumb tower during erection eliminates the need for time-consuming adjustments later. Final tensioning of the guy cables and a plumbness check are done after the entire tower is erected.

INSPECTION AND MAINTENANCE PROCEDURES

To ensure trouble-free performance of a tower and its appurtenances, it is desirable to have a regular inspection and maintenance program. Portions of the program can be done by station personnel while others require experienced tower personnel.

Safety precautions should be observed at all times when working on or around the tower. If the tower itself is energized or if a high intensity RF field exists from antennas mounted on it, no work should be done on the tower without clearing it with the station engineer. When climbing the tower, safety belts and climbing devices should always be used. Automatic safety features on elevators should never be by-passed to save time. It is a good idea to never work alone. Failure to observe proper safety measures can result in serious injury or death.

Tower Structure

1. *Damage or Deformed Member*

   A visual inspection should be made of the entire tower structure to determine if any of the members have been deformed or damaged. Any bowed or kinked member should be noted as to type, location in tower, and nature and magnitude of deformation or damage. This information should be reported to the tower designer for evaluation and recommended action.

2. *Condition of Paint*

   A visual inspection should be made of the entire tower structure to determine the condition of the paint. If the painting of the tower is for aircraft observation marking only, and not for corrosion protection, it is necessary only to note any general deterioration rather than small blemishes and scratches. If repainting is necessary, it is important to properly prepare all surfaces and select paints that are compatible with the existing finish.

3. *Corrosion*

   Small scratches in the galvanized surface are not detrimental as the exposed surfaces will be protected by cathodic action of the adjacent zinc. If corrosion is observed, the source should be determined and noted. The affected areas should be wire brushed clean to bare metal and then painted with a zinc rich prime coat and, if necessary, a finish enamel coat of the appropriate color.

4. *Connections*

   All bolts should be checked for tightness. Any loose bolts should be tightened in accordance with the original installation instructions.

5. *Alignment*

   The tower structure should be checked for alignment using an engineer's transit. This check should be done only on a calm day, i.e., with wind velocity less than 10 mph, and in conjunction with measuring the guy tensions (described later).

   Two transit positions, each a distance of at least one-half the tower height from the tower base and separated by a 90 degree azimuth angle should be used.

   When the transit has been properly leveled, set the vertical cross-hair on the edge of one of the vertical legs at the tower base and lock the instrument in this position. By moving the telescope upward it is then possible to observe the straightness of the tower over its entire height. The magnitude of misalignment can be accurately estimated by comparison with the tower leg diameter. A record should be made of the observations at each guy level. Tolerances for plumbness and straightness should be as provided by the designer. EIA Standard RS-222 gives a plumbness tolerance of one to 400 for guyed towers, one to 250 for self-supporting towers, and a straightness tolerance of one to 1000. These are extremely generous and should never be exceeded. A good rule of thumb in the absence of other data is to keep the tower plumb and straight within the diameter of the leg members.

If straightening of the tower is required, it should be done by adjusting the guy wires as described later.

When checking the plumbness of top mounted poles and pylon antennas, the effects of direct sunlight on them must be considered. It is best to make these checks early in the morning or on a cloudy day.

Guys and Guy Insulators

Inspection of the guys can be done visually only for those portions adjacent to the anchors and tower. The range of this visual inspection can be extended by using binoculars, but its reliability is limited. If experienced riggers are available, it is possible to ride down the guy on a bosun's chair, but this method should be used only under the supervision of qualified personnel.

1. *Damaged Components*

   A visual inspection should be made of the guy cables, insulators, and hardware. Cables and dead end grips should be checked for nicks or cuts in the individual strands. Break-up insulators should be checked for cracks or chips in the glazed ceramic surfaces. Fiberglass should be checked for deterioration of the epoxy coatings and exposure of individual glass strands.

2. *Corrosion*

   If the guy cables show signs of corrosion, consideration should be given to coating or replacing them. The cost of cleaning and coating the cables should be considered along with the life expectancy of the coating when comparing it to the cost of replacement. All guy hardware should be checked using the same procedures for inspection and corrective actions as previously described for the tower structure.

3. *Connection*

   All pins should be checked for tightness and the condition of the cotter keys. Dead end grips should be checked to ensure that their ends are completely snapped close, preventing any ice from forming inside. The surface appearance of the guy strand immediately next to the connections should be noted for evidence of slippage. Threads should be given a light petrolatum coating.

4. *Tensions*

   Guy tensions should be checked in conjunction with the tower alignment. These tensions should be measured at the anchor end and compared to the specified values. It is important to remember that they are dependent upon the ambient temperature.

For the usual guy arrangement with cables in three directions, it is necessary to measure the tensions in only one direction while keeping the tower plumb in all directions. For guy arrangements with cables in four or more directions, it is necessary to measure the tensions in only one of the two guys in the same vertical plane while keeping the tower plumb in that plane.

There are several methods of measuring guy tensions with varying degrees of accuracy. For small guys up to ¾ inch, a shunt dynometer calibrated for the size and type of strand is often used.

For larger guys, a series dynamometer may be placed in a temporary line between the anchor and a clamp on the cable. This line is then tightened until the permanent connection is relieved, and the tension is indicated on the dynamometer. Hydraulic jacks with a calibrated pressure gauge or load cells can be used in place of the temporary line and dynamometer. These are particularly effective for large guys attached with bridge sockets.

There are two indirect methods of measuring tensions in guys that do not have any large insulators or other loads in them. The intercept method consists of sighting along a straight bar attached at the bottom of the guy and measuring the vertical distance between the point where the line of sight intercepts the tower and the point where the guy is attached. This distance can be accurately estimated by counting the number of bracing panels in it. The tension in the guy is directly related to this intercept distance, the weight of the guy, and its length and slope.

The tension in a guy cable is also directly related to its length, weight, and natural frequency of free vibration. The natural frequency can be determined by putting the guy in motion with your hand and measuring the fundamental period with a stop watch. It should be noted that because a guy slopes, the tension on it varies along its length, and this method will only provide the average tension and not the tension at the anchor point. For long cables, this difference can be significant.

All tension measurements should be recorded along with temperature and wind speed and direction. If any substantial changes are noted from the values previously measured, careful checks for slippage of all connections should be made.

Tolerances for guy tensions should be as provided by the designer. In the absence of any other tolerance, tensions should be within plus or minus five percent of the specified values.

SUGGESTED INSPECTION AND MAINTENANCE SCHEDULE

ITEM	Daily	Monthly	Before Each Use	Annually	After a major wind or ice storm	Manufacturer's Recommendation
Tower Structure:					•	
Damaged or deformed members				•		
Condition of paint				•		
Corrosion				•		
Connections				•		
Alignment				•	•	
Guys and Insulators:						
Damaged components				•	•	
Corrosion				•		
Connections				•	•	
Tensions				•	•	
Base Insulator				•		
Tower Base and Guy Anchors				•	•	
Ladder Safety Device			•			
Elevator System						•
Operate		•				
Lighting System						•
Lamp Failure	•					
Conduit Systems, fixtures				•		

Fig. 11. Suggested Inspection and Maintenance Schedule.

Any necessary adjustments in tensions can be made by adjusting the turnbuckle or bridge socket at the anchor. Make such adjustments slowly and carefully. Never leave less than three threads sticking through the turnbuckle body or nut on the socket U-bolt. Remember that the tower must be kept plumb.

Base Insulator

The porcelain surface should be wiped clean with a soft cloth to remove any salt deposits or other foreign substances. A check should be made for any evidence of cracks in the porcelain surfaces. Any such defects should be noted.

Any signs of corrosion in the upper and lower bearing plates, rain shield or lightning gap should be noted and corrected in a manner similar to that described for the tower structure. The lightning gap should only be adjusted in accordance with instructions from the station engineer.

Tower Base and Guy Anchors

The tower base and guy anchors above grade should be visually inspected for spalling and cracking of the concrete. The soil surrounding the tower base foundation should be inspected for evidence of settlement. The anchor arms and surrounding soil should be examined for evidence of movement of the anchor. Any such settlement or movement should be noted.

Appurtenances

1. *Ladder and Safety Device*

   The ladder and its connections should be checked for corrosion and tightness along with the tower. The sleeve and belt of the safety device should be visually examined and tested near the ground level before each use.

2. *Elevator System*

   Inspection and maintenance of the elevator system should be in accordance with the manufacturer's instructions. It is a good practice to operate the elevator at least once a month.

3. *Lighting System*

   Inspection and maintenance of the lighting system should be in accordance with the manufacturer's instructions. Checks for corrosion in the conduit, junction boxes and light fixtures should be made along with the tower inspection. Any obstructions in the breather or drain in the conduit should be removed. Broken or cracked glass and any leaking gaskets should be replaced.

Frequency of Inspection and Maintenance

A suggested schedule for inspection and maintenance performance is shown in Fig. 11.

Reports

A written report of each maintenance and inspection procedure performed should be made and filed with the station engineer.

2.2

Lightning Protection for Broadcast Facilities

Marvin M. Frydenlund
Managing Director,
Lightning Protection Institute
Harvard, Illinois

and

Frank C. Breeze
Associate Principal and Electronics System Consultant,
Tilden, Lobnitz and Cooper, Inc.
Orlando, Florida

Lightning, shown by National Oceanic and Atmospheric Administration studies to be the leading cause of weather-related deaths in America, is at the same time the most frequent yet least well understood of the atmospheric forces.

Lightning is also a leading destroyer. Identified as electric current by Benjamin Franklin more than 230 years ago, lightning has kept pace with every electrical and electronic advance of man, exhibiting a new destructive facet to match each technological advance.

As semiconductors, and later, integrated circuits found widespread use in the electronics industry, it became apparent that measures were necessary to protect these components from exposure to surges. Protection was required not only from lightning but from man made sources as well.

It is hoped that the reader will obtain a basic understanding of the fundamentals of protection from this chapter. A wealth of information is available to the reader who wishes to understand this subject in greater detail. Several of these sources are listed in the references at the end of this chapter.

THE THUNDERSTORM CELL

Thunderclouds are created by convective action of the atmosphere, as an invasion of cool air causes lighter, warm moist air to migrate upward into the cooler upper atmosphere. Cooling of this moisture-laden air causes condensation of the moisture on small dust particles forming a cloud. Cooler dry air surrounding the cloud is forced downward as displacement occurs. This updraft and downdraft mechanism can become quite intense as demonstrated by an aircraft flying through a cloud.

The convective action generally stems from solar heating of the earth's surface and adjacent atmosphere or from frontal activity where warm moist air is displaced upward by an encroaching cooler air mass.

The exact mechanisms of cloud electrification are not completely understood and at present there is no consensus of opinion by researchers. It is known, however, that a separation of electrical charges occurs causing pockets of positive and negative charge within the cloud. As this activity continues, the lower portion of the cloud typically assumes a net negative charge with respect to both the earth and upper portions of the cloud.

THE LIGHTNING DISCHARGE

The cloud action continues until sufficient potentials are achieved to cause a point discharge. This mechanism is not unlike dielectric breakdown of a capacitor where the charged bodies

represent plates and the atmosphere represents the dielectric. Discharges can occur within the cloud, between clouds or between cloud and ground. For purposes of this document, only the latter will be considered.

An intense electric field is developed between the cloud and earth prior to a discharge. Voltage gradients are present ranging from very positive to very negative between the cloud and ground. As field intensity increases, corona discharge or "St. Elmos Fire" is sometimes observed from conductive bodies. This is a form of leakage between the charge bodies and is similar to leakage caused by impurities and irregularities in a capacitor.

As field intensity continues to increase, the air between cloud and ground begins to ionize and pockets of ionized air are formed and shifted by the wind. These pockets are more conductive than the surrounding air and form irregular conductive paths of increased current flow.

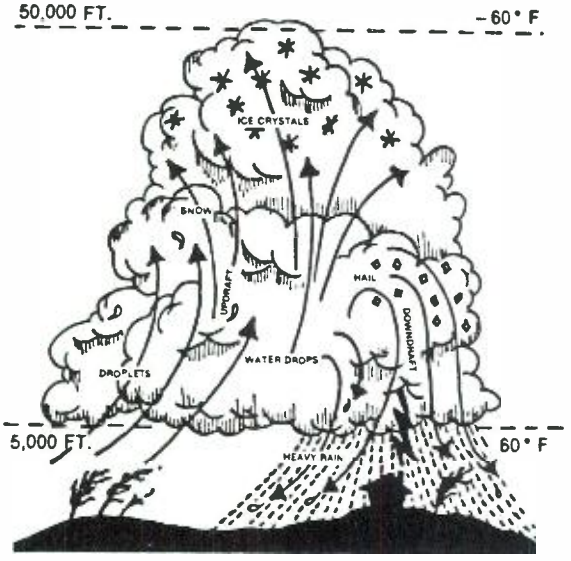


Fig. 1a. This thundercloud has reached its mature stage and a downdraft has developed on the cloud's lee side, producing a sudden drop in temperature, wind gusts, rain and perhaps hail, and lightning flashes.

These are the sequential stages of a typical lightning flash to a protected structure....

(1) typical charge configuration of a thundercell prior to a lightning flash; (2) local discharge between a small P region at the cloud's base and its N region; (3) free electrons start downward, propagating in steps averaging 150 feet; (4) leader stroke may fork as it moves downward, neutralizing positive ion pockets; (5) as negative stepped leader nears effective earth, positive point-discharge currents strain upward; (6) several positive streamers may reach upward; (7) when a positive return stroke rises upward; (8) the return stroke makes the trip from earth to cloud at near the speed of light as thousands of amperes of current flow down the channel to earth.

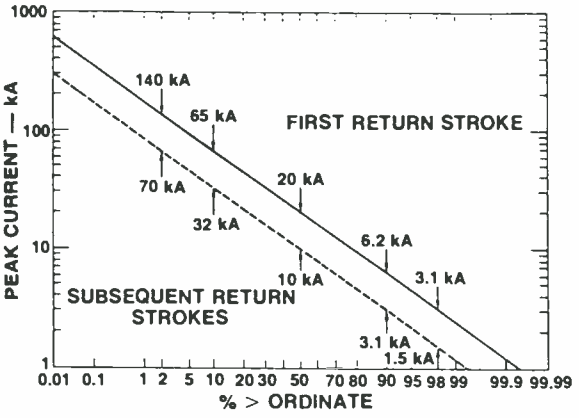


Fig. 1b. Lightning stroke intensity. Courtesy SRI International (Stanford Research Institute), Menlo Park, California 94025.

THE LIGHTNING ROD

From the previous discussion on behavior of upward streamers, it is apparent that lightning rods and tall grounded objects such as towers are effective in controlling where a lightning point discharge will occur.

A certain amount of protection is afforded to bodies in areas of lower elevation in the vicinity of a lightning rod or tower. For many years this "zone of protection" was described as a 45 degree cone extending downward from the uppermost tip or structure. Statistical data is revealing that this zone should be reduced by defining the sides of the cone with a concave hyperbolic shape. It is also not uncommon for the upper sides of a tower or other tall structures to receive a direct strike from lightning.

THE LIGHTNING CONDUCTOR

Lightning currents must be carried safely to ground by allowing them to travel along a predetermined path. This path consists of dedicated lightning conductors or through the steel framework of a tower or building. The lightning current waveform will typically have a very fast risetime on the order of 1 microsecond. Decay will be slower and is largely dependent on impedance characteristics of the current carrying circuit. Lightning currents of 200,000 amperes are not uncommon with the average stroke falling within the 20 to 30 kiloampere range.

Inductance plays a major role in performance of any conductor to be used for lightning protection or bonding. Inductance of a straight circular conductor is approximately 1 to 1.5 microhenries per meter and does not change appreciably with conductor size. During the fast risetime of the current, the inductance is responsible for most of the voltage drop through the conductor. During the slower decay, the resistive voltage drop is a larger part of the total. This behavior may be best explained by example.

Voltage drop through a lightning conductor is given by the formula:

$$E = IR + L(di/dt) \quad [1]$$

Where:

I = current in amperes
R = conductor dc resistance in ohms
L = conductor inductance in henries
di = change of current in amperes
dt = change of time in seconds (risetime)

Assuming:

conductor length = 10 meters
conductor material: copper
conductor size = #6 AWG
total DC resistance = .013 ohms
total inductance = 10 microhenries
current = 1,000 amperes
risetime = 1 microsecond

$E = (1000. \times .013) + .000010\ (1000/.000001)$
$E = 13 + 10{,}000$
$E = 10013$ volts

The resistive voltage drop is only 13 volts. The reactive voltage drop, however, is 10,000 volts. The lesson to be learned by this example is that conductor length is far more important than size. Minimum conductor size is a function of thermal properties (temperature rise), corrosion resistance, and mechanical properties.

Conductor arrangement should be such that conductors always run either horizontally or downward along their path to the ground. Multiple "down" conductors are required by most codes for two reasons. First, if one should become damaged, a path to the ground will be maintained by the others. The second and equally important reason is to lower the impedance of the overall network. As you recall, increasing the size of conductors has little effect on its surge impedance. Providing multiple paths, however, will substantially decrease system impedance and provide a better path to ground.

GROUNDING

Grounding of protected buildings and metallic structures such as towers, earth stations, etc., may be accomplished in a number of ways. Driven rods, buried electrodes, counterpoise system, and underground mats are among the common grounding systems. The specific method used will depend largely on soil and rock conditions at the site.

Grounding effectiveness will vary depending on soil conductivity, type of system, and size of the system used. Lightning protection codes explain grounding requirements and indicate those systems which are considered acceptable.

For a better understanding of the fundamentals of grounding, it is necessary to examine the lightning current on its way to ground. Assuming consistent soil structure, a lighting current entering a ground rod will radiate equally in all directions. Passage of this current through the resistive soil will establish a voltage gradient decreasing in strength with distance. The ground rod will also exhibit a similar impedance to that described for conductors, thereby reducing effectiveness of deeper portions of the rod.

If one were to install a number of ground rods or electrodes at a reasonable distance apart, the overall system effectiveness would increase due to division of currents between rods. A greater distance between rods will result in less overlap of their individual voltage gradients and better overall grounding. The counterpoise system, common to AM radio tower, provides a very effective ground if installed properly.

BONDING

In the section dealing with lightning conductors, it became apparent that substantial voltages are developed as lightning currents pass through a conductor. It is also virtually impossible to achieve a perfect ground leading to production of even higher voltages along the conductor.

Voltages of this type may pose a hazard to personnel or equipment whether on dedicated lightning conductors or finding their own way through a building. The most common problems are as follows:

Touch Voltages:
Injury of a grounded person in contact with a conductive body energized by a lightning current.

Step Voltages:
The earth forms a voltage divider around a grounding electrode during a discharge. A person or livestock standing on the ground may be subjected to injury due to potential difference between different parts of their body.

Sideflash:
Voltage on a lightning conductor or other energized body reaches enough magnitude to create

a secondary lightning flash or "sideflash" to a nearby grounded body.

Dealing with these voltages is where bonding plays an important role. Bonding is simply the practice of equalizing the potential difference between conductive bodies through metallic connections.

As an example of bonding, we will examine a typical television transmitter site with remote studio facilities:

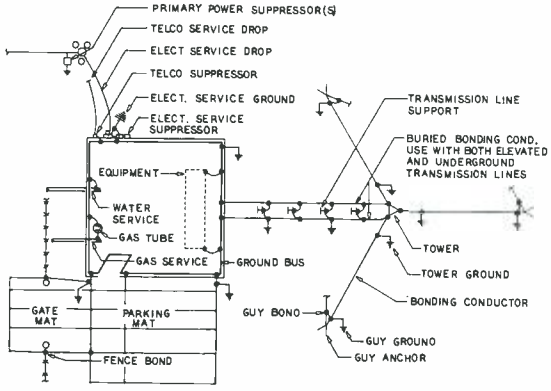


Fig. 2. Typical transmitter site.

The tower structure for this example constitutes a superb lightning rod due to its height and conductivity. Vertical tower elements must be electrically contiguous; if not, copper or aluminum lightning downconductors should be used. The base of the tower should connect to a suitable grounding system such as a counterpoise or a ground rod array.

Except in the case of AM towers, each guy cable should be bonded to the tower and to a ground rod array at each anchor or to the counterpoise system.

If a counterpoise system is not used, a bonding conductor should be installed between the ground array at each guy anchor and the base of the tower. This bonding arrangement will help to minimize step voltages near the base of the tower. The transmitting antenna should be properly bonded to the tower through its mounting. Transmission lines should be bonded to the tower at a minimum of 100 foot intervals.

Transmission lines supporting structures, between the tower and transmitter building, should be bonded to the tower grounding system with the bonding conductor extended into the transmitter building and attached to a ground bus. All transmitter, utility and other grounds should attach to this bus. Any combustible gas service should be bonded to this bus through a spark gap arrestor if direct bonding is not permitted by local codes. (Stray voltages may present a spark hazard to gas companies.)

Surge suppression devices should be installed on all electrical and communications services entering the building with their ground leads attached to the bus. Transmission line suppressors should also be bonded to the grounding system.

A ground mat should be installed below grade along paths traveled by personnel and at vehicle parking locations. This mat should be bonded to the tower grounding system to minimize step voltage hazard to personnel.

Bonding requirements for an AM radio facility will differ slightly since the tower is an active radiator. In this case, a spark gap arrestor should be installed across the base insulator in parallel with a choke coil or isolation stub. The spark gap serves as a discharge path for lightning currents. The choke coil or stub provides a path for draining static charges to ground.

Lightning rods are essential to protect warning lights or other vulnerable equipment from direct strikes. And a full lightning downconductor system is recommended on towers whose electrical continuity may be interrupted, either by design or by an accumulation of rust at joints with aging. Proper maintenance should prevent the latter, but the additional safety of the downconductor system is still important.

Fig. 3 shows optimum protection with lightning rods at the top of the tower and at the ends of all outriggers. In this instance, grounding consists of standard copperclad steel rods driven to a minimum depth of 10 feet. If superior grounding is required due to soil conditions, three rods may be used in an in-line or triangular configuration, with a minimum 10 feet separation between rods.

It is not possible to cover all conceivable aspects of bonding in this document. As stated earlier, the goal in bonding is to equalize potentials during a surge. These potentials may rise to many thousands of volts during a strike. If all conductive bodies rise and fall in potential at the same rate, there will be no stray current flow and no damage or injury.

SURGE SUPPRESSION: BONDING THE UNBONDABLE

By now, you realize the importance of bonding to equalize potential. Surge suppressors provide a means of bonding a wide variety of circuits, but only during a surge.

Many of us recall the days when lightning induced transients had little effect on equipment. Technology keeps marching on and much of today's equipment has remarkably low tolerance for noise and surges.

Most manufacturers of equipment provide limited surge suppression in the design of their

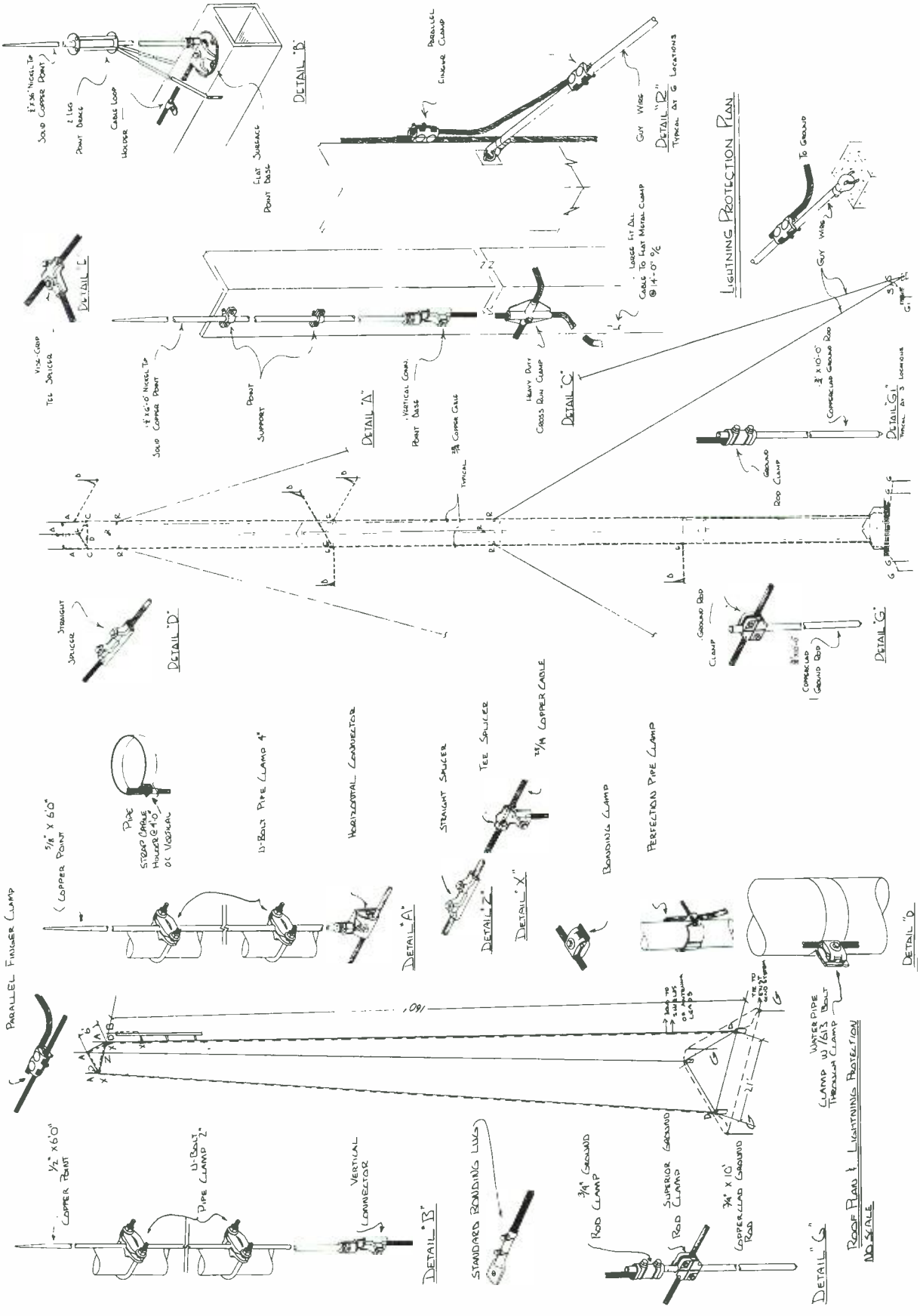


Fig. 3. "Total" lightning protection for towers.

equipment. This suppression is often not adequate for locations where exposure to transients is high.

A surge suppression device must meet the following criteria to be of value to the user:

1. Under normal operating conditions, it must not interfere with the circuit it protects.
2. Its clamping voltage must not be greater than the surge withstand rating of the protected equipment.
3. Clamping speed must be fast enough to prevent damage to the protected equipment.
4. The device must be capable of withstanding surges without damage.

SURGE SUPPRESSOR COMPONENTS

Surge suppression assemblies are packaged by a number of manufacturers to protect a variety of circuits. To understand the operation of these devices, one must be knowledgeable in the characteristics of their component parts. The following section describes each basic type of device with its inherent advantages and disadvantages.

Spark Gaps

The spark gap consists of two electrodes placed in free air or some arc quenching material. One important characteristic of the spark gap involves "flow current" when used on power circuits. Once an arc is established by a surge, the normal circuit voltage may be high enough to sustain the arc. This characteristic is normally dealt with by using a series interrupting device (circuit breaker), magnetic blow out, series resistive element or deionizer.

Advantages:

1. Simple and reliable.
2. High energy handling capacity.
3. Very low voltage drop across gap during conduction (typically 10-20 volts).
4. Bipolar operation.
5. Reasonably fast response.
6. Zero power consumption.
7. Long life expectancy.
8. Low capacitance.

Disadvantages:

1. Used alone, will not extinguish follow current.
2. Limited to use on circuits of relatively high voltage.
3. Firing voltage depends on atmospheric conditions and surge risetime.

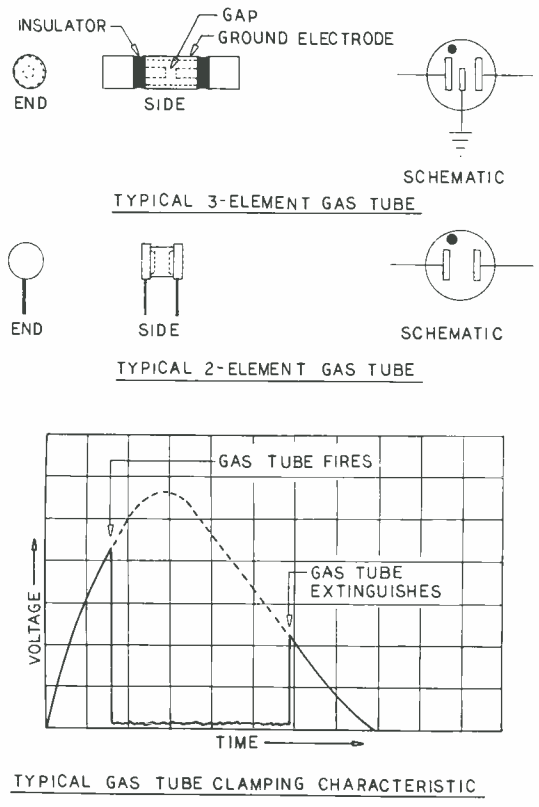


Fig. 4. Typical gas tube details.

Gas Tubes

Gas tubes exhibit many of the characteristics of the spark gap. The problems associated with atmospheric influence are eliminated by enclosing the gap in an atmosphere of neon, argon, krypton, or other gas easily ionized at low pressure.

Advantages:

1. Low cost.
2. Small physical size.
3. Good life expectancy.
4. Fairly low capacitance.
5. High energy capacity.
6. Lower breakdown voltage than spark gap.
7. Very high current capacity and low clamping voltage.

Disadvantages:

1. Follow current limiting required on power circuits.
2. Firing voltage depends on surge risetime.
3. Does not absorb appreciable surge energy.
4. May be ionized by strong RF fields.

Metal Oxide Varistors

Metal oxide varistors, or MOVs, are composed of sintered zinc oxide particles pressed in to a

wafer and equipped with connecting leads or terminals. These devices exhibit a non-linear resistance characteristic and a more gradual clamping action than either spark gaps or gas tubes. As a surge voltage increases, these devices conduct more heavily and provide clamping action. Unlike spark gaps or gas tubes, these devices absorb energy during surge conditions.

Advantages:

1. Available for low voltage applications.
2. Absorb energy.
3. No external follow current protection required.
4. Fast response time.

Disadvantages:

1. Clamping time depends on surge wavefront.
2. External fusing required for power applications (fails partially shorted).
3. Limited surge life expectancy.
4. High capacitance.

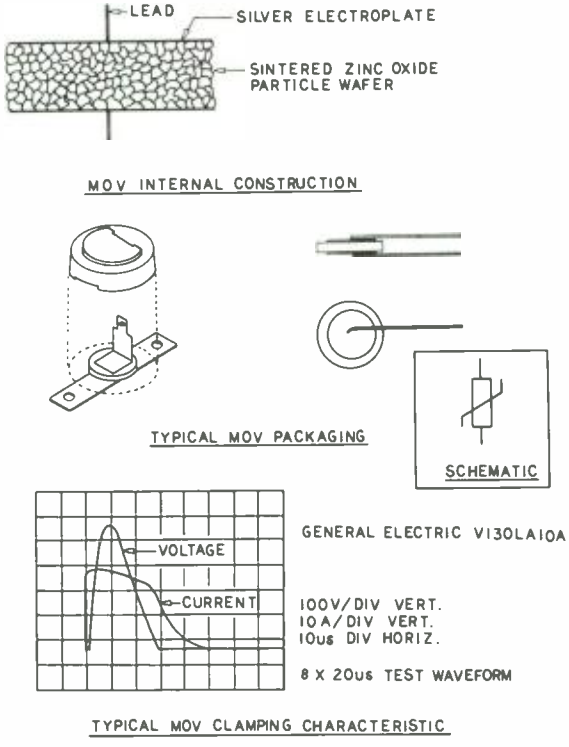


Fig. 5. Typical varistor details.

Silicon Avalanche Devices

Silicon avalanche devices used for surge suppression are similar to Zener diodes except they are designed to handle large surge currents without damage. Junction construction for these devices is typically 10 times larger than an equivalent Zener device. The junction is sandwiched between silver electrodes to improve current distribution and aid in thermal dissipation. These devices exhibit an extremely fast clamping action with an absolute clamping level.

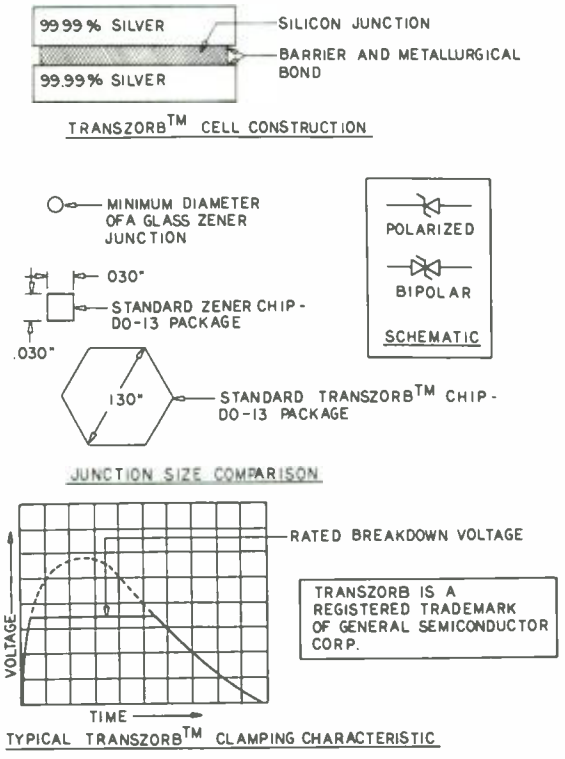


Fig. 6. Typical silicon avalanche suppressor details.

Advantages:

1. High clamping speed (less than one nanosecond).
2. Hard clamping threshold.
3. Available in bipolar configuration.
4. Small size.

Disadvantages:

1. Subject to damage by large surges.
2. Lead length substantially affects clamping time.

After reviewing characteristics of the basic surge suppression components, it is apparent that no single component is appropriate for all situations. It is, however, possible to use these devices in combination to fit almost any surge suppression need.

SURGE SUPPRESSOR ASSEMBLIES FOR POWER APPLICATION

To best explain the function of power surge suppressors, it is appropriate to examine the path a surge might follow on its way to your equip-

ment. For this example, we will assume the surge begins on the power company primary electrical system and your equipment is located within your control room at the studio.

The Primary Suppressor

The first line of defense against a power line lightning or switching surge is the primary suppressor installed by the power company. These devices are installed between each phase conductor and the grounded neutral. They are commonly located at step down transformers and at poles serving underground primary distribution.

These devices are intended to clamp surges to a value below the insulation breakdown rating of power company transformers and cables.

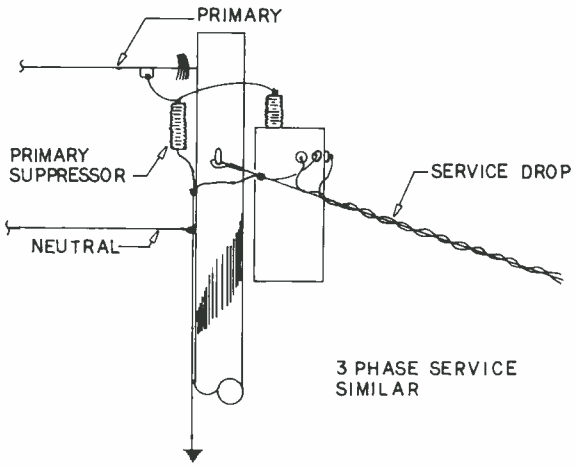


Fig. 7. Typical primary suppressor installation.

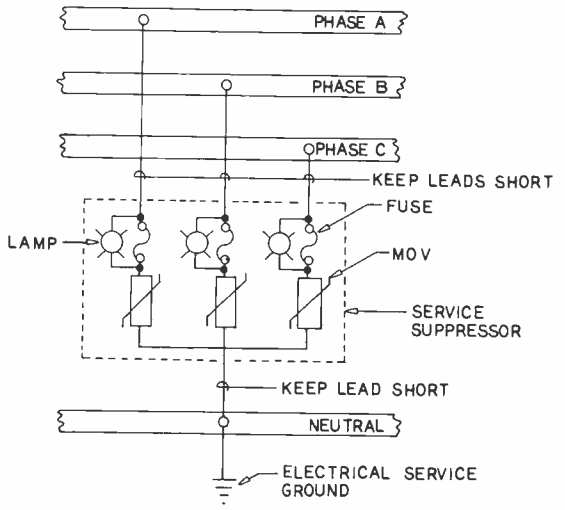


Fig. 8. Typical electrical service suppressor.

The Secondary Suppressor

The second line of defense against surges is a suppressor installed at the building electrical service location. Most of us are familiar with the common cylindrical lightning arrestors installed on commercial and residential electrical services. These devices consist of a low voltage spark gap with a series thyrite element connected between each phase conductor and the grounded neutral. The thyrite element provides follow current limiting allowing the arc to extinguish following a surge. This type of suppressor will clamp a typical surge at a level of 1000 to 2000 volts, dependent on surge current and waveform. Clamping at this level is sufficient to prevent insulation breakdown on internal wiring, motors, and more rugged electrical devices.

A more effective device utilizes a large metal oxide varistor (with protective fuse) connected between each phase conductor and the grounded neutral. Inductance of the connecting leads plays a major role in the effectiveness of the suppressor. The voltage drop through these leads is additive with the rated clamping voltage of the device. (Keep suppressor leads as short as possible.)

It is interesting to note that many codes do not require service surge suppressors on underground electrical services even though the service is fed from a pole a few feet away. It is advisable to provide service suppression in all applications.

Equipment Suppressors

It is quite possible to experience voltage surges, within a building, of 2000 volts. These surges may be in the form of residual energy from an external event or generated within the building itself.

Equipment surge suppressors range in both complexity and cost. These factors are usually in direct proportion to the clamping effectiveness of the device. Most of these devices depend on installation of a suppressor at the electrical service to prevent their exposure to large transients.

One of the simplest and most common forms of equipment suppressors is a varistor and thermal fuse connected across the line and neutral conductors. Packaging is usually in the form of a series plug and socket arrangement or as part of a plugstrip. For a typical 2000 volt, 15 ampere surge, these devices will typically limit equipment exposure to 500 volts.

For more sensitive equipment, hybrid suppressors are available which provide a lower clamping voltage and very fast response time. These devices use a high energy metal oxide varistor first stage with the varistor and fuse connected in series between line and neutral. The line voltage then passes through a large air core inductor to a silicon avalanche second stage consisting of series

connected bipolar suppression diodes between line and neutral. This configuration permits the varistor to absorb the majority of the surge while the diodes provide fast clamping. The inductor provides sufficient voltage drop during the surge to prevent damage to the diodes.

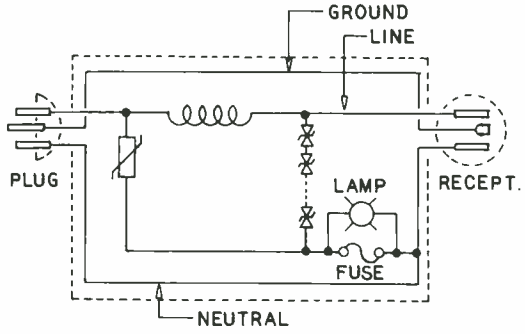


Fig. 9a. Typical 120 VAC hybrid equipment suppressor.

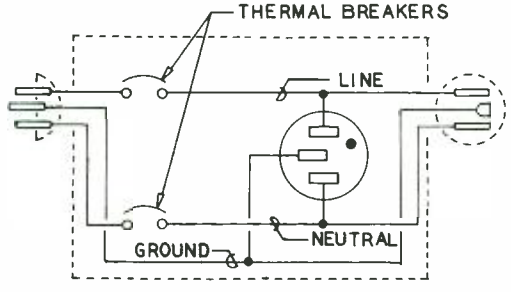


Fig. 9b. Typical 120 VAC gas tube equipment suppressor.

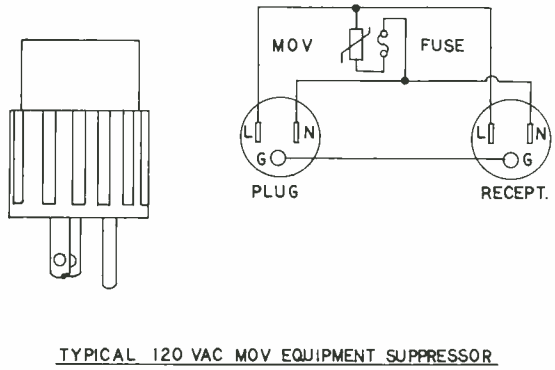


Fig. 9c. Equipment suppressor configurations.

SURGE ASSEMBLIES FOR SIGNAL APPLICATION

Surge suppression for signal lines encompasses a broad variety of circuit types and characteristics. Suppression techniques for video, RF, telephone, audio, data and similar circuits are slightly different but the fundamentals remain the same.

Careful consideration of the operating characteristics for each circuit and the level of protection required will usually make one device stand out as most appropriate for the application.

Shielding and use of twisted pairs is also an important part of obtaining an acceptable level of protection. During tests conducted in Orlando, Florida, we found common mode transients of 300 volts on a 24 volt dc unshielded circuit. This would not be too remarkable except the circuit was in PVC conduit, buried 24 inches deep, and the lightning discharges were several miles away.

Let us examine methods for protecting several different circuit types.

Single (Non-Paired) Conductors

Circuit protection for individual conductors will depend largely on the sensitivity of the equipment being protected and on impedance characteristics of the circuit. For low sensitivity applications, a simple varistor or gas tube, connected from the line to ground, will suffice. The gas tube would be the obvious choice if normal leakage current through a varistor could not be tolerated.

For more sensitive applications, the gas tube should be followed by a series inductor and a silicon avalanche second stage from the circuit to ground. A resistance may be substituted for the inductor (typically 10 ohms) if the circuit will tolerate the additional voltage drop.

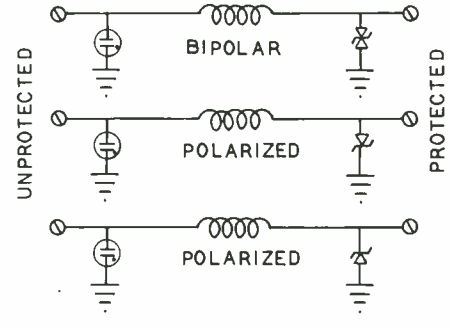


Fig. 10. Typical unbalanced signal line suppressors.

Balance Pairs

Balanced pairs are often protected with a 3-element gas tube. In this application, each side of the pair is connected to an element with the third element connected to ground. This configuration will insure both sides of the pair are clamped to ground at the same instant; thus avoiding possible damage from differential mode surges.

If equipment sensitivity dictates, a series inductance can be inserted in each side of the pair followed by a silicon avalanche device across the pair. Here again, resistors may be substituted if circuit characteristics permit.

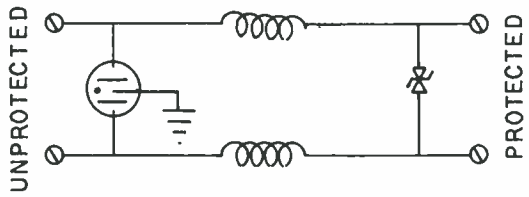


Fig. 11. Typical balanced line suppressor.

Low Level Audio Circuits

Low level audio circuits are treated in a manner similar to balanced pairs except they are normally shielded. Standard engineering practice normally requires these shields be bonded to ground at one point to prevent ground loop problems. In addition to suppression for the pair, a gas tube is connected between the shield and ground at its remote end and at intermediate points. With this configuration, the shield floats under normal conditions but is bonded during a surge.

Video Circuit Protection

Triaxial cable should be used for all video circuits. The outer shield of this cable should be kept electrically isolated from the inner shield and bonded to ground as often as possible. The inner, or signal, shield of the triaxial cable is generally grounded at one point only to minimize ground loop interference.

A video surge suppressor is a low capacitance device equipped with two coaxial connectors and a ground lug. At the point of installation, the following procedure should be observed:

1. Install appropriate connectors on the inner shield and center conductor and connect to the video surge suppressor.
2. Bond the outer shields together and to ground exercising care to prevent contact with the inner shield, connectors, or suppressor body.

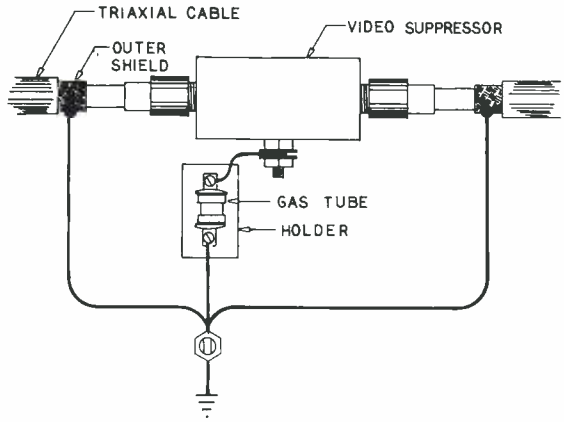


Fig. 12. Typical video suppressor connection.

3. Install a 2-element gas tube between the suppressor ground lug and grounded outer shield.

RF Circuit Protection

Coaxial RF cables should be equipped with a coaxial gap type suppressor with its ground lug bonded to ground. The coaxial sheath should be bonded to ground frequently in areas where exposure to lightning is high. Bonding in this manner will reduce potentials induced into the cable sheath.

SHIELDING—GENERAL GUIDELINES

A lightning discharge radiates an intense electric and electromagnetic field. It is not uncommon to find electric field intensities approaching 1 volt per meter at a distance of 10 kilometers

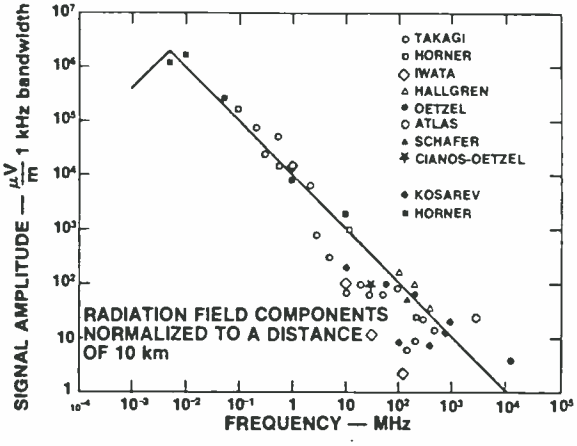


Fig. 13. Lightning signal amplitude vs frequency. Courtesy SRI International (Stanford Research Institute), Menlo Park, California 94025).

from a discharge. Close discharges may produce field intensities of 100 volts per meter. An exposed conductor subjected to an intense electrical field will produce a substantial voltage across its length.

Shielding and use of twisted pair wiring where possible (for common mode rejection) will help relieve some of the induced voltage problems. The following guidelines should be observed:

1. Bond shields to ground as often as possible. For ground loop reduction, bond through gas tubes.
2. Use metallic conduits instead on non-metallic types.
3. In direct burial application, use cable with polyethylene jacketing and a flooding compound between the jacket and shield. This compound seals jacket pinhole damage resulting from lightning, prevents water migration into the cable, and electrolytic decay of the shield.
4. Where pairs are required, consider using telephone type cables which have a corrugated copper shield.
5. If cable must be run aerially, bond the cable shield to the vertical ground conductor at the first, every fifth, and last pole. Bond more frequently if practical.
6. In areas of high lightning exposure, provide a grounded lightning shield wire several feet above the cable on the poles. This wire should be bonded to ground at every pole. For direct burial cables or duct banks in high exposure areas, a counterpoise system is recommended. This system consists of two or more bare wires buried above and to the side of the cable. Counterpoise conductors should be bonded together and to driven rods at manholes, 150 foot intervals, and at each change in cable direction.

CONCLUSIONS

Your interest in lightning protection and surge suppression will largely be dictated by the area of the country in which you live. For some, this information will prove invaluable; for others not plagued by lightning, it should provide a basic understanding of the principles involved.

In this chapter we have dealt briefly with the subjects of lightning physics, lightning protection, and surge suppression. Many volumes have been written on these subjects and the reader is encouraged to study them in greater detail.

Another point to consider is that lightning is an electrical current, and like any other electrical current, it is both predictable and can be controlled.

Please consult an engineer familiar with lightning protection or a lightning protection contractor when planning a lightning protection system or adding surge suppression devices to your electrical system.

REFERENCES

1. Golde, R.H.: *Lightning* (Volume 1 and 2), Academic Press, 1977.
2. Viemeister, Peter E.: *The Lightning Book*, The MIT Press, 1972.
3. Clark, O. Melville: *A Guide for Transient Suppression Using Tranzorbs*, General Semiconductor Industries; Tempe, AR, 1978.
4. *Electrical Protection Fundamentals:* Rural Electrification Administration, Telephone Engineering and Construction Manual, Sections 801-823, July 1974.
5. Fischer, F. A.: "Generation of, and Protection Against, Transients", General Electric Corporation Research and Development.
6. Martzloff, F. D.: "Surge Voltage Suppression in Residential Power Circuits", General Electric Corporation Research and Development, Report 76 CRDO92, May 1976.
7. "Transient Voltage Suppression Manual", General Electric, Semiconductor Products Department, Syracuse, NY (Varistor Data).
8. Alpeter, Henry M.: "Surge Protection for Todays Telephone Plant and Equipment", ITT Industries, Lindenhurst, NY.
9. "Lightning Protection Code—1980" (N.F.P.A.—78): National Fire Protection Association, Inc.; Quincy, MA 02269.

2.3

Transmission Lines

Spencer J. Smith
Vice President, Engineering
Dielectric Communications
Raymond, Maine

INTRODUCTION

The intent of this chapter is to give detailed information, tables and charts, which can be used as a type of cookbook by broadcast station engineers in evaluating their present systems, planning modifications to their existing systems, or planning a completely new installation. The area of coverage will be from the transmitter output up to the antenna input, including AM, FM and TV installation.

The transmission line system for any transmission site has always been the vital link connecting the power generator to the antenna. We have seen the evolution from open wire line to coaxial lines and finally to hollow tube waveguide transmission systems. This evolution has been brought about by both higher frequencies and increased power requirements. In addition, the increased sophistication of the system in areas of performance and philosophy of operations have made the current transmission systems completely unrecognizable when compared with initial broadcast systems.

TRANSMISSION LINES

In general, this chapter deals with two basic types of transmission lines: coaxial and hollow tube waveguides. The use of open wire seems to be fading for new installations both in commercial broadcast, as well as the HF frequency band (international shortwave broadcast).

COAXIAL TRANSMISSION LINES

Coaxial transmission lines are characterized by a circular inner conductor supported within a circular outer innerconductor. Usually both conductors are copper, especially in the high power transmission line used in broadcast. There are two major categories of coaxial transmission lines, one being rigid and the second being a semi-rigid, and both types have achieved wide acceptance in AM, FM and TV installations. The designs for the most part have exhibited a well proven track record for trouble free operation over years of use. The graphs and charts that follow represent a cross-section of manufacturers' data available to the transmission line users. On close examination, one will see that, for a given size, rigid transmission lines with air dielectric will tend to have slightly lower attenuation and, therefore, slightly improved power handling capabilities. Also the rigid line is usually used in installations where extremely low VSWR is required of the system. The costs are for all practical purposes the same; however, during installation the semi-rigid line will provide a lower cost for the physical installation due to its continuous nature as op-

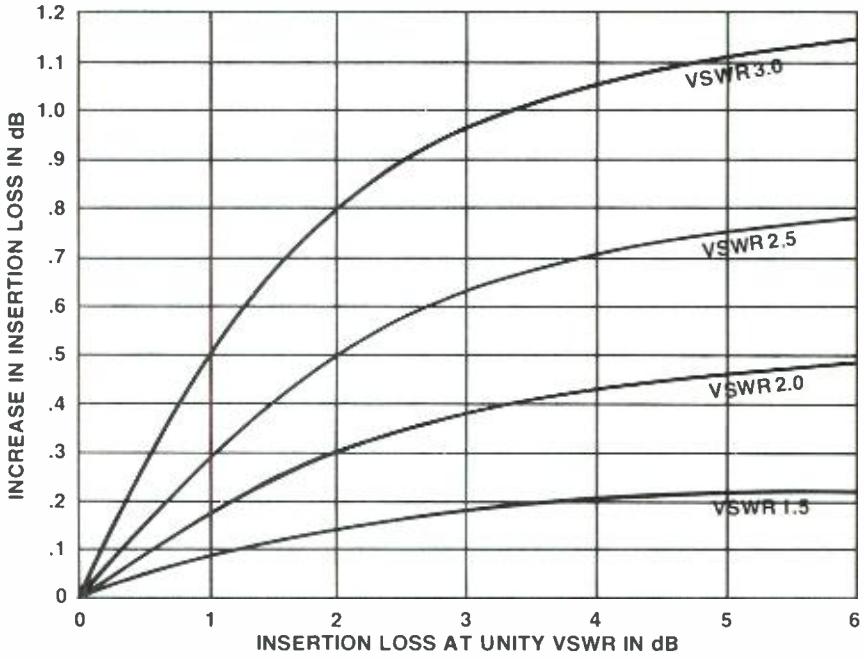


Fig. 1. Insertion loss correction due to load VSWR.
(Courtesy of Cablewave Systems, Inc.)

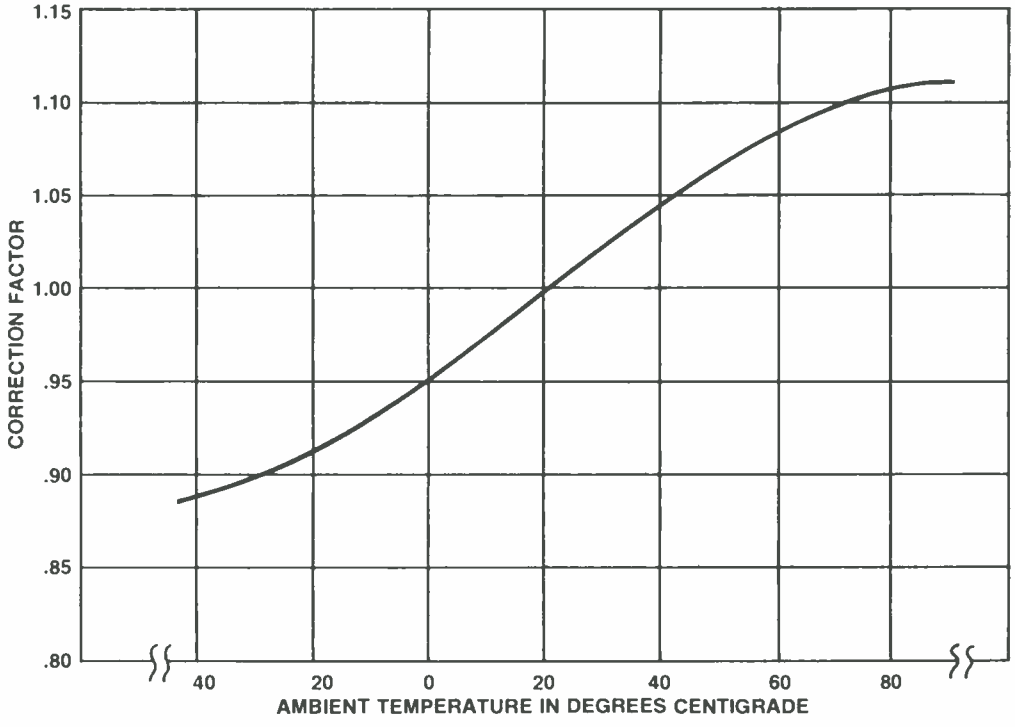


Fig. 2. Attenuation changes due to ambient temperature.
(Courtesy of Cablewave Systems, Inc.)

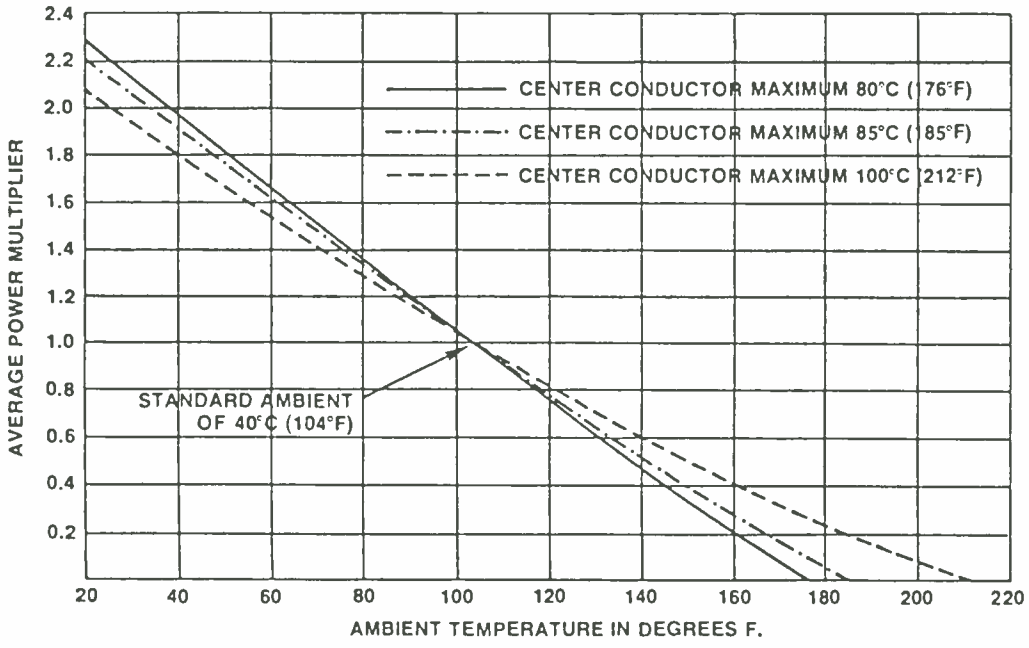


Fig. 3. Variation of average power rating with changes in ambient temperature. (Courtesy of Cablewave Systems, Inc.)

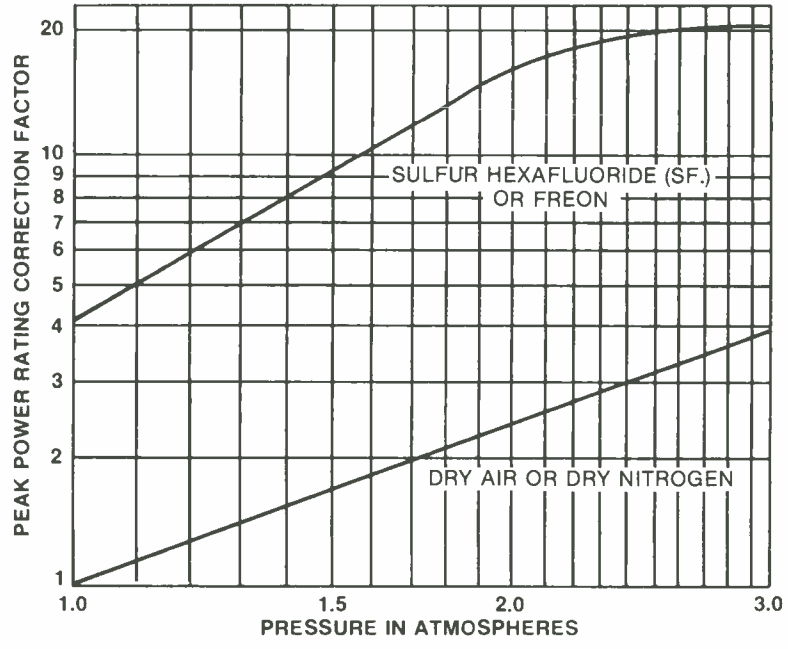


Fig. 4. Peak Power rating improvement due to pressurization. (Courtesy of Cablewave Systems, Inc.)

posed to the approximate 20 foot length in the rigid line sections. In addition semi-rigid line can be attached directly to the tower members while rigid line requires the use of hangers to allow for differential expansion between the tower and the rigid line.

The primary questions of any transmission line for broadcast use is, "how much power will it transmit?" Shown in respective areas are some attenuation and power curves taken from manufacturers' data and adjusting it for the exact conditions the transmission line has to operate in. Shown below are some general curves applicable to all transmission lines. Fig. 1 shows the increase in insertion loss due to VSWR at the output of the transmission system. Fig. 2 represents attenuation change due to ambient temperature, showing that as the temperature goes up so does the attenuation. Fig. 3 shows the variation of average power rating with changes in ambient temperature for three different center conductor temperatures. This is closely related to the change in attenuation due to ambient temperature. Fig. 4 shows the improvement in peak power handling one might achieve in coaxial lines due to pressurization with either dry air or sulfurhexafloride. It is essential always to use manufacturers' data in planning a new installation or evaluating or repairing an existing system. Almost all manufacturers of transmission line put out very complete data and performance curves for their product. These particular curves for any manufacturer represent the limits they have placed on their product. Close examination will show that these curves do differ slightly in various areas. Only through direct contact with the manufacturer should a broadcaster plan to exceed these ratings for whatever reason.

SEMI-RIGID TRANSMISSION LINE

The use of semi-rigid transmission line is almost as old as the use of transmission line itself in the broadcast area. As the power levels have increased in the broadcast industry, we have seen the use of solid dielectric cables give way to foam dielectric cables and further give way to air dielectric semi-rigid transmission line. The data shown at the end of this section reflect the performance curves of one manufacturer and should not be construed as being the absolute value for all manufacturers. The semi-rigid transmission line, especially in larger sizes, is generally characterized by a corrugated outer conductor of copper; this is how the flexibility is achieved. However, it should be noted that the term "semi-rigid" is used because in larger sizes, 1⅝" and up, the semi-rigid bending radius becomes quite large (Fig. 5). The major manufacturers of semi-rigid transmission line have a very wide variety of adapters from most cable sizes to either rigid line or flexible fittings, such as type N, L, C, etc. Typical construction of these is shown in Fig. 6.

LINE SIZE	TYPICAL BEND RADIUS
1 5/8"	20"
3"	30"
3 1/2"	30"
4 1/8"	30"
5"	35 1/2"
6 1/8"	47"
8"	67"

Fig. 5. Typical bend radius for semi-rigid cable.

Installation

General

Smooth wall aluminum and copper corrugated cables can be installed without special tools or equipment. Hoisting grips are employed to support the cable to the hoisting line during lifting. Wrap-lock or cable hangers are used to affix the cable securely to the tower and angle and round member adaptors eliminate any need to drill holes.

Preparation For Installation

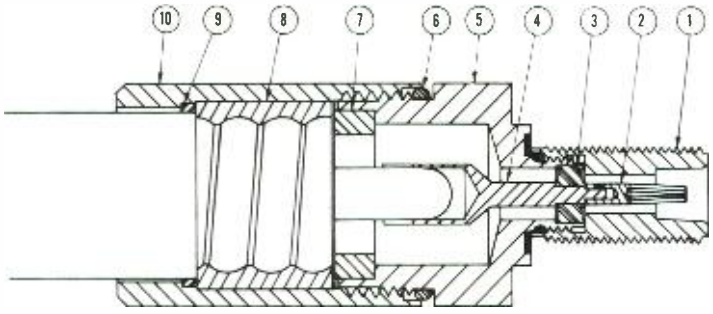
Coaxial cables are usually shipped coiled in crates or cartons, or on non-returnable deposit-type wooden reels. Although cable on reels is protected by wooden lagging or a fiberboard wrap, it should be handled carefully. Reels should rest on their flanges and never be dropped during handling. If fork lifts are used, the forks must be long enough to engage both flanges or cable damage can result. When cable is ordered with factory installed connectors, the antenna end is wound on the outside of the coil and hoisted by means of a cable grip, which can also be factory installed if specified on the order.

After carefully unlagging the reel, inspect the cable for any signs of shipping damage. Air dielectric cables have been pressure tested and each assembly is tagged with the factory pressure test verification, there should also be instructions to be followed should the pressure be found to have declined substantially in shipment. Factory installed EIA connectors (Gas Pass) include a sealing cover to retain pressure during shipment. This cover may be left in place for protection during cable hoisting.

Hanger Spacing

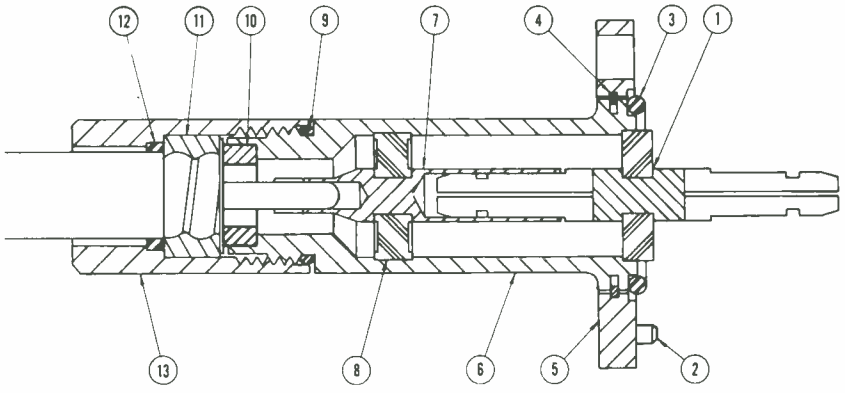
The coaxial cable should be attached to a good electrical ground by grounding kits at the top of

Connector For Foam Wellflex Cable



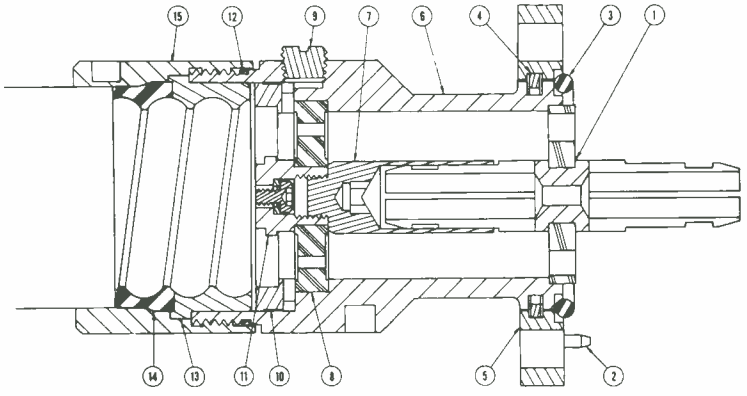
1. NF NOSE
2. NF CONTACT
3. BEAD
4. CONTACT
5. BODY
6. 'O' RING
7. INSERT
8. COLLET
9. REAR SEAL
10. BACK NUT

Connector (EIA) For Foam Wellflex Cable



1. BULLET ASSY
2. PIN
3. 'O' RING
4. SNAP RING
5. FLANGE
6. EIA BODY
7. CONTACT
8. BEAD
9. 'O' RING
10. INSERT
11. COLLET
12. REAR SEAL
13. BACK NUT

Connector For Air Wellflex Cable



1. BULLET ASSY
2. PIN
3. 'O' RING
4. SNAP RING
5. FLANGE
6. EIA BODY
7. CONTACT
8. BEAD (G.P.)
9. PIPE PLUG
10. INSERT
11. ANCHOR SUB-ASSY
12. 'O' RING
13. COLLET
14. THREADED GASKET
15. BACK NUT

Fig. 6. Typical connectors.

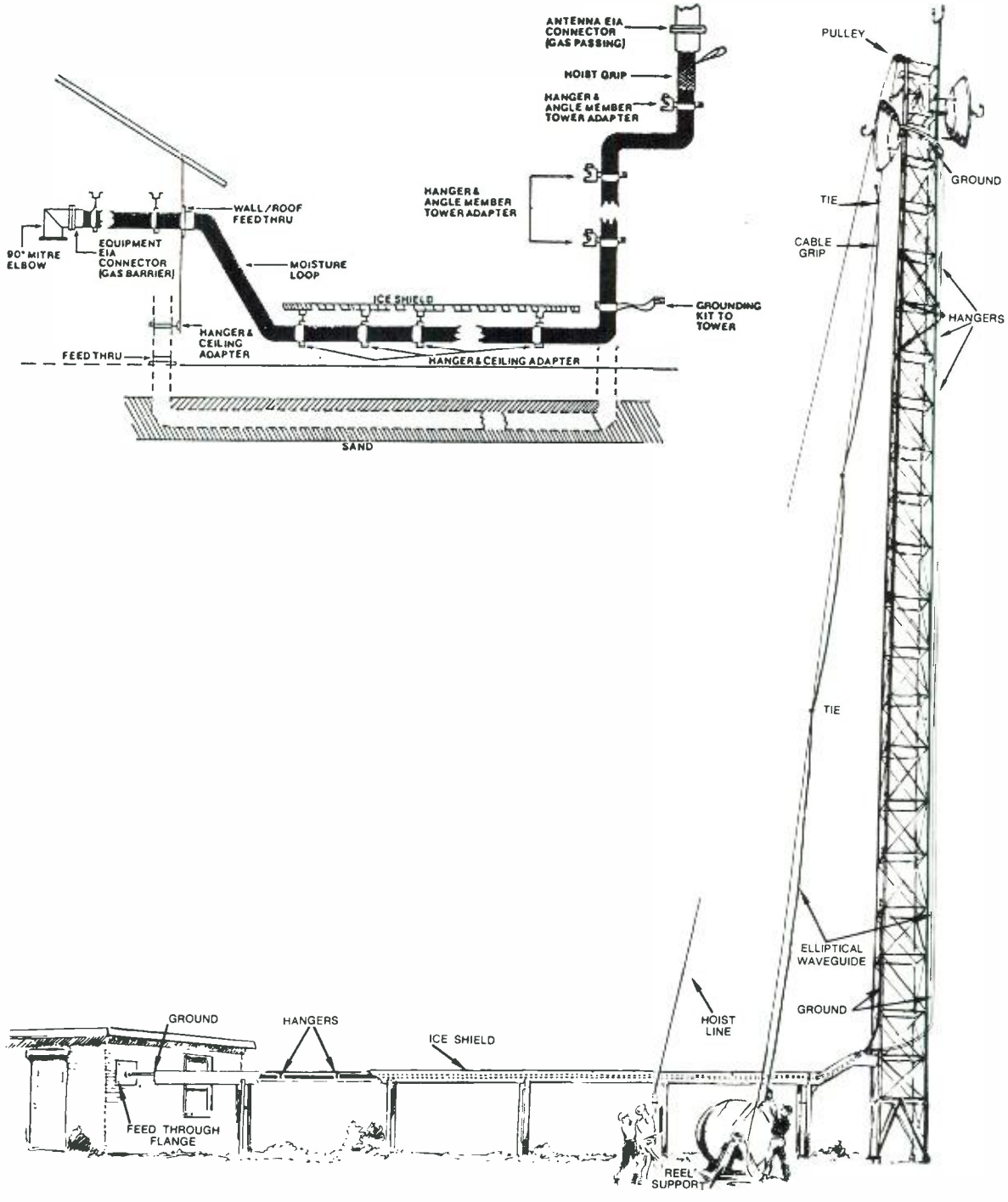


Fig. 7. Typical tower installation.

Rated Max. Wind Speed mph	(km/h)	Radial Ice inches	(mm)	1⅝" to 3" feet	(m)	⅞" feet	(m)	⅜" to ½" feet	(m)
90	(145)			6	(1.8)	4	(120)	3	(90)
110	(180)	no		5	(1.5)	4	(120)	3	(90)
130	(210)	ice		5	(1.5)	3	(90)	3	(60)
180	(290)			4	(1.2)	3	(90)	2	(60)
90	(145)	½	(12)	6	(1.8)	4	(120)	3	(90)
110	(180)			5	(1.5)	3	(90)	2	(60)
130	(210)			4	(1.2)	3	(90)	2	(60)
90	(145)	1	(25)	4	(1.2)	3		2½	(75)
110	(180)			4	(1.2)	3	(90)	2	(60)
130	(210)			3	(0.9)	2	(60)	1½	(45)
90	(145)	2	(50)	4	(1.2)	3	(90)	2	(60)
110	(180)			3	(0.9)	2½	(75)	1½	(45)
130	(210)			3	(0.9)	2	(60)	1½	(60)

Fig. 8. Recommended cable hanger spacing.

the vertical run near the antenna, at the bottom of the tower and at the building entrance. Further information on this is included in the "Lightning Protection" chapter in this section of the Handbook.

Tower Installation

Few tower installations are identical and only typical planning considerations are outlined herein. A pulley and line are recommended for safe lifting of coaxial cables. The hoist line should be long enough to allow tying it to the cable along the vertical run about every 50 feet (15 m) for hoisting. Cable grips are used to support the cable every 200 feet (60 m) and may be fastened to the tower as permanent hangers.

For short lengths, uncoil the cable along the ground, away from the base of the tower, and attach the hoist line. For longer lengths, position reel at the base of the tower, supported on an axle to allow smooth and controlled unreeling. Attach the hoisting grip and line. Place a protective wrap covering over the connector to prevent damage during hoisting and slowly hoist the cable.

After the cable has been raised, the cable grip is permanently secured to the tower and the connector attached to the antenna. For the standard case, ties or cable hangers may be spaced approximately 3 feet (1 m) apart for cables up to 1⅝" diameter, and 5 feet (1.6 m) apart for 3" cable. The chart of recommended hanger spacing for different wind and ice loadings is shown in Fig. 8.

Horizontal Runs Supported By An Ice Shield

Horizontal cable runs suspended from ice shields or support structures normally require the same hanger intervals as the vertical run. A broad drip loop will prevent undesired moisture build-up at the building entry feed-thru.

Horizontal Runs Supported By Messenger Cables

Horizontal cable runs may be supported by a steel messenger cable from the tower to the equipment building. The size of the messenger is dependent upon the weight of cable and length between supports. Cable may be spun to the messenger by a spinning machine similar to those used by many utility companies.

Buried Horizontal Runs

Jacketed smooth wall aluminum cables can be safely buried in many cases; however, jacketed corrugated copper cable is inherently more corrosion resistant and is normally recommended. Cable should be located below the frost line and placed in the middle of a 12" inch layer of sand to protect the jacket from stones or sharp objects. A duct or conduit should be used to protect cable which runs under a service road or in similar situations. All buried connectors or splices should be carefully sealed with a splice protection kit, and the cables should include good electrical grounds at both ends to reduce any lightning effects. In any buried installation there is always the possibility that certain soil conditions can lead to premature deterioration of the cable. Therefore, it is desirable to review local practice and, if in doubt, contact an experienced engineering firm for specific guidance.

Pressurization

Air dielectric coaxial cables should be pressurized with dry air or nitrogen to prevent moisture condensation within the cable and deterioration of electrical performance. If any cable has

suffered from condensation it should be dried out by flushing with dry air. The cable may be considered "dry" when the insulation resistance between the center and outer conductors, tested on a "megger," reaches 100,000 megohms.

Power Handling of Semi-Rigid Transmission Line

Line sizes of primary interest to the broadcast engineer range from 1⅝" diameter up to 8" diameter. The attenuation, peak power handling, and average power handling for typical lines in these sizes are given in Fig. 9a & b. Again, caution should be exercised in using exact data from the manufacturer of the transmission line that is to be installed.

RIGID COAXIAL TRANSMISSION LINE

Rigid coaxial line has been used by the broadcast industry since the mid-Forties. It represents a well-proven method of transmitting RF power to the antenna. In general, a high quality broadcast transmission line has the following features:

- High conductivity of the inner conductor,
- Flange expansion joint on the inner conductor which will compensate for the differential mechanical expansion between inner and outer conductors,
- Welded flange to prevent excessive softening of the outer conductor especially in the area of the flange expansion joint,
- Expansion connection designed to capture any contamination generated by the mechanical motion,
- Retention of the inner conductor within the outer for vertical installations,
- Teflon support structures on the inner conductor and the interfacing connector joints.

On long transmission lines, allowances must be provided for differential expansion between outer and inner conductors. Therefore, the inner conductor provides for some relative movement of inner and outer conductors. The result is a very small electrical discontinuity which is a function of differential temperature and which can be compensated to zero at only one temperature differential. Since these discontinuities are a fixed distance apart and numerous in a run of, for example, 300 feet, the combination can produce an undesirable VSWR at frequencies where each section length is a multiple of a half wavelength. The resulting VSWR is, of course, also a function of temperature and is sharply frequency sensitive. If the operating frequency should coincide with one of the critical frequencies for 20-foot section lengths, 19½-foot sections may be used to avoid the possible buildup of standing wave ratio. Fig. 10 gives the critical frequencies for both section lengths. It is not advisable to work closer than ± 2 MHz to the frequencies listed.

Small reflections at inner conductor connectors under flanged areas may add at the following frequencies. For 20-foot and 19½-foot sections, the frequencies in megahertz are 24.52 n and 25.12 n where n is any integer. For other lengths, the critical frequencies in megahertz may be calculated by:

$$f = \frac{490.4n}{L} \qquad [1]$$

Where: L is the length in feet.

Fig. 10 shows recommended section lengths for various frequencies. In addition 17½-feet length has been established as an accepted length for Multi Station FM installation. Fig. 22 gives typical mechanical dimensions for coaxial line 1⅝" thru 9³⁄₁₆". The dimensions shown are for EIA style transmission lines which is the most common flange in the broadcast industry. At present however, it should be noted that other styles of flanges i.e., universal, bolt universal are in existence. In the area of power rating on coaxial lines, exact information should be obtained for the manufacturer of the line to ensure its accuracy.

Electrical Specifications

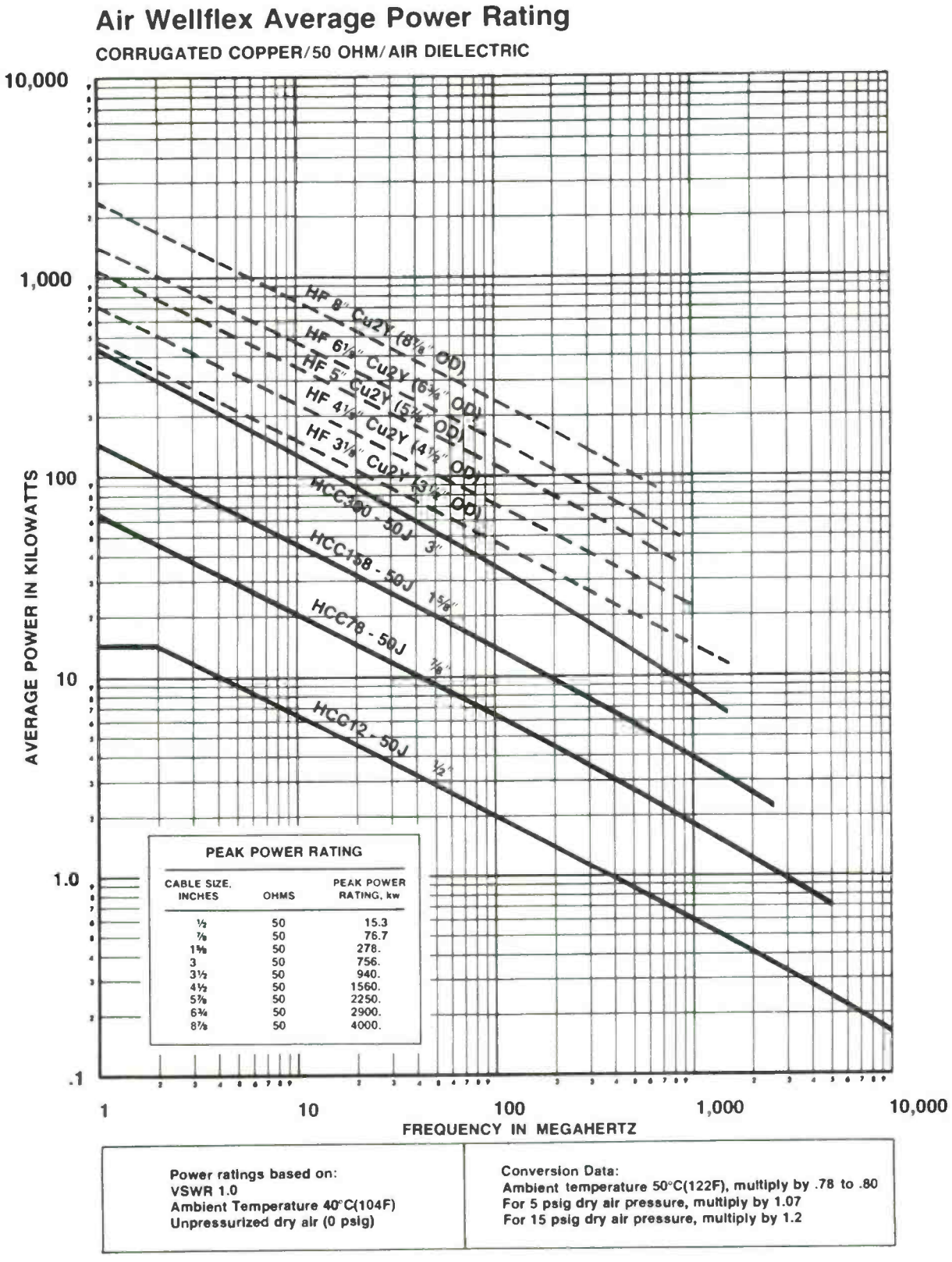
Rigid transmission line does offer generally better electrical specifications than semi-rigid as comparison for dealing with normal sections 20 feet long as opposed to the continuous run. Typical VSWR figures, both as installed and with special tunning, are given in Fig. 11. The average power rating vs. frequency for typical high quality coaxial lines is given in Fig. 12. The attenuation of these various lines is given in Fig. 13. In addition, Figs. 14 through 19 contain tabulated data for attenuation vs. frequency as well as power transfer efficiency for various lengths of transmission lines.

Installation Instructions

Installation Precautions

Care is required in handling the various transmission line components to prevent damage and assure proper installation. Procedures are outlined in "Transmission Line Do's and Don'ts" (Fig. 23). These recommendations are important.

Tower steel must be designed to support the vertical run in a straight line and maintain line clearance within spring hanger guide rings under load.



PEAK POWER RATING

CABLE SIZE, INCHES	OHMS	PEAK POWER RATING, kw
½	50	15.3
⅞	50	76.7
1⅝	50	278.
3	50	756.
3½	50	940.
4½	50	1560.
5⅛	50	2250.
6¾	50	2900.
8⅛	50	4000.

Power ratings based on:
VSWR 1.0
Ambient Temperature 40°C(104F)
Unpressurized dry air (0 psig)

Conversion Data:
Ambient temperature 50°C(122F), multiply by .78 to .80
For 5 psig dry air pressure, multiply by 1.07
For 15 psig dry air pressure, multiply by 1.2

Fig. 9a. Air wellflex average power rating.

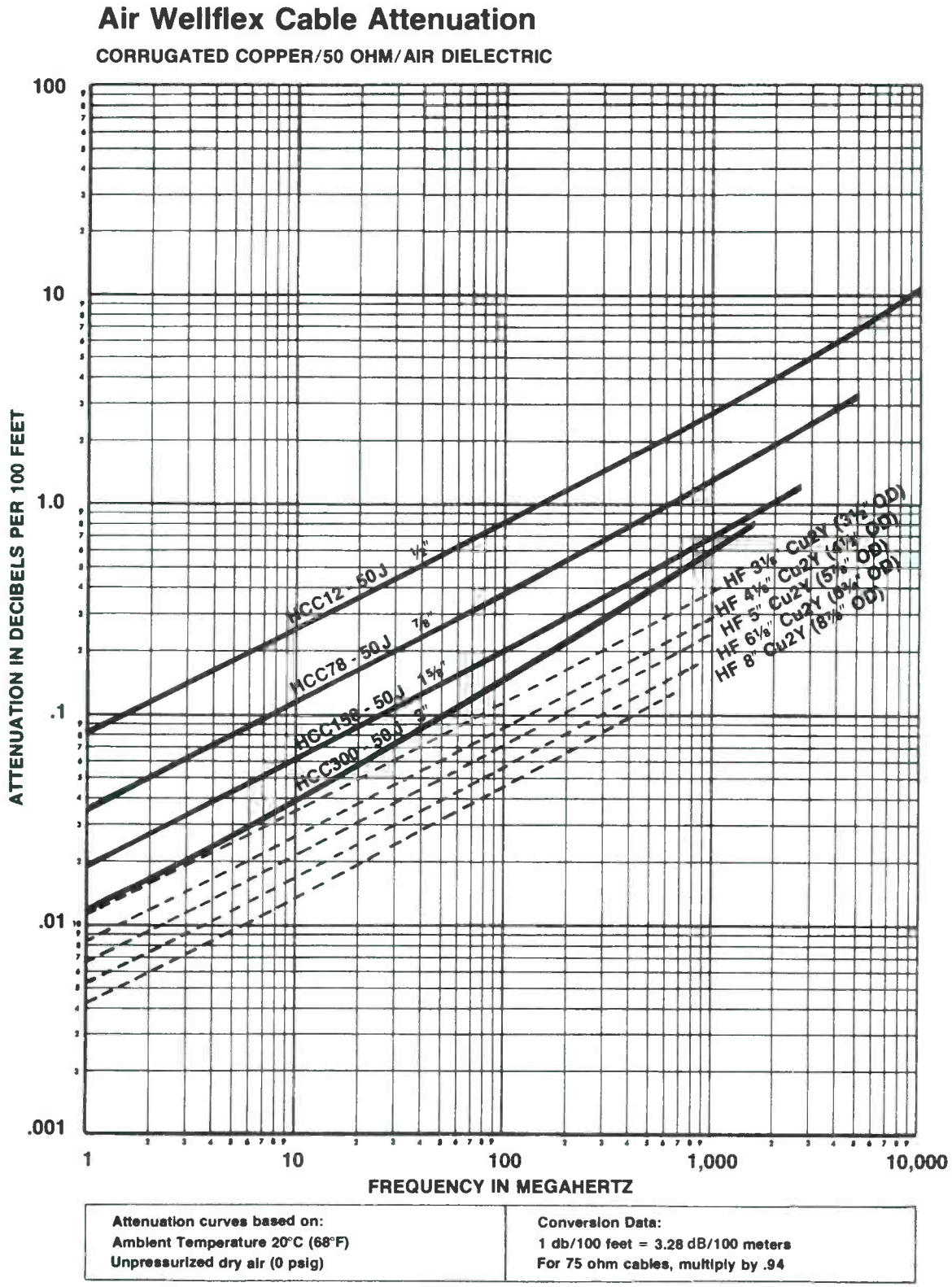


Fig. 9b. Air wellflex cable attenuation.

Channel No.	20' Only	19½' Only	Either 19½' or 20'
2			●
3			●
4			●
5	●		
6			●
7	●		
8			●
9			●
10		●	
11	●		
12			●
13			●
14			●
15	●		
16			●
17		●	
18			●

Channel No.	20' Only	19½' Only	Either 19½' or 20'
19	●		
20			●
21		●	
22			●
23	●		
24			●
25		●	
26			●
27	●		
28			●
29		●	
30			●
31	●		
32	●		
33		●	
34			●
35			●

Channel No.	20' Only	19½' Only	Either 19½' or 20'
36	●		
37		●	
38			●
39			●
40	●		
41		●	
42		●	
43			●
44	●		
45		●	
46		●	
47			●
48	●		
49		●	
50		●	
51			●
52	●		

Channel No.	20' Only	19½' Only	Either 19½' or 20'
53	●		
54		●	
55			●
56			●
57	●		
58		●	
59			●
60			●
61	●		
62		●	
63			●
64			●
65	●		
66		●	
67			●
68			●
69	●		
70		●	

Fig. 10. Recommended section lengths—U.S. TV channels.

CHANNEL RANGE	LENGTH T/L RUN	3⅛ DIA.	4 1/16 DIA.	6⅛ DIA.	8 3/16 9 3/16 DIA.
2-6 and F M	0 to 1000'	Regular 1.05	Regular 1.05	Regular 1.05	Regular 1.05
	1000' to 1500'	Regular 1.06	Regular 1.06	Regular 1.06	Regular 1.06
	0 to 1000'	*Special 1.04	*Special 1.04	*Special 1.035	*Special 1.03
	1000' to 1500'	*Special 1.05	*Special 1.05	*Special 1.05	*Special 1.05
7-13	0 to 1000'	Regular 1.05	Regular 1.05	Regular 1.05	Regular 1.05
	1000' to 1500'	Regular 1.06	Regular 1.06	Regular 1.06	Regular 1.06
	0 to 1000'	*Special 1.04	*Special 1.04	*Special 1.035	*Special 1.03
	1000' to 1500'	*Special 1.05	*Special 1.05	*Special 1.05	*Special 1.05
14-30	0 to 800'	Regular 1.05	Regular 1.05	Regular 1.05	Regular 1.05
	800' to 1500'	Regular 1.07	Regular 1.07	Regular 1.07	Regular 1.07
	0 to 800'	*Special 1.035	*Special 1.035	*Special 1.03	*Special 1.03
	800' to 1500'	*Special 1.05	*Special 1.05	*Special 1.05	*Special 1.05
31-62	0 to 800'	Regular 1.06	Regular 1.06	Regular 1.05	----------
	800' to 1500'	Regular 1.08	Regular 1.08	Regular 1.08	----------
	0 to 800'	*Special 1.05	*Special 1.05	*Special 1.04	----------
	800' to 1500'	*Special 1.05	*Special 1.05	*Special 1.05	----------
31-52	0 to 800'	----------	----------	----------	Regular 1.05
	800' to 1500'	----------	----------	----------	Regular 1.08
	0 to 800'	----------	----------	----------	*Special 1.04
	800 to 1500'	----------	----------	----------	*Special 1.05

Fig. 11. VSWR maximum limit values.

POWER RATING VS. FREQUENCY

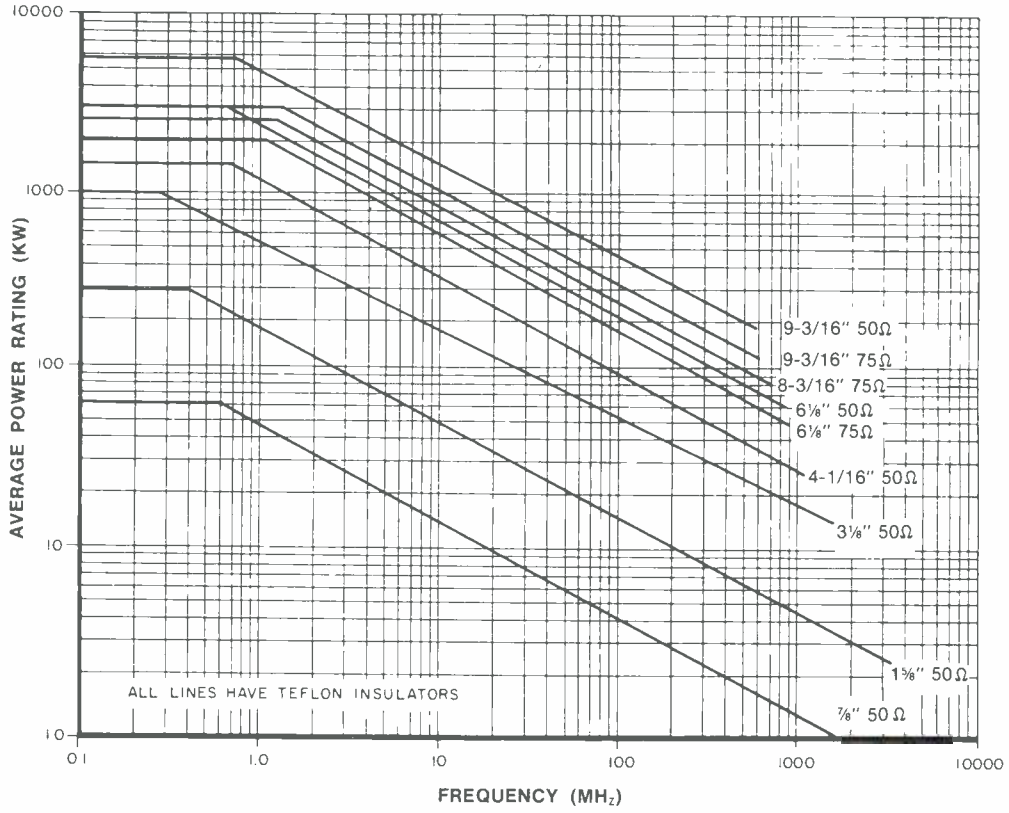


Fig. 12. Power rating of rigid transmission line.

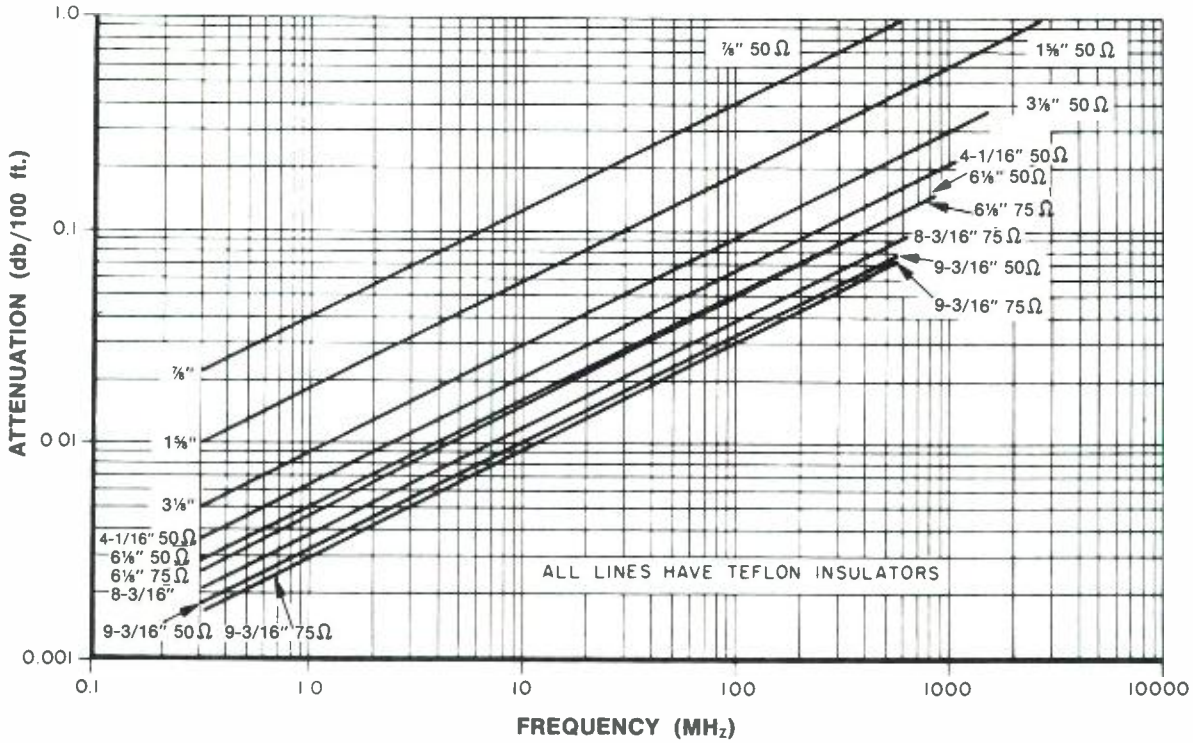


Fig. 13. Transmission line attenuation.

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)									
		200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
2	0.072	96.7	93.6	90.5	87.5	84.7	81.9	79 2	76 6	74.1	71.7
3	0.076	96 6	93.2	90.0	87.0	83.9	81.0	78.2	75.5	72.9	70.3
4	0.080	96.4	92.9	89.5	86.3	83.2	80.2	77.3	74 5	71.7	69.2
5	0.086	96.1	92 4	88 9	85.4	82.1	78.9	75.9	72.8	69.8	67.4
6	0.089	96.0	92.1	88.4	84.9	81.5	78.2	75 1	72.0	69 2	66 4
7	0 130	94 2	88.7	83.6	78.7	74.1	69.9	65.8	62 0	58.3	54 9
8	0.132	94 1	88 5	83 4	78.4	73.8	69.5	65.3	61.5	57.9	54.4
9	0 134	94.0	88.3	83.1	78.1	73.4	69.2	64.9	61 0	57 3	53 8
10	0 136	94 0	88 1	82 9	77.8	73.1	68.8	64.5	60.6	56.8	53.4
11	0 138	93.8	88.1	82.6	77.6	72.8	68.3	64.1	60 2	56 4	52 9
12	0.141	93.7	87.8	82 3	77.1	72.3	67.7	63.5	59.5	55.8	52 2
13	0 143	93.6	87.7	82.1	76.8	71.9	67.4	63.1	59 1	55 3	51 6
14	0 223	90.2	81.4	73 5	66.3	59.8	54.0	48.7	44.0	39.6	35.7
15	0.225	90.2	81.3	73.3	66.1	59.6	53.7	48.4	43 7	39 3	35 5
16	0 227	90.1	81 1	73 1	65.8	59.3	53.4	48.1	43.3	39.0	35.1
17	0.229	90.0	81.0	72.9	65.6	59.0	53.1	47.8	43.0	38 6	34.8
18	0 231	89.9	80.8	72 7	65 3	58.8	52.8	47.5	42.7	38.4	34.5
19	0 233	89.8	80.7	72 5	65.1	58.5	52.5	47.2	42.4	38.0	34 2
20	0.234	89 8	80 6	72 4	65.0	58.3	52.4	47.0	42.2	37.9	33.9
21	0 235	89.7	80.5	72 3	64.9	58.2	52.2	46.9	42 1	37.8	33 8
22	0.237	89.7	80 4	72 1	64.6	57.9	52.0	46.6	41.8	37.4	33 5
23	0 239	89.6	80.2	71.9	64.4	57.7	51.7	46.3	41 5	37 0	33 2
24	0.240	89 5	80 2	71.8	64.3	57.5	51.5	46.1	41.3	36.9	33.0
25	0.242	89.5	80.0	71.6	64 0	57.3	51 2	45.8	41 0	36 7	32 8
26	0 243	89 4	80 0	71 5	63.9	57.2	51.1	45.7	40.9	36.4	32.7
27	0 245	89.3	79.8	71.3	63.7	56.9	50.8	45.4	40.6	36 2	32.3
28	0.247	89 3	79 7	71.1	63.5	56.6	50.5	45 1	40.3	36 0	32.0
29	0.249	89.2	79.5	70.9	63.2	56.4	50.3	44.8	40.0	35 7	31 8
30	0.250	89.1	79.4	70.8	63.1	56.2	50.1	44.7	39.8	35 5	31.5
31	0 252	89.0	79.3	70.6	62.9	56.0	49.8	44.4	39 5	35 1	31 3
32	0.254	89.0	79 1	70.4	62.6	55.7	49.6	44.1	39.2	34.9	31.1
33	0.255	88.9	79.1	70.3	62.5	55.6	49.4	43.9	39.1	34.8	30.9
34	0.256	88.9	79 0	70.2	62.4	55.5	49.3	43.8	38 9	34.5	30.8
35	0.257	88.8	78.9	70.1	62.3	55.3	49.2	43.7	38.8	34 4	30 5
36	0.258	88.8	78.9	70.0	62.2	55.2	49.0	43.5	38.7	34.3	30.4

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)									
		200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
37	0 260	88.7	78.7	69.8	61.9	55.0	48.8	43.3	38.4	33 9	30.2
38	0.262	88.6	78 6	69.6	61.8	54.7	48.5	43.0	38.1	33.7	29.9
39	0 264	88.6	78.4	69.4	61.5	54 5	48.2	42.7	37.8	33.5	29.7
40	0.265	88.5	78 3	69.3	61.4	54 3	48.1	42.6	37.7	33.2	29.4
41	0 266	88.5	78.3	69.3	61 3	54.2	48.0	42.4	37.5	33 1	29 3
42	0.267	88 4	78 2	69.2	61.2	54.1	47.8	42.3	37.4	33.0	29.2
43	0 269	88.3	78.0	69.0	60.9	53 8	47.6	42.0	37.1	32 8	28.9
44	0.270	88 3	78 0	68.9	60.8	53.7	47.4	41.9	37.0	32.7	28.8
45	0 272	88.2	77.8	68.7	60.6	53.5	47.2	41.6	36.7	32 3	28.6
46	0.274	88.1	77 7	68.5	60.4	53.2	46.9	41.3	36.4	32.1	28.3
47	0 275	88.0	77.6	68.4	60.3	53.1	46.8	41.2	36 3	32 0	28 2
48	0.276	88.1	77.6	68.3	60.1	53.0	46.6	41.1	36 2	31.8	28.0
49	0.278	88.0	77.4	68.1	59 9	52.7	46.4	40.8	35.9	31 5	27.7
50	0.279	87.9	77 3	68.0	59.8	52.6	46.3	40.7	35.8	31.4	27.6
51	0.281	87.9	77.2	67.8	59.6	52.4	46.0	40.4	35.5	31 2	27.4
52	0 282	87.8	77 1	67.7	59.5	52.2	45.9	40.3	35.4	31.1	27.2
53	0 283	87.8	77.1	67.6	59.4	52.1	45.7	40.2	35.3	30 9	27.1
54	0.284	87.7	77 0	67.5	59.3	52.0	45.6	40.0	35.1	30.8	27.0
55	0 285	87.6	76.9	67.5	59 2	51.9	45.5	39.9	35.0	30.6	26.9
56	0.286	87.7	76.8	67.4	59.1	51.8	45.4	40.0	34.9	30.5	26.8
57	0.287	87.6	76.8	67.3	58 9	51.6	45.2	39.6	34.7	30 4	26 6
58	0.290	87.5	76.6	67 0	58.6	51.3	44 9	39.3	34.4	30.0	26.3
59	0.292	87.4	76.4	66.8	58.4	51.1	44.6	39.0	34 1	29 8	26 1
60	0.294	87 3	76 3	66 6	58 2	50.8	44.4	38.8	33.9	29.6	25.8
61	0.295	87 3	76.2	66.5	58.1	50.7	44.3	38.6	33.7	29.4	25.7
62	0.297	87.2	76 1	66.3	57 9	50.5	44.0	38.4	33.5	29.1	25.5
63	0.298	87.2	76.0	66.3	57 8	50 3	43.9	38.3	33.4	29 0	25 3
64	0.299	87 1	75 9	66 2	57 7	50.2	43 8	38.1	33.2	28.9	25.2
65	0.300	87.1	75.9	66.1	57.5	50.1	43.7	38.0	33.1	28.8	25.1
66	0.301	87 1	75 8	66.0	57 4	50.0	43 5	37.9	33.0	28.7	25.0
67	0.302	87.0	75 7	65.9	57 3	49 9	43 4	37.8	32.9	28.6	24 9
68	0.2025	87.0	75.7	65.8	57 3	49.8	43 4	37.7	32.8	28.5	24.8
69	0.303	87.0	75.6	65.8	57.2	49.8	43.3	37.7	32 7	28.5	24.8
70	0.3035	87.0	75 6	65.8	57 2	49.7	43.2	37.6	32.7	28.4	24.7

Fig. 14. Transfer efficiency (%) 3-1/8" 50-ohm line.

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)								
		200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
2	0.050	97.7	95.5	93.4	91.3	89.2	87.2	85.2	83.3	81.4	79.5
3	0.052	97.6	95.3	93.0	90.8	88.7	86.5	84.5	82.5	80.5	78.6
4	0.055	97.5	95.1	92.7	90.4	88.2	86.0	83.8	81.7	79.7	77.7
5	0.059	97.3	94.7	92.2	89.8	87.4	85.0	82.8	80.6	78.4	76.3
6	0.061	97.2	94.5	91.9	89.4	86.9	84.5	82.2	79.9	77.7	75.5
FM	0.066	97.0	94.1	91.3	88.6	86.0	83.4	81.0	78.6	76.2	74.0
7	0.089	96.0	92.2	88.5	84.9	81.6	78.3	75.2	72.2	69.3	66.5
8	0.090	95.9	92.0	88.3	84.7	81.3	78.0	74.8	71.8	68.8	66.0
9	0.092	95.9	91.9	88.1	84.5	81.0	77.6	74.4	71.4	68.4	65.6
10	0.093	95.8	91.8	87.9	84.3	80.7	77.3	74.1	71.0	68.0	65.2
11	0.094	95.7	91.7	87.8	84.0	80.4	77.0	73.7	70.6	67.6	64.7
12	0.096	95.7	91.5	87.6	83.8	80.2	76.7	73.4	70.2	67.2	64.3
13	0.097	95.6	91.4	87.4	83.6	79.9	76.4	73.1	69.9	66.8	63.9
14	0.146	93.5	87.4	81.7	76.4	71.4	66.8	62.4	58.4	54.6	51.0
15	0.147	93.4	87.3	81.6	76.3	71.3	66.6	62.2	58.2	54.3	50.8
16	0.148	93.4	87.3	81.5	76.1	71.1	66.4	62.0	58.0	54.1	50.6
17	0.149	93.4	87.2	81.4	76.0	71.0	66.3	61.9	57.8	53.9	50.4
18	0.150	93.3	87.1	81.3	75.9	70.8	66.1	61.7	57.6	53.7	50.1
19	0.151	93.3	87.0	81.2	75.7	70.7	65.9	61.5	57.4	53.5	49.9
20	0.152	93.3	87.0	81.1	75.6	70.5	65.7	61.3	57.2	53.3	49.7
21	0.153	93.2	86.9	81.0	75.5	70.4	65.6	61.1	57.0	53.1	49.5
22	0.154	93.2	86.8	80.9	75.4	70.2	65.4	61.0	56.8	52.9	49.3
23	0.154	93.1	86.7	80.8	75.2	70.1	65.3	60.8	56.6	52.7	49.1
24	0.155	93.1	86.7	80.7	75.1	69.9	65.1	60.6	56.4	52.5	48.9
25	0.156	93.1	86.6	80.6	75.0	69.8	64.9	60.4	56.2	52.3	48.7
26	0.157	93.0	86.5	80.5	74.9	69.6	64.8	60.3	56.1	52.1	48.5
27	0.158	93.0	86.5	80.4	74.7	69.5	64.6	60.1	55.9	51.9	48.3
28	0.159	92.9	86.4	80.3	74.6	69.4	64.5	59.9	55.7	51.8	48.1
29	0.160	92.9	86.3	80.2	74.5	69.2	64.3	59.7	55.5	51.6	47.9
30	0.161	92.9	86.2	80.1	74.4	69.1	64.2	59.6	55.3	51.4	47.7
31	0.161	92.8	86.2	80.0	74.3	68.9	64.0	59.4	55.2	51.2	47.5
32	0.162	92.8	86.1	79.9	74.2	68.8	63.9	59.3	55.0	51.0	47.3
33	0.163	92.8	86.0	79.8	74.0	68.7	63.7	59.1	54.8	50.8	47.2
34	0.164	92.7	86.0	79.7	73.9	68.5	63.6	58.9	54.6	50.7	47.0
35	0.165	92.7	85.9	79.6	73.8	68.4	63.4	58.8	54.5	50.5	46.8

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)									
		200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
36	0.166	92.7	85.8	79.5	73.7	68.3	63.3	58.6	54.3	50.3	46.6
37	0.167	92.6	85.8	79.4	73.6	68.1	63.1	58.5	54.1	50.1	46.4
38	0.167	92.6	85.7	79.4	73.5	68.0	63.0	58.3	54.0	50.0	46.3
39	0.168	92.5	85.6	79.3	73.4	67.9	62.8	58.1	53.8	49.8	46.1
40	0.169	92.5	85.6	79.2	73.2	67.8	62.7	58.0	53.6	49.6	45.9
41	0.170	92.5	85.5	79.1	73.1	67.6	62.5	57.8	53.5	49.5	45.7
42	0.171	92.4	85.5	79.0	73.0	67.5	62.4	57.7	53.3	49.3	45.6
43	0.172	92.4	85.4	78.9	72.9	67.4	62.3	57.5	53.2	49.1	45.4
44	0.172	92.4	85.3	78.8	72.8	67.2	62.1	56.4	53.0	49.0	45.2
45	0.173	92.3	85.3	78.7	72.7	67.1	62.0	57.2	52.8	48.8	45.1
46	0.174	92.3	85.2	78.6	72.6	67.0	61.8	57.1	52.7	48.6	44.9
47	0.175	92.3	85.1	78.6	72.5	66.9	61.7	56.9	52.5	48.5	44.7
48	0.176	92.2	85.1	78.5	72.4	66.8	61.6	56.8	52.4	48.3	44.6
49	0.176	92.2	85.0	78.4	72.3	66.6	61.4	56.6	52.2	48.2	44.4
50	0.177	92.2	84.9	78.3	72.2	66.5	61.3	56.5	52.1	48.0	44.2
51	0.178	92.1	84.9	78.2	72.1	66.4	61.2	56.4	51.9	47.8	44.1
52	0.179	92.1	84.8	78.1	72.0	66.3	61.0	56.2	51.8	47.7	43.9
53	0.179	9.21	84.8	78.0	71.9	66.2	60.9	56.1	51.6	47.5	43.8
54	0.180	92.0	84.7	78.0	71.8	66.0	60.8	55.9	51.5	47.4	43.6
55	0.181	92.0	84.6	77.9	71.6	65.9	60.6	55.8	51.3	47.2	43.5
56	0.182	92.0	84.6	77.8	71.5	65.8	60.5	55.7	51.2	47.1	43.3
57	0.183	91.9	84.5	77.7	71.4	65.7	60.4	55.5	51.0	46.9	43.1
58	0.183	91.9	84.5	77.6	71.3	65.6	60.3	55.4	50.9	46.8	43.0
59	0.184	91.9	84.4	77.5	71.2	65.5	60.1	55.3	50.8	46.6	42.8
60	0.185	91.8	84.3	77.5	71.1	65.3	60.0	55.1	50.6	46.5	42.7
61	0.186	91.8	84.3	77.4	71.0	65.2	59.9	55.0	50.5	46.3	42.5
62	0.186	91.8	84.2	77.3	71.0	65.1	59.8	54.8	50.3	46.2	42.4
63	0.187	91.7	84.2	77.2	70.9	65.0	59.6	54.7	50.2	46.1	42.3
64	0.188	91.7	84.1	77.1	70.8	64.9	59.5	54.6	50.1	45.9	42.1
65	0.189	91.7	84.1	77.1	70.7	64.8	59.4	54.5	49.9	45.8	42.0
66	0.189	91.7	84.0	77.0	70.6	64.7	59.3	54.3	49.8	45.6	41.8
67	0.190	91.6	83.9	76.9	70.5	64.6	59.2	54.2	49.7	45.5	41.7
68	0.191	91.6	83.9	76.8	70.4	64.5	59.0	54.1	49.5	45.4	41.5
69	0.191	91.6	83.8	76.8	70.3	64.3	58.9	53.9	49.4	45.2	41.4
70	0.192	91.5	83.8	76.7	70.2	64.2	58.8	53.8	49.3	45.1	41.3

Fig. 15. Transfer efficiency (%) 4-1/16" 50-ohm.

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)									
		200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
2	0.039	98.2	96.4	94.7	93.0	91.4	89.7	88.1	86.5	85.0	83.5
3	0.041	98.1	96.3	94.5	92.7	90.9	89.2	87.5	85.9	84.3	82.7
4	0.043	98.0	96.1	94.2	92.4	90.5	88.7	87.0	85.3	83.6	82.0
5	0.046	97.9	95.8	93.8	91.8	89.9	88.0	86.2	84.3	82.6	80.8
6	0.048	97.8	95.7	93.6	91.5	89.5	87.6	85.7	83.8	82.0	80.2
FM	0.051	97.7	95.4	93.1	91 0	88.8	86.7	84.7	82.7	80.8	78.9
7	0.069	96.9	93.8	90.9	88.0	85.3	82.6	80.0	77.5	75.1	72.7
8	0.070	96.8	93.7	90.7	87.8	85.0	82.3	79.7	77.2	74.7	72.3
9	0.071	96.8	93.6	90.6	87.7	84.8	82.1	79.4	76.8	74.4	71.9
10	0.073	96.7	93.5	90.5	87.5	84.6	81.8	79.1	76.5	74.0	71.6
11	0.074	96.7	93.4	90.3	87.3	84.4	81.6	78.8	76.2	73.7	71.2
12	0.075	96.6	93.3	90.2	87.1	84.2	81.4	78.6	75.9	73.3	70.9
13	0.076	96.6	93.2	90.0	87.0	84.0	81.1	78.3	75.6	73.0	70.5
14	0.113	94.9	90.1	85.5	81.2	77.1	73.2	69.4	65.9	62.6	59.4
15	0.114	94.9	90.0	85 5	81.1	76.9	73.0	69.3	65.8	62.4	59.2
16	0.115	94.9	90.0	95.4	81.0	76.8	72.9	69.1	65.6	62.2	59.0
17	0.115	94.8	89.9	85.3	80.9	76.7	72.7	69.0	65.4	62.0	58.8
18	0.116	94.8	89.9	85.2	80.8	76.6	72.6	68.8	65.2	61.8	58.6
19	0.117	94.8	89.8	85.1	80.7	76.4	72.5	68.7	65.1	61.7	58.4
20	0.117	94.7	89.8	85.0	80.6	76.3	72.3	68.5	64.9	61.5	58.3
21	0.118	94.7	89.7	85.0	80.5	76.2	72.2	68.4	64.7	61.3	58.1
22	0.119	94.7	89.6	84.9	80.4	76.1	72.0	68.2	64.6	61.1	57.9
23	0.119	94.7	89.6	84.8	80.3	76.0	71.9	68.1	64.4	61.0	57.7
24	0.120	94.6	89.5	84.7	80.2	75.8	71.8	67.9	64.3	60.8	57.5
25	0.121	94.6	89.5	84.6	80.1	75.7	71.6	67.8	64.1	60.6	57.4
26	0.121	94.6	89.4	84.6	80.0	75.6	71.5	67.6	63.9	60.5	57.2
27	0.122	94.5	89.4	84.5	79.9	75.5	71.4	67.5	63.8	60.3	57.0
28	0.123	94.5	89.3	84.4	79.8	75.4	71.2	67.3	63.6	60.1	56.8
29	0.123	94.5	89.3	84.3	79.7	75.3	71.1	67.2	63.5	60.0	56.7
30	0.124	94.4	89.2	84.3	79.6	75.2	71.0	67.0	63.3	59.8	56.5
31	0.125	94.4	89.2	84.2	79.5	75.0	70.9	66.9	63.2	59.6	56.3
32	0.125	94.4	89.1	84.1	79.4	74.9	70.7	66.8	63.0	59.5	56.1
33	0.126	94.4	89.0	84.0	79.3	74.8	70.6	66.6	62.9	59.3	56.0
34	0.127	94.3	89.0	84.0	79.2	74.7	70.5	66.5	62.7	59.2	55.8
35	0.127	94.3	88.9	83.9	79.1	74.6	70.4	66.3	62.6	59.0	55.7
36	0.128	94 3	88.9	83 8	79.0	74.5	70.2	66.2	62.4	58.9	55 5
37	0.129	94.3	88 8	83.7	78.9	74.4	70.1	66.1	62.3	58 7	55.3
38	0.129	94.2	88.8	83 7	78.8	74.3	70.0	65.9	62.1	58.5	55.2
39	0.130	94.2	88 7	83.6	78.7	74.2	69.9	65.8	62.0	58.4	55.0
40	0 130	94 2	88.7	83 5	78.6	74.1	69.7	65.7	61.8	58.2	54 8
41	0.131	94.1	88 6	83.4	78.6	74.0	69.6	65.5	61.7	58.1	54.7
42	0.132	94 1	88.6	83.4	78.5	73.8	69.5	65.4	61.6	57.9	54.5
43	0.132	94.1	88 5	83.3	78.4	73.7	69.4	65.3	61.4	57.8	54.4
44	0 133	94.1	88.5	83 2	78.3	73.6	69.3	65.2	61.3	57.7	54 2
45	0 133	94.0	88.4	83.2	78.2	73.5	69.2	65.0	61.2	57 5	54.1
46	0.134	94.0	88.4	83.1	78.1	73.4	69.0	64.9	61.0	57.4	53 9
47	0.135	94.0	88 3	83.0	78.0	73.3	68.9	64.8	60.9	57 2	53.8
48	0.135	94.0	88.3	83.0	77.9	73.2	68.8	64.7	60.7	57.1	53.6
49	0.136	93.9	88.2	82.9	77.9	73.1	68.7	64.5	60.6	56.9	53.5
50	0.136	93.9	88.2	82.8	77.8	73.0	68.6	64.4	60.5	56.8	53 3
51	0.137	93.9	88.1	82.7	77.7	72.9	68.5	64.3	60.3	56.7	53.2
52	0.138	93.9	88.1	82 7	77.6	72.8	68.4	64.2	60.2	56.5	53.0
53	0.138	93.8	88.0	82.6	77.5	72.7	68.2	64.0	60.1	56 4	52.9
54	0.139	93.8	88.0	82 5	77.4	72.6	68.1	63.9	60.0	56.2	52.8
55	0.139	93.8	87.9	82.5	77.3	72.5	68.0	63.8	59.8	56.1	52.6
56	0.140	93.8	87.9	82 4	77.3	72.4	67.9	63.7	59.7	56.0	52.5
57	0.141	93.7	87.9	82.3	77.2	72.3	67.8	63.6	59.6	55.8	52.3
58	0.141	93.7	87.8	82.3	77.1	72 2	67.7	63.4	59.4	55.7	52.2
59	0.142	93.7	87.8	82.2	77.0	72.2	67.6	63.3	59.3	55.6	52.1
60	0.142	93.7	87 7	82.2	76.9	72.1	67.5	63.2	59.2	55 4	51.9
61	0.143	93.6	87.7	82.1	76.9	72.0	67.4	63.1	59.1	55.3	51.8
62	0.143	93.6	87.6	82.0	76.8	71.9	67.3	63.0	58.9	55.2	51.7
63	0.144	93.6	87.6	82.0	76.7	71.8	67.2	62.9	58.8	55.1	51.5
64	0.145	93.6	87.5	81.9	76.6	71.7	67.1	62.7	58.7	54.9	51.4
65	0.145	93.5	87.5	81.8	76.5	71.6	67.0	62.6	58.6	54.8	51.3
66	0.146	93.5	87.4	81.8	76.5	71.5	66.9	62.5	58.5	54.7	51.1
67	0.146	93.5	87.4	81.7	76.4	71.4	66.8	62.4	58.3	54.5	51.0
68	0.147	93.5	87.4	81.6	76.3	71.3	66.7	62.3	58.2	54.4	50.9
69	0.147	93.4	87.3	81.6	76.2	71.2	66.6	62.2	58.1	54.3	50.7
70	0.148	93.4	87.3	81.5	76.2	71.1	66.5	62.1	58.0	54.2	50.6

Fig. 16. Transfer efficiency (%) 6-1/8" 50-ohm.

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)									
		200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
2	0.0339	98.5	96.9	95.4	94.1	92.5	91.1	89.6	88.3	86.8	85.5
3	0.0355	98.4	96.8	95.2	93.7	92.1	90.7	89.2	87.7	86.3	84.8
4	0.0372	98.3	96.6	95.0	93.4	91.8	90.2	88.7	87.2	85.7	84.2
5	0.040	98.2	96.4	94.6	92.9	91.2	89.5	87.9	86.3	84.6	83.1
6	0.0417	98.1	96.2	94.4	92.6	90.8	89.1	87.4	85.8	84.0	82.4
7	0.0615	97.1	94.5	91.8	89.4	86.7	84.4	82.0	79.7	77.4	75.1
8	0.0625	97.1	94.4	91.7	89.1	86.6	84.1	81.7	79.4	77.0	74.9
9	0.0635	97.0	94.3	91.6	88.9	86.4	83.9	81.5	79.1	76.8	74.6
10	0.0645	97.1	94.2	91.5	88.8	86.2	83.7	81.2	78.9	76.5	74.3
11	0.0655	97.0	94.1	91.4	88.6	86.0	83.5	81.0	78.6	76.4	73.9
12	0.0665	97.0	94.1	91.2	88.5	85.8	83.2	80.7	78.3	75.8	73.6
13	0.0675	96.9	94.0	91.1	88.3	85.6	83.0	80.4	78.0	75.5	73.2
14	0.105	95.3	90.8	86.5	82.4	78.5	74.8	71.3	67.9	64.6	61.6
15	0.106	95.2	90.7	86.4	82.3	78.4	74.6	71.1	67.7	64.4	61.4
16	0.107	95.2	90.6	86.3	82.1	78.2	74.4	70.8	67.4	64.1	61.1
17	0.1075	95.2	90.6	86.2	82.0	78.1	74.3	70.7	67.3	64.0	60.9
18	0.108	95.2	90.5	86.1	82.0	78.0	74.2	70.6	67.2	64.0	60.8
19	0.109	95.1	90.5	86.0	81.8	77.8	74.0	70.4	66.9	63.6	60.5
20	0.1095	95.1	90.4	86.0	81.7	77.7	73.9	70.3	66.8	63.5	60.3
21	0.110	95.1	90.4	85.9	81.7	77.6	73.8	70.2	66.7	63.3	60.2
22	0.111	95.0	90.3	85.8	81.5	77.5	73.6	70.0	66.4	63.0	60.0
23	0.112	95.0	90.2	85.7	81.4	77.3	73.4	69.7	66.2	62.8	59.7
24	0.113	94.9	90.1	85.5	81.2	77.1	73.2	69.5	65.9	62.5	59.4
25	0.1135	94.9	90.1	85.5	81.1	77.0	73.1	69.4	65.8	62.4	59.3
26	0.1140	94.9	90.0	85.4	81.1	76.9	73.0	69.3	65.7	62.4	59.1
27	0.1145	94.9	90.0	85.4	81.0	76.8	72.9	69.1	65.6	62.2	58.9
28	0.115	94.8	90.0	85.3	80.9	76.7	72.8	69.0	65.5	62.0	58.8
29	0.116	94.8	89.9	85.2	80.8	76.6	72.6	68.8	65.2	61.7	58.6
30	0.117	94.8	90.0	85.1	80.6	76.4	72.4	68.6	65.0	61.6	58.3
31	0.1175	94.7	89.7	85.0	80.5	76.3	72.3	68.5	64.9	61.4	58.2
32	0.118	94.7	89.7	85.0	80.5	76.2	72.2	68.4	64.7	61.2	58.0
33	0.1185	94.7	89.7	84.9	80.4	76.1	72.1	68.3	64.6	61.1	57.9
34	0.119	94.7	89.6	84.8	80.3	76.0	72.0	68.2	64.5	60.9	57.8
35	0.120	94.6	89.5	84.7	80.2	75.9	71.8	67.9	64.3	60.8	57.7
36	0.1205	94.6	89.5	84.7	80.1	75.8	71.7	67.8	64.2	60.7	57.4
37	0.121	84.6	89.5	84.6	80.0	75.7	71.6	67.7	64.0	60.5	57.3
38	0.1215	94.6	89.4	84.5	79.9	75.6	71.5	67.6	63.9	60.3	57.1
39	0.122	94.5	89.4	84.5	80.0	75.5	71.4	67.5	63.8	60.3	57.0
40	0.123	94.5	89.3	84.4	79.7	75.3	71.2	67.3	63.6	60.0	56.8
41	0.1235	94.5	89.2	84.3	79.6	75.2	71.0	67.1	63.4	59.9	56.5
42	0.124	94.5	89.2	84.3	79.6	75.2	71.0	67.1	63.3	59.7	56.5
43	0.1245	94.4	89.2	84.2	79.5	75.1	70.9	66.9	63.2	59.7	56.4
44	0.125	94.4	89.1	84.1	79.4	75.0	70.8	66.8	63.1	59.5	56.2
45	0.126	94.4	89.0	84.0	79.3	74.8	70.5	66.6	62.9	59.3	55.9
46	0.1265	94.3	89.0	84.0	79.2	74.7	70.0	66.5	62.7	59.1	55.8
47	0.127	94.3	89.0	83.9	79.1	74.6	70.4	66.4	62.6	59.1	55.6
48	0.128	94.3	88.9	83.8	79.0	74.0	70.2	66.2	62.4	58.8	55.3
49	0.129	94.2	88.8	83.7	78.9	74.3	70.0	66.0	62.2	58.5	55.2
50	0.130	94.2	88.7	83.6	78.7	74.1	69.8	65.8	61.9	58.3	54.9
51	0.1305	94.2	88.7	83.5	78.6	74.0	69.7	65.7	61.8	58.2	54.7
52	0.131	94.1	88.6	83.4	78.6	74.0	69.6	65.6	61.7	58.0	54.7
53	0.132	94.1	88.5	83.3	78.4	73.8	69.4	65.3	61.5	57.9	54.4
54	0.1325	94.1	88.5	83.3	78.3	73.7	69.3	65.2	61.4	57.7	54.3
55	0.133	94.1	88.5	83.2	78.3	73.6	69.3	65.1	61.3	57.6	54.1
56	0.1335	94.0	88.4	83.2	78.1	73.5	69.1	65.0	61.2	57.4	54.0
57	0.134	94.0	88.4	83.1	78.1	73.5	69.1	64.9	61.0	57.4	54.0
58	0.1345	94.0	88.3	83.0	78.0	73.4	69.0	64.8	60.9	57.3	53.8
59	0.135	94.0	88.3	83.0	78.0	73.3	68.9	64.7	60.8	57.1	53.7
60	0.136	93.9	88.2	82.9	77.8	73.1	68.7	64.5	60.6	56.8	53.4
61	0.1365	93.9	88.2	82.8	77.8	73.0	68.6	64.4	60.5	56.8	53.2
62	0.137	93.9	88.1	82.8	77.7	72.9	68.5	64.3	60.4	56.8	53.1
63	0.1375	93.9	88.1	82.7	77.6	72.9	68.4	64.2	60.3	56.5	53.1
64	0.138	93.8	88.1	82.6	77.6	72.8	68.3	64.1	60.2	56.4	52.9
65	0.1385	93.8	88.0	82.6	77.5	72.7	68.2	64.0	60.0	56.2	52.8
66	0.139	93.8	88.0	82.5	77.4	72.6	68.1	63.9	60.0	56.2	52.7
67	0.140	93.8	87.9	82.4	77.3	72.4	67.9	63.7	59.7	55.9	52.4
68	0.141	93.7	87.8	82.3	77.1	72.3	67.7	63.5	59.5	55.8	52.3
69	0.1415	93.7	87.8	82.2	77.1	72.2	67.6	63.4	59.4	55.6	52.1
70	0.142	93.7	87.7	82.2	77.0	72.1	67.5	63.3	59.3	55.5	52.0

Fig. 17. Transfer efficiency (%) 6-1/8" 75-ohm.

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)							
		800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)	2200 (670.6)
14	0.0789	86.5	83.4	80.4	77.5	74.8	72.1	69.5	67.0
15	0.0794	86.4	83.3	80.3	77.4	74.6	72.0	69.4	66.9
16	0.0799	86.3	83.2	80.2	77.3	74.5	71.8	69.2	66.7
17	0.0804	86.2	83.1	80.1	77.2	74.4	71.7	69.0	66.5
18	0.0809	86.2	83.0	80.0	77.0	74.2	71.5	68.9	66.4
19	0.0814	86.1	82.9	79.9	76.9	74.1	71.4	68.7	66.2
20	0.0819	86.0	82.8	79.7	76.8	74.0	71.2	68.6	66.0
21	0.0824	85.9	82.7	79.6	76.7	73.8	71.1	68.4	65.9
22	0.0829	85.8	82.6	79.5	76.6	73.7	70.9	68.3	65.7
23	0.0833	85.8	82.5	79.4	76.4	73.6	70.8	68.1	65.6
24	0.0838	85.7	82.4	79.3	76.3	73.4	70.7	68.0	65.4
25	0.0843	85.6	82.4	79.2	76.2	73.3	70.5	67.8	65.2
26	0.0848	85.5	82.3	79.1	76.1	73.2	70.4	67.7	65.1
27	0.0852	85.5	82.2	79.0	76.0	73.1	70.2	67.5	64.9
28	0.0857	85.4	82.1	78.9	75.9	72.9	70.1	67.4	64.8
29	0.0862	85.3	82.0	78.8	75.8	72.8	70.0	67.3	64.6
30	0.0866	85.3	81.9	78.7	75.6	72.7	69.8	67.1	64.5
31	0.0871	85.2	81.8	78.6	75.5	72.6	69.7	67.0	64.3
32	0.0875	85.1	81.7	78.5	75.4	72.4	69.6	66.8	64.2
33	0.0880	85.0	81.7	78.4	75.3	72.3	69.4	66.7	64.0
34	0.0884	85.0	81.6	78.3	75.2	72.2	69.3	66.5	63.9
35	0.0889	84.9	81.5	78.2	75.1	72.1	69.2	66.4	63.7
36	0.0893	84.8	81.4	78.1	75.0	72.0	69.1	66.3	63.6
37	0.0898	84.8	81.3	78.0	74.9	71.8	68.9	66.1	63.5
38	0.0902	84.7	81.2	77.9	74.8	71.7	68.8	66.0	63.3
39	0.0906	84.6	81.2	77.8	74.7	71.6	68.7	65.9	63.2
40	0.0911	84.6	81.1	77.7	74.6	71.5	68.6	65.7	63.0
41	0.0915	84.5	81.0	77.7	74.5	71.4	68.4	65.6	62.9
42	0.0920	84.4	80.9	77.6	74.3	71.3	68.3	65.5	62.8
43	0.0924	84.4	80.8	77.5	74.2	71.2	68.2	65.3	62.6
44	0.0928	84.3	80.8	77.4	74.1	71.0	68.1	65.2	62.5
45	0.0932	84.2	80.7	77.3	74.0	70.9	67.9	65.1	62.4
46	0.0937	84.2	80.6	77.2	73.9	70.8	67.8	65.0	62.2
47	0.0941	84.1	80.5	77.1	73.8	70.7	67.7	64.8	62.1
48	0.0945	84.0	80.4	77.0	73.7	70.6	67.6	64.7	62.0
49	0.0949	84.0	80.4	76.9	73.6	70.5	67.5	64.6	61.8
50	0.0954	83.9	80.3	76.8	73.5	70.4	67.4	64.5	61.7
51	0.0958	83.8	80.2	76.8	73.4	70.3	67.2	64.3	61.6
52	0.0962	83.8	80.1	76.7	73.3	70.2	67.1	64.2	61.4
53	0.0966	83.7	80.1	76.6	73.2	70.1	67.0	64.1	61.3
54	0.0970	83.6	80.0	76.5	73.1	70.0	66.9	64.0	61.2
55	0.0974	83.6	79.9	76.4	73.1	69.8	66.8	63.9	61.1
56	0.0978	83.5	79.8	76.3	73.0	69.7	66.7	63.7	60.9

Fig. 18. Transfer efficiency (%) 8-3/16" 75-ohm line.

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)							
		800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)	2200 (670.6)
14	0.0682	88.2	85.5	82.8	80.3	77.8	75.4	73.1	70.8
15	0.0686	88.1	85.4	82.7	80.2	77.7	75.3	72.9	70.6
16	0.0690	88.1	85.3	82.6	80.0	77.5	75.1	72.8	70.5
17	0.0695	88.0	85.2	82.5	79.9	77.4	75.0	72.6	70.3
18	0.0699	87.9	85.1	82.4	79.8	77.3	74.9	72.5	70.2
19	0.0703	87.9	85.1	82.3	79.7	77.2	74.7	72.3	70.0
20	0.0707	87.8	85.0	82.2	79.6	77.1	74.6	72.2	69.9
21	0.0712	87.7	84.9	82.2	79.5	76.9	74.5	72.1	69.7
22	0.0716	87.6	84.8	82.1	79.4	76.8	74.3	71.9	69.6
23	0.0720	87.6	84.7	82.0	79.3	76.7	74.2	71.8	69.4
24	0.0724	87.5	84.6	81.9	79.2	76.6	74.1	71.6	69.3
25	0.0728	87.4	84.6	81.8	79.1	76.5	74.0	71.5	69.2
26	0.0732	87.4	84.5	81.7	79.0	76.4	73.8	71.4	69.0
27	0.0736	87.3	84.4	81.6	78.9	76.2	73.7	71.2	68.9
28	0.0740	87.3	84.3	81.5	78.8	76.1	73.6	71.1	68.7
29	0.0744	87.2	84.3	81.4	78.7	76.0	73.5	71.0	68.6
30	0.0748	87.1	84.2	81.3	78.6	75.9	73.3	70.9	68.5
31	0.0752	87.1	84.1	81.2	78.5	75.8	73.2	70.7	68.3
32	0.0756	87.0	84.0	81.1	78.4	75.7	73.1	70.6	68.2
33	0.0760	86.9	83.9	81.1	78.3	75.6	73.0	70.5	68.0
34	0.0764	86.9	83.9	81.0	78.2	75.5	72.9	70.3	67.9
35	0.0768	86.8	83.8	80.9	78.1	75.4	72.7	70.2	67.8
36	0.0772	86.8	83.7	80.8	78.0	75.3	72.6	70.1	67.6
37	0.0775	86.7	83.6	80.7	77.9	75.2	72.5	70.0	67.5
38	0.0779	86.6	83.6	80.6	77.8	75.0	72.4	69.8	67.4
39	0.0783	86.6	83.5	80.5	77.7	74.9	72.3	69.7	67.3
40	0.0787	86.5	83.4	80.5	77.6	74.8	72.2	69.6	67.1

Fig. 19. Transfer efficiency (%) 9-3/16" 75-ohm line.

Vertical Run Considerations

Provision must be made to accommodate the difference in expansion coefficients between the copper of the line and the steel of the tower. Copper temperature rise due to RF heating as well as ambient temperature changes must be taken into account. In the vertical run this is accomplished by fixing the line at the tower top and "floating" it down the tower on spring hangers with expansion accumulating at the bottom of the tower. To accommodate for this movement, the length of the horizontal run must be as specified in Fig. 20. In addition, the minimum distance from the horizontal run to the first vertical support ring must be maintained as specified in Fig. 21 to accommodate for movement of the horizontal run.

Generally, only standard lengths should be included in the vertical run except at the top where a field-cut section is utilized. However, one or two special lengths may be inserted if it permits a better pattern of hangers. Positions of flanges relative to hangers, guide rings and tower members must be carefully planned to avoid interference as the line moves relative to the tower. Where interference between line flanges and spring hangers may occur due to a particular spacing of tower horizontal members, a steel plate may be used to mount the hanger a sufficient distance above or below the flange to avoid such interference.

Ideally, spring hangers supporting the vertical run of transmission line should occur every 10 feet (3.1 m); however minor variations may be

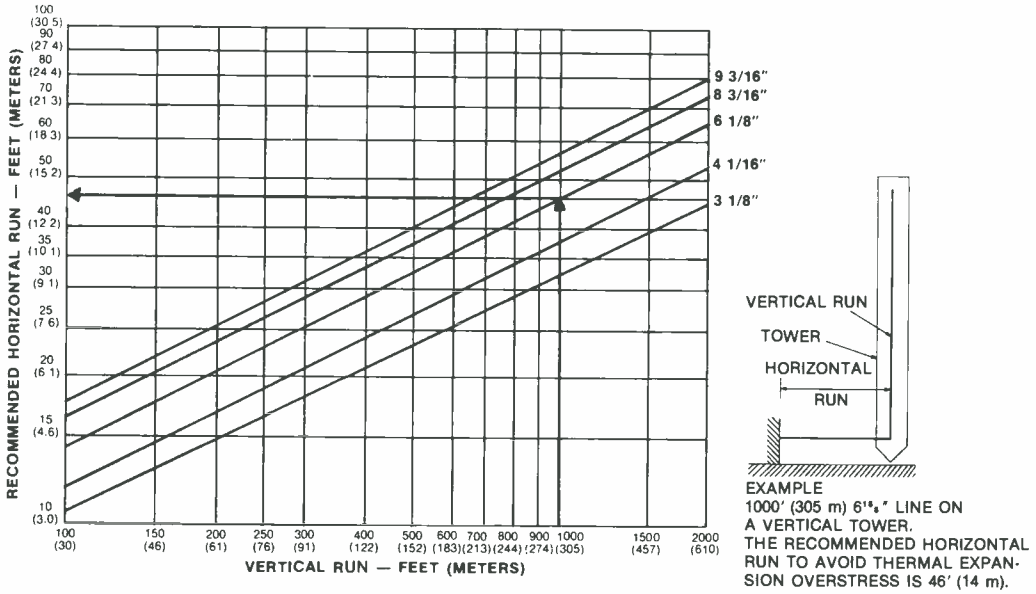


Fig. 20. Recommended horizontal run.

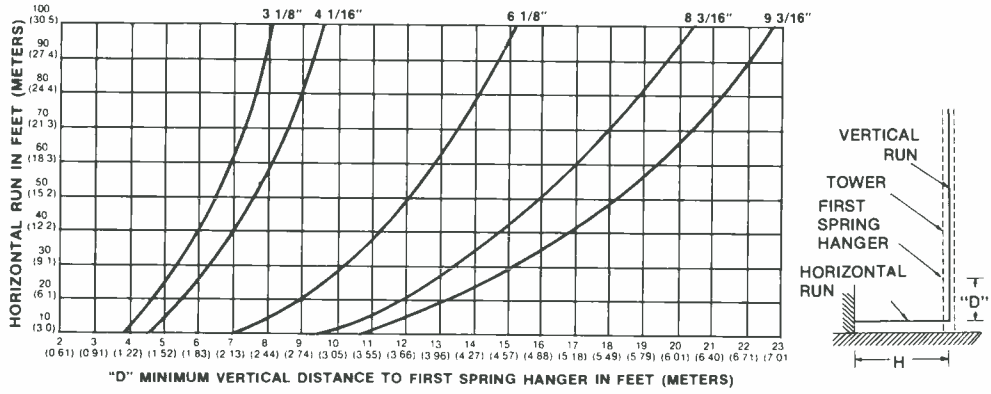


Fig. 21. Minimum distance to first support ring vs. horizontal run length.

used provided an average of one hanger for each 10 feet of line is maintained. The vertical portion of line near the top of the run should be anchored firmly using the appropriate fixed hanger(s). Spring-loading charts are used to set spring tensions of expansion hangers. As finally installed, the line must be vertical and free to move in the hanger guides, and the tower must be designed to keep the vertical hangers perpendicular to the line and the fixed hanger(s) from moving. When installing transmission line, the preferred method is to start at the bottom and work toward the top. The transmission line must be mounted with the anchor insulator of each section in the "up" position.

In most cases, the elbow which joins the vertical and horizontal runs should be a reinforced type.

Horizontal Run Considerations

In complex horizontal-line layouts involving elevation and direction changes, care must be exercised not to overstress mitre elbows or introduce excessive flexing of the line. Back-to-back elbows may be used to achieve desired vertical and horizontal angles.

As stated previously, the horizontal run should be at least as long as indicated in Fig. 20 to allow for sufficient movement due to expansion of the vertical run. Adequate bending of the vertical line to allow for movement of the horizontal run is assured by proper placement of the first vertical supporting ring as specified in Fig. 21. Three-point-suspension spring hangers should be used in the horizontal run for at least the distance shown in Fig. 20. Beyond the minimum distance specified, horizontal roller assemblies or swivel hangers may be used to support the line. Where several lines are in close proximity, special provision may be required to prevent lateral movement while allowing vertical movement. The line should be secured at the wall of the building using a horizontal anchor plate. Lines should be protected from falling ice.

Indoor Installation Considerations

The indoor part of the transmission line is normally not pressured. Therefore, a Gas Stop is installed inside the building wall, and unpressurized line components are used between that point and the output of the transmitter. The arrangement permits disconnection of the ungassed portion of the line anywhere before the Gas Stop without loss of pressure in the outside line.

Purging Moisture From New Line

A transmission line installation must be free of moisture before power is applied since operating a line with moisture inside is likely to cause substantial damage. If moisture is suspected, the uppermost part of the line should be opened by using the petcock supplied or by slightly loosening the most-distant flange. The line should then be bled with dry (oil-pumped) nitrogen. Lines should be continuously pressurized from a nitrogen or a dry-air source. After any complete loss of pressure where moisture may have entered, the line should be purged before it is again placed in use.

WAVEGUIDE TRANSMISSION LINE

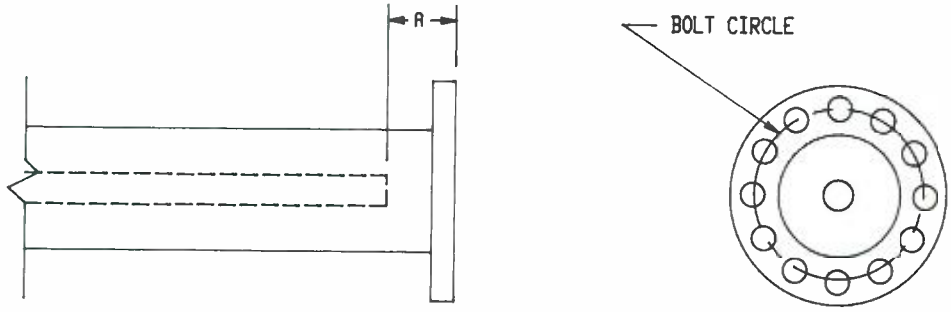
Any enclosure that restrains the electric magnetic fields and directs the flow of energy is a form of waveguide. In a sense, coaxial line is a form of waveguide, however, in the chapter when we refer to waveguide we are referring to a hollow tube waveguide. Which either takes the form of a hollow rectangular metal pipe with an approximate height to width ratio of 1 to 2 or a hollow circular pipe of varying diameters. Each commonly accepted form of transmission line has certain features which makes its use more advantageous over other types of transmission systems. Waveguide offers the following advantages:

1. Its simple construction with no inner conductor makes it less susceptible to distortion due to shock vibration due to shipment installation and operation.
2. Since there are no supports and the waveguide is air filled, there is very little dielectric loss and attenuation is minimized. The physical parameters of the waveguide are such that for dominant mode operation, the dimensional separation in waveguide minimizes charge concentration thus resulting in reduced electric field intensity as compared to coaxial transmission line.
3. The large cross sectional surface area provides for high power handling capacity. Consequently waveguide will handle all the significant power the broadcast industry is presently generating for any station or groups of stations in the U.S.

Due to its large size and lower attenuation, hollow tube waveguide will run with considerably less temperature rise for given power level than any of the coaxial lines. The major draw back for putting waveguide on the tower is the size waveguide which is generally larger than most coaxial lines and hence, you have an increase wind load which in some cases i.e., existing towers, could be a problem.

Circular Waveguide

The newest member of the high power transmission line family for broadcast industry, is Cir-



T/L SIZE	IMPEDANCE IN OHMS	APPROX. WT. U.S.	APPROX. WT. METRIC	GENERAL SPECIFICATIONS OUTER OD	OUTER ID	INNER OD	INNER ID	A	BOLT SIZE	BOLT CIRCLE	NO. OF BOLTS
1 5/8	50	27 LB	(12.2 kg)	1.625" (41 mm)	1.527" (38 mm)	0.664" (17 mm)	0.588" (15 mm)	.777±.03	5/16	2.812	4
3 1/8	50	60 LB	(26.8 kg)	3.125" (79 mm)	3.027" (77 mm)	1.315" (33 mm)	1.231" (31 mm)	1.00±.03	3/8	4.375	6
4 1/16	50	110 LB	(49.9 kg)	4.062" (103 mm)	3.935" (110 mm)	1.711" (43 mm)	1.661" (42 mm)	1.22±.03	3/8	5.375	8
6 1/8	50	145 LB	(65.8 kg)	6.125" (156 mm)	5.981" (152 mm)	2.600" (66 mm)	2.520" (64 mm)	1.28±.03	3/8	7.375	12
6 1/8	75	140 LB	(63.5 kg)	6.125" (156 mm)	5.981" (152 mm)	1.711" (43 mm)	1.666" (42 mm)	1.400±.03	3/8	7.375	12
8 3/16	75	192 LB	(87 kg)	8.150" (207 mm)	8.000" (203 mm)	2.293" (58 mm)	2.229" (57 mm)	1.80±.06	3/8	10.312	18
9 3/16	75	229 LB	(103 kg)	9.166" (233 mm)	9.000" (229 mm)	2.598" (66 mm)	2.516" (64 mm)	1.81±.03	3/8	11.312	20

Fig. 22. Mechanical dimensions of rigid coaxial line.

cular Waveguide. This has come about as a natural extension of rectangular waveguide with an effort to reduce windloading on the tower. A typical installation is shown in Fig. 24. Circular Waveguide has been in use for a number of years at much higher frequency, however, it has only been in the last few years that installations have been attempting high power UHF broadcast. Consequently, the transmission line does not have a proven track record in the broadcast field. In general it has all the attributes of any hollow tube waveguide transmission system and in theory should prove to be a viable transmission system.

Fig. 24 shows a typical installation with components noted beside the layout. Fig. 25 lists a typical set of attenuation and average power ratings for three sizes of circular waveguide. Fig. 26 shows one manufacturer recommendation for horizontal vs. vertical length as a function of temperature. It should be noted that field experience on installation of circular waveguide is minimal and the mechanical configuration of the waveguide on the tower should be defined by the manufacturer of the waveguide.

Rectangular Waveguide

Rectangular waveguide has been used in high power UHF broadcast since the mid-Fifties, however, it has only been since the mid-Seventies that any reasonable amount of use has occured depending on the content and the attenuation design. There are four prevalent waveguide sizes currently being used in UHF broadcast. Typical dimensions for the flange and waveguide are given in Fig. 27. In addition, you will note that the flange holes are numbered and refer to the proper tightening sequence. In general, the material is 1100 aluminum which offers the highest conductivity available in aluminum material. General construction is flat aluminum welded at the four corners with a true flange welded at each end. The pressure seal is built into one flange of each waveguide component. The attenuation for the typical waveguide sizes is shown in Fig. 28. Again actual performance characteristics should be exactly defined by the manufacturer of the product. VSWR of an installation is approximately the same as could be expected in the coax installation. Typical length for broadcast waveguide is approximately 12 feet.

The physical parameters of the waveguide determine the electrical operating characteristics. The inside cross-sectional width, or "a" dimension, determines the frequency range of operation for the dominant mode. The "a" dimension must be greater than $\lambda/2$ and less than λ for efficient operation in the dominant mode (TE_{10}). The

DO'S

1. DO store packaged transmission line in clean dry place to prevent contamination.
2. DO withdraw and inspect inner and outer conductors completely if in previously opened or damaged shipping boxes.
3. DO withdraw and inspect all short pieces of line.
4. DO check operation of inner expander assembly* and any components suspected of contamination with dirt or moisture.
5. DO cap all unpacked components against the entry of mositure.
6. DO hoist components with connector end up unless component is marked otherwise.
7. DO check the line in the spring hanger guides after each section is installed to insure free movement for expansion. Shimming of guides at tower support may be necessary.
8. DO consult spring-loading dimensions chart (in Hangers section) for proper spring tension on expansion hangers and adjust each position on the tower accordingly.
9. DO ascertain that inner conductors of adjacent sections match alignment to prevent inadvertent damage to the connector. Hold top connector insulator in place and see that the insulator is well sealed before installing the next section.
10. DO tighten flange bolts alternately, one side, then the other, before final torquing. See Table 8.
11. DO use torque wrench for final tightening.
12. DO pressurize line immediately following installation and maintain 3 lbs/in² (0.21 kg/cm²) at all times. Leaks must be repaired immediately.
13. DO keep ends of transmission line capped during installation. If installation is halted, seal installed line ends and pressurize to at least 0.5 lbs/in² (0.04 kg/cm²) with dry air or nitrogen.
14. DO coat O-ring gaskets lightly with Dow-Corning DC-4 silicone compound to ease assembly.
15. DO check O-ring and its groove for dirt or other foreign material and ascertain that ring is properly seated before flange assembly.

DON'TS

1. DON'T withdraw complete line section if shipping box appears to be new and intact. ONLY inspect inner conductor expander.
2. DON'T hoist coupled sections of transmission line. The stresses involved damage components.
3. DON'T use force when fitting components one to another. If cause cannot be corrected or isn't evident visually, call for DC assistance.
4. DON'T assemble line components that contain water or condensation.
5. DON'T assemble line components that contain dust, dirt, packing material or other foreign objects. Consult Dielectric regarding any loose or suspicious material in the line as it is unpacked.
6. DON'T assemble match-marked components unless the marking is clear and understood. DON'T interchange match-marked items. Consult DC about proper assembly.
7. DON'T install any line component with dust, dirt or grease on insulators.
8. DON'T install line that exhibits any evidence of damage.
9. DON'T attempt to correct defects discovered unless instructed and authorized by Dielectric.
10. DON'T dismiss rigger until transmission line is completely installed and pressurized for at least 12 hours and the appropriate electrical tests performed.
11. DON'T power the transmission line until the line is known to be dry and pressurized to at least 3 lbs/in² (0.2 atm.).
12. DON'T exceed specified torque for flange bolts (see Table 8).
13. DON'T use a line flange with evidence of over-stressed.
14. DON'T use a damaged O-ring gasket. Use a new gasket whenever in doubt.
15. DON'T bend elbow components to fit. If leg angle is incorrect, consult Dielectric.
16. DON'T let rigging equipment damage components. Provide proper protection.
17. DON'T cut tubing without a cut-off gauge and remove all burrs and chips from inside and outside of tubing.
18. DON'T assemble a horizontal run without proper support.

*Check inner conductor expansion joint for an excursion of 0.2 inch (5 mm) travel and in the extended position check for presence of contacting spring through exposed groove on inner conductor. In some lines the contacting spring is not visible in the extended position. Presence of the spring can be determined by inserting a 6-mil (0.15 mm) thick feeler gauge (0.5-inch or 13-mm wide) between the tubing inner surface and the connector body outer surface. If spring is present the feeler gauge can be inserted 0.25 inch (6.4 mm). If gauge goes in 0.5 inch (13 mm), spring is missing and line section must not be used.

Fig. 23. Transmission line do's and don'ts.

1 Rectangular to Coax Transition (Side Launch)
2 Rectangular Field Cut Straight Section
3 90° "E" Plane Miter Bend
4 180° "E" Plane "U" Bend
5 Coax Elbow Complex
6 Rectangular to Coax Transition (End Launch)
7 Rectangular to Circular Transition with Test/Monitoring Ports
8 Top Support Hanger with Load Bearing Waveguide Section
9 Circular Step Transformer
10 Circular Swivel Section
11 Vertical Restraining Spring Hanger
12 Vertical Restrainer
13 Axial Ratio Compensator (Vertical Application)
14 Circular Straight Section
15 Circular Field Cut Straight Section
16 XFMR/Mode Filter Including Circular Step Transformer
17 Circular Swivel Section with Test/Monitoring Ports
18 90° Circular Bend
19 Circular Swivel Section
20 Circular Field Cut Straight Section
21 Coaxial Loads with Mounts and HELIAX Cable
22 Axial Ratio Compensator (Horizontal Application)
23 Horizontal Spring Hanger
24 Circular Pin Twist with Load/Test Ports
25 Circular Pin Twist Section
26 Rectangular to Circular Transition
27 Rectangular Gas Barrier
28 Coax Gas Barrier

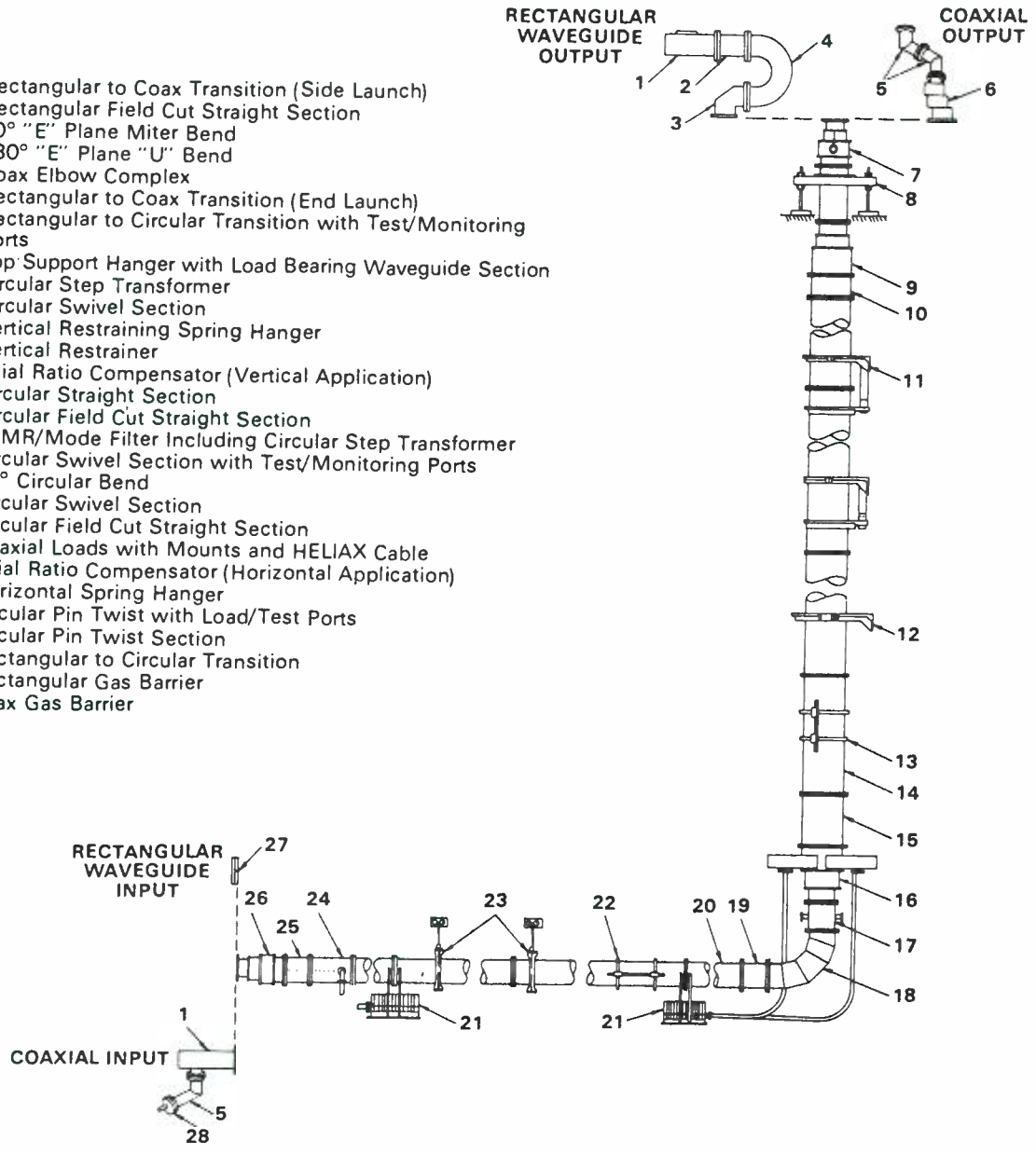


Fig. 24. Components for typical circular waveguide system. (Courtesy of Andrew Corporation)

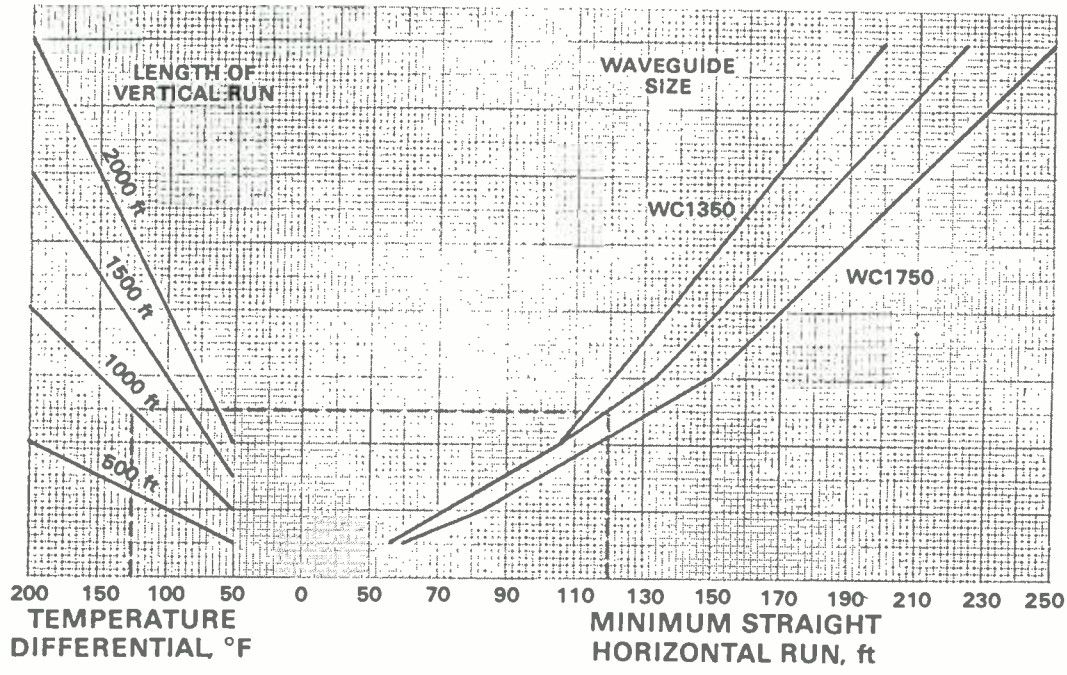
Channel Number	Visual Carrier MHz	Attenuation dB/100 ft	Average Power Kilowatts
WC1750			
14	471.25	0.0521	386.9
15	477.25	0.0502	401.9
16	483.25	0.0484	416.4
17	489.25	0.0469	430.3
18	495.25	0.0454	443.7
19	501.25	0.0441	456.7
20	507.25	0.0480	469.2
21	513.25	0.0467	481.3
22	519.25	0.0454	493.1
23	525.25	0.0439	504.5
24	531.25	0.0391	515.6
25	537.25	0.0383	526.3
26	543.25	0.0375	536.7
27	549.25	0.0368	546.9
28	555.25	0.0362	556.7
29	561.25	0.0356	566.3
30	567.25	0.0350	575.7
31	573.25	0.0344	584.8
32	579.25	0.0339	593.6
33	585.25	0.0334	602.2
34	591.25	0.0330	610.6
35	597.25	0.0325	618.8
36	603.25	0.0321	626.7
37	609.25	0.0317	634.5
38	615.25	0.0314	642.2
39	621.25	0.0310	649.4
40	627.25	0.0307	656.6
41	633.25	0.0303	663.6
WC1500			
39	621.25	0.0490	352.7
40	627.25	0.0482	358.9
41	633.25	0.0474	365.0
42	639.25	0.0466	370.9
43	645.25	0.0459	376.7
44	651.25	0.0452	382.4
45	657.25	0.0445	387.9
46	663.25	0.0439	393.3
47	669.25	0.0433	398.6
48	675.25	0.0428	403.7
49	681.25	0.0423	408.8
50	687.25	0.0418	413.7
51	693.25	0.0413	418.5
52	699.25	0.0408	423.2
53	705.25	0.0404	427.8
54	711.25	0.0399	432.3
55	717.25	0.0395	436.7
56	723.25	0.0392	441.1
57	729.25	0.0388	445.3
58	735.25	0.0384	449.4
59	741.25	0.0381	453.4
WC1350			
56	723.25	0.0530	293.9
57	729.25	0.0523	297.7
58	735.25	0.0516	301.5
59	741.25	0.0510	305.1
60	747.25	0.0504	308.7
61	753.25	0.0498	312.3
62	759.25	0.0493	315.7
63	765.25	0.0488	319.1
64	771.25	0.0483	322.4
65	777.25	0.0478	325.7
66	783.25	0.0473	328.9
67	789.25	0.0469	332.0
68	795.25	0.0464	335.0
69	801.25	0.0460	338.0

STANDARD CONDITIONS

For Attenuation VSWR 1.0, Ambient Temperature 24°C (75°F).

For Average Power VSWR 1.0, Ambient Temperature 24°C (75°F)
Waveguide Temperature 64°C (147°F).

Fig. 25. Attenuation and average power ratings.
(Courtesy of Andrew Corporation)



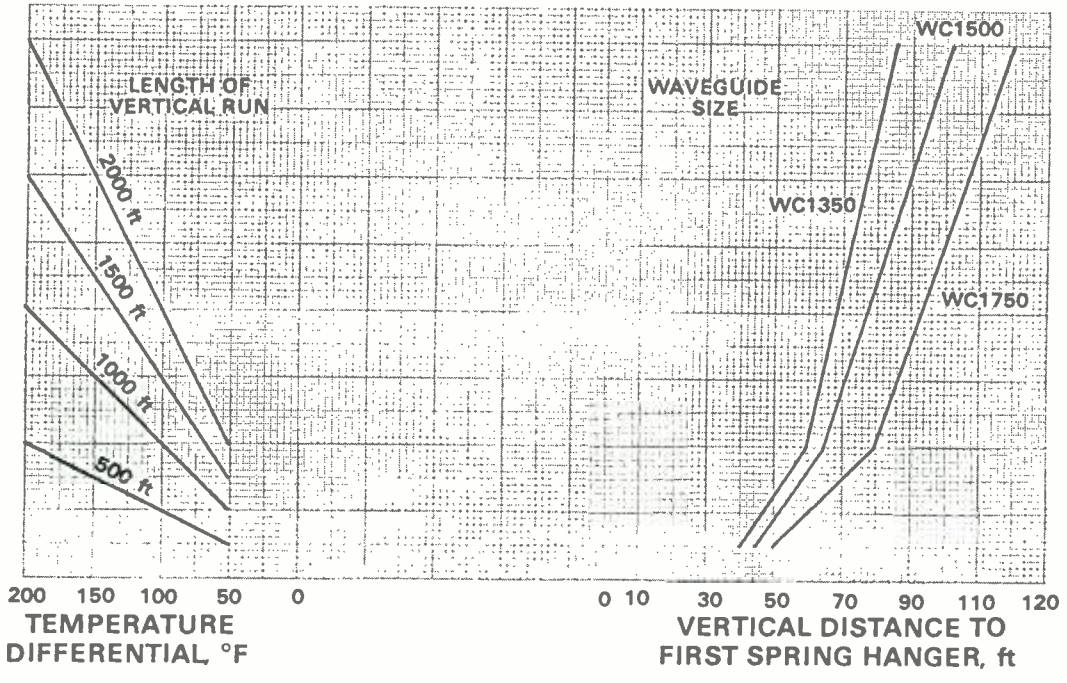
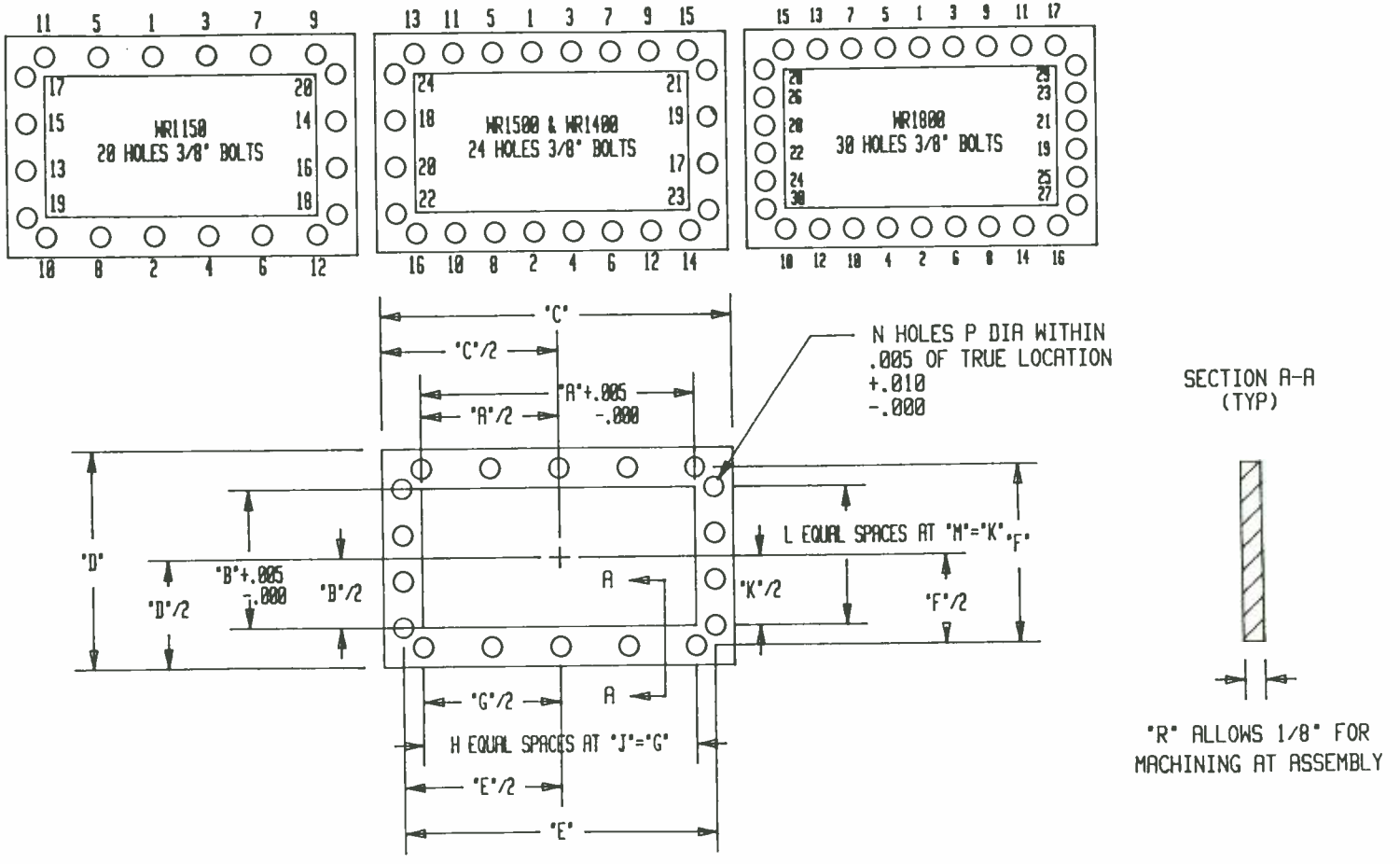


Fig. 26. Mechanical setting for circular waveguide installations. (Courtesy of Andrew Corporation)



WAVEGUIDE SIZE	A	B	C	D	E	F	G	H	I	J	K	L	M	N	P	R	UNIT FLANGE WEIGHT
WR1800	18.00"	9.00"	21.50"	12.50"	20.000"	11.000"	16.000"	8	NA	2.000"	9.063"	5	1.813"	30"	.406"	.625"	6.7 LBS.
WR1500	15.00"	7.50"	18.50"	11.00"	17.000"	9.500"	14.000"	7	NA	2.000"	6.000"	3	2.000"	24"	.406"	.438"	4.7 LBS.
WR1400	14.00"	7.50"	17.50"	11.00"	16.000"	9.500"	14.000"	7	NA	2.000"	6.000"	3	2.000"	24"	.406"	.438"	4.5 LBS.
WR1150	11.50"	5.75"	15.00"	9.50"	13.500"	7.750"	10.000"	5	NA	2.000"	5.814"	3	1.938"	20"	.406"	.438"	3.5 LBS.

Fig. 27. Typical waveguide flange detail.

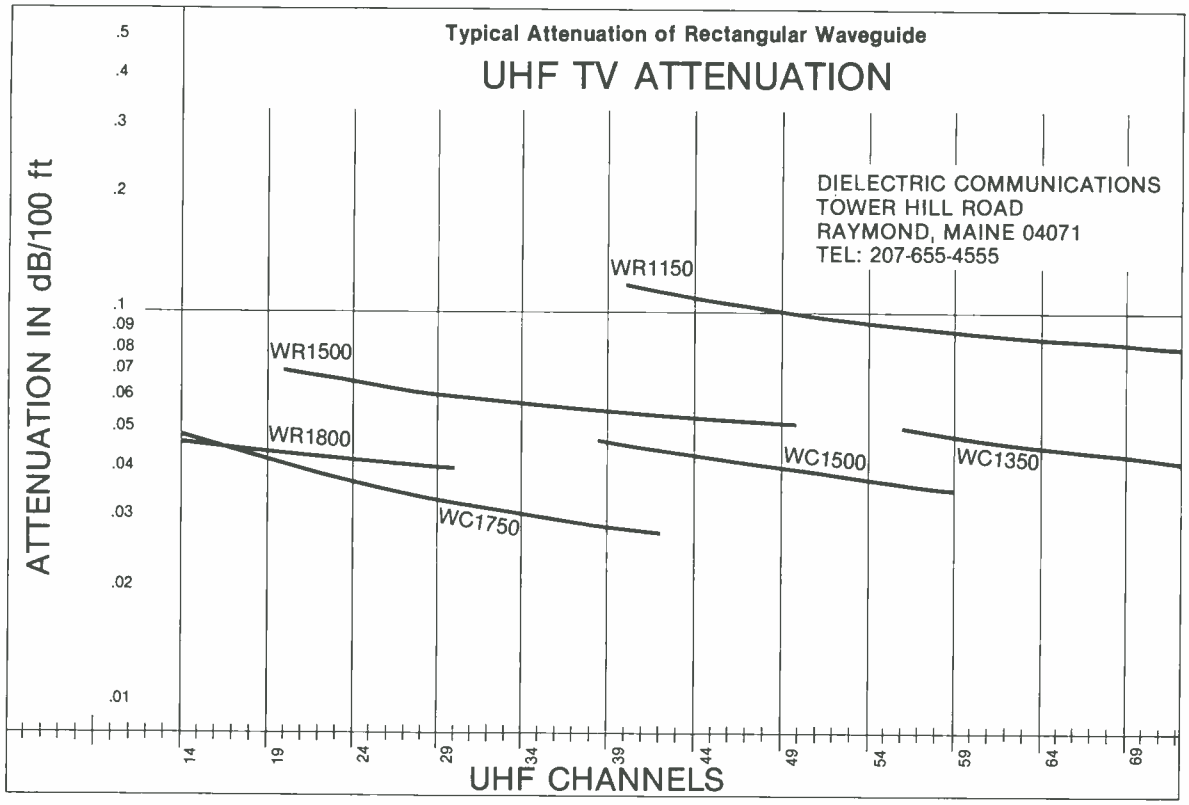


Fig. 28. Typical attenuation of rectangular waveguide.

WAVEGUIDE SIZE	CHANNEL	SECTION LENGTH REQ'D
1800	17,18,22,23,24,28,29	11.5 ft.
1800	14,15,16,19,20,21,25, 26,27, and 30	11.95 ft.
1500	20,21,25,26,30,31,35, 36,40,41,45,46 and 47	11.5 ft.
1500	22,23,24,27,28,29,32, 33,34,37,38,39,42,43, 44,48,49, and 50	11.95 ft.
1150	40,41,45,49,50,54,59, 64,65,69, and 70	11.5 ft.
1150	42,43,44,46,47,48,51 52,53,55,56,57,58,60, 61,62,63,66,67, and 68	11.95 ft.

Fig. 29. Recommended waveguide section length per channel.

generally accepted operating range is from .6λ to .95λ or 60% to 95% of the cut off frequency of the next higher mode (TE_{20}).

The inside cross-sectional height, or "b" dimension, determines the voltage breakdown and as "b" is reduced, the power handling capacity is also reduced. It should also be noted that as the "b" dimension is reduced the attenuation of the waveguide increases.

The practical combination of mechanical and electrical parameters for large waveguide is recommended by the Electronic Industries Association to be a b:a ratio of approximately 1:2.

A typical feed system includes such items as straight waveguide, sweeps and elbows, mitre bends, twists, switches, couplers, and other components as required for a specific application. In order to provide system compatibility, each component should be manufactured with stringent electrical and mechanical controls.

Waveguide Installation

General Information

As in all transmission line installations, preliminary layout work must be done for the installation of rectangular waveguide. (see Fig. 29)

It must be noted that prior to doing the layout work, up-to-date catalogs and literature must be obtained from the manufacturer.

List of Material

When creating a list of materials, the most common point to start is at the waveguide elbow located at the base of the tower. Working toward the building from the bend, use standard 11.95 ft. or 11.50 ft. lengths (as frequency dictates refer to Fig. 30) through the building opening. If a cut length is required and is known, specify on the L/M. If the dimension is not known, specify of the L/M as one piece of waveguide, length unknown. This is to advise the manufacturer that materials must be made available for last minute measurements. If more than one piece is required, specify as two or more line items same description. For each line item, one maximum length section will be set aside for the particular location.

The vertical run should be laid out by stacking each designated length of waveguide end-to-end until the appropriate height is reached for positioning the waveguide to coax transition. The same rule for unknown lengths should be applied as is in the horizontal run.

WR 1800	14 - 30
WR 1500	20 - 50
WR 1150	40 - 70

Fig. 30. Recommended waveguide size per channel.

Hangers

For layout of hangers, see the manufacturers catalog for dimensions required to attach hangers to the bridge or tower structure.

When laying out the hangers, you must keep in mind that the coefficient of thermal expansion of the aluminum is 13×10^{-6} per degree F, and of the structural steel approximately 6.5×10^{-6} per degree F. This leads to a relative differential movement of approximately ¾ inch per 100 feet for 100°F differential. Also keep in mind that ambient temperatures of the guide and tower are different and must be considered during installation.

When placing the waveguide inside the tower, sufficient clearance must be maintained around horizontal tower members so thermal expansion of the vertical run does not cause the horizontal portion to make contact with these horizontal members. Keep in mind that the heating of the waveguide due to RF will cause the waveguide to expand and the tower will not, as in the case of ambient temperature change where one is concerned with the differential expansion.

It also must be noted that all waveguide external to the building is pressure-tight; so the "sex" of the sections must be observed. The sections in the horizontal run are positioned so that the seal is away from the building, which results in the seal being on the top of each vertical section. This allows the rigger to observe the seal prior to the mating of the flanges.

Horizontal Hangers

Starting from the base elbow, always position the hanger approximately in the center of each piece of waveguide. Each section must be supported by one mount.

Vertical Hangers

Again, starting at the base elbow, each section of waveguide must be supported by one hanger. For specific hanger requirements, refer to manufacturers recommendation. Each hanger should be located as close to the center of each section of waveguide as possible.

Lateral Braces

On towers exceeding 350 feet, locate one every 150 feet to the top.

The last section of waveguide in the horizontal run (and vertical) may have to be fabricated to size by the manufacturer. If so, measure the required length and call this into the manufacturer.

Tower Top

The vertical run is secured at the top with an "Anchor Plate" which is usually attached to the

waveguide flange bolts on the waveguide-to-coax transition.

Tuners

For VSWR adjustment, it is recommended that one section of waveguide with tuners be located every 72 feet, both in the vertical and horizontal runs. A good starting point is the elbow between the horizontal and vertical portions of the run. There should be a tuner located within a few feet of this elbow; it does not matter whether it is on the vertical or horizontal side. After this tuner has been placed, the rest may be spaced at 72 foot intervals both toward the antenna and toward the transmitter.

Unloading And Storage At Site

Unload sections and carefully stack in an area where tower work will not endanger it. Use Mylar plastic sheeting, available in rolls, to cover the waveguide. Plastic sheeting is available at contractor supply houses and some hardware stores. Lay the "Visqueen" on ground and stack waveguide on top of it. After waveguide is stacked, bring the sheeting up on the sides of the waveguide and tape using duct tape. Put "Visqueen" over the stacked waveguide, extending down and over the bottom sheet and tape the two pieces together. This results in a well protected waveguide, even from wind and rain. It is essential that the waveguide be clean and dry when installed as this will eliminate much work later.

Hanger Installation

Before any waveguide is uncovered, all hangers should be installed on the tower and bridge, taking care to use the proper hangers at the approximate locations on the tower, i.e. tall towers have hangers which are larger (stick out from tower further and have larger springs) on the bottom portion of the tower than on the upper portion. Also, the last several bottom hangers have long "arms" which attach the hangers to the waveguide to allow the vertical run to move further "in and out" due to expansion of the horizontal run without binding in the hangers. A check should be made to insure that, as the waveguide moves up and down due to expansion, the resulting "in and out" movement (due to hanger construction) does not allow the waveguide flanges to hit the horizontal member of the tower. If installation is properly designed mechanically, this will not happen; but check it. It has happened and all the hangers had to be removed and remounted with spacers.

Installing Waveguide

Two pieces of waveguide should be bolted to the "E" plane bend which is to be at the bottom of the tower. This will be the last section of the horizontal run and the first section of the vertical run with the "E" plane bend in between. The seal must be located away from the building or toward the tower top. Taking into account the ambient temperature, locate the placement of the combination of tower and bridge. This exercise is important as it locates the vertical run in relation to the tower, and the horizontal run in relation to the bridge. If this is not properly done, it is possible (depending upon length of vertical run) for the end of the horizontal run to hit the bridge when the waveguide "moves up" in the winter. This is really no different than in coax installation, except in coax the hangers have no movement and in waveguide, the hangers do move and precautions must be taken so expansion of the guide does not bind them. Initial alignment, therefore, is critical to proper installation.

After initial location of this group, fix the vertical section so that it cannot move down. This is best accomplished using a "come-along" (small ratchet hoist) to suspend the section to a point on the tower. The vertical waveguide section should be able to be raised by pushing on the bottom section of the waveguide, so it is important not to fix the waveguide so that it cannot move upward.

Small variations in materials and manufacturing processes can introduce a slight twist in waveguide. Over a long run, these twists can accumulate to a degree that causes binding in the hangers. To correct this, "reverse twist" sections are supplied and are inserted as needed.

In preparation for installing the waveguide sections, locate reverse twist sections, (they should be marked as such), and keep them separate from "regular" sections. This is best done at the same time as the initial stacking and covering upon arrival.

As the sections of waveguide are removed from the storage area for installation, check for dirt inside the guide. If any foreign matter is found, run a large, clean blanket through the sections to clean it.

Assembly of the waveguide is done by inserting locating pins in any two opposite corners of the flanges and installing bolts, washers and nuts in remaining holes of the flange. After torquing bolts, remove the pins and replace with bolts.

As a suggestion, drill a hole in the end of each locating pin and attach two of them together with a long and strong cord, such as lacing cord. Have the rigger wear them around his neck like a child's pair of mittens. This will keep him from dropping the pins from the tower while installing and removing them. They are difficult to find in the dirt when dropped from 1000 feet.

Now install the remainder of the horizontal run (back to the transmitter). If the horizontal run starts to twist, install a section of the "reverse

twist'' waveguide to bring it back. Make sure the waveguide is fitting properly in the hangers to prevent distortion of the guide.

Once inside the building, install a gas dumping section and a gas barrier. The operation of the pressurization system and gas dump is discussed below.

The gas dump section should have a seal on both ends. The gas barrier, commonly called a "waveguide window", utilizes a polystyrene plate as the pressure barrier and is designed to operate at .25 PSIG for the WR1400 thru WR1800, and .50 PSIG for WR1150.

The last section of waveguide in the horizontal run (and vertical) may have to be fabricated to size by the manufacturer. If so, measure the required length and call this into the manufacturer.

At this time, install a waveguide to coax adaptor (match to the channel) to enable test equipment to be attached.

The vertical run is now installed from the bottom up as in coax. Unlike coax, the waveguide can twist and either bind in the hanger or not go in at all. If twist causes a bind in the hanger, a reverse section is selected and installed to bring the run back. The object is not to let it twist too far and cause the waveguide to bind but rather to install a reverse section that will bring the waveguide back past square, at which point the regular sections are again used. As hangers can tolerate some twist in either direction, this method will result in the best installation and the least problems. Try to plan so that the vertical run is kept square at the tower top.

After a number of sections of guide have been installed (the number is optional), determine if waveguide run can be pushed upward by one person pushing on the bottom of the vertical run. If this is not possible, the hangers are not properly tensioned and corrective action should be taken.

When the vertical run is complete, measure the last section needed to complete the run and call this dimension into the manufacturer. Install the necessary fixed anchor assembly to fix the run.

Pressurization Systems

Rectangular waveguide by the nature of its shape and relatively thin walls will not withstand high pressurization; but a slight positive pressure in any transmission line system is necessary to prevent condensation during temperature change. A pressure in the range of .25–.50 PSIG is typical. Too high a pressure will deform the walls, affecting VSWR, and the waveguide window could rupture.

Because of the large volume of air and large surface area of the guide, a rapid change of ambient temperature can cause a relatively fast change in the internal pressure. The extra pressure must be bled off rapidly, and this is accomplished by the gas dump. The gas dump consists of a precisely weighted cap over opening in the guide. The cap "pops" off at the maximum pressure for which the guide is designed. When the guide cools, the automatic dehydrator must have sufficient capacity to replace the air in a short time.

The coaxial output of the transition may require a gas barrier which may be connected directly to the conventional coax elbow complex.

Installations where both coaxial line and waveguide is used, a separate higher pressure air feed is run for the coax and/or antenna.

An automatic dehydrator system is ideally suited for most guide installations. This unit should provide 2400 SCFD at $-40\,°F$ dew point and be equipped with humidity alarm and bypass. A one cubic foot storage tank charged to the standard 60 PSIG will provide a reserve of 4.8 cubic feet at .5 PSIG.

Tuning Waveguide

The waveguide may have been shipped and installed with the tuning probes installed in the tuning sections. If this is the case, they must be pulled out to where they are still in the sockets but do not protrude inside the guide, even a little bit. To do this, remove the caps which cover the probes. There are two small hex screws in the caps that must be loosened and the cap removed. There is an O-ring inside so you will have to pull hard. Once the cap is removed, you will notice a tapped hole in the Teflon probe. Screw in a ¼" 20 TPI bolt and pull the probe out until no part is inside the guide. Do this for all tuning sections keeping in mind that there are four probes per tuning section.

The elbow at the base of the tower is removed and a sliding load inserted into the end of the horizontal run. A test transition is installed at the input of the horizontal run and test equipment to measure VSWR attached to the transition. The tuning probes are adjusted for best match as indicated on the VSWR measuring equipment. Each tuning section is adjusted starting at the section closest to the measuring equipment and working toward the load.

When the horizontal run is completed, the sliding load is removed from the end of the run. At this point the top of the vertical run is opened and a rope dropped through the waveguide run to the bottom. The sliding load is attached to the rope in such a manner that the load can be pulled up the vertical run. Insert the sliding load into

the bottom of the vertical run and re-install the elbow between the horizontal and vertical run. When this is completed, pull the sliding load up and stop at the section just above the tuning section. This can best be accomplished by removing one of the Teflon probes and watching to see when the load goes by. It is easy to judge when you are in the next section of waveguide.

The tuning probes are adjusted in the vertical run starting with the section closest to the bottom and working up. After each section is tuned it will be necessary to pull the sliding load up as was done before. Repeat the procedure until you reach the top when you will remove the load and re-install the top piece that was removed previously. Tuning is now complete.

2.4

AM Broadcast Antenna Systems

CHAPTER 2.4:
Part I: System Design
Part II: Phasing, Coupling
Part III: Maintenance

Part I: System Design

Carl E. Smith
President, Smith Electronics, Inc.
Cleveland, Ohio

INTRODUCTION

Standard broadcast (AM) antenna systems can reach a high degree of sophistication, much of which is based on advanced mathematics. The purpose of this section is to provide the station engineer with an understanding of some of the basic concepts of antenna design and an appreciation for the complexities of this specialty. An extensive bibliography is included for those who wish to pursue further study.

The chief purpose of a broadcasting antenna system is to radiate efficiently the power supplied to it by the transmitter. A simple antenna can do this job quite well. This is often a single vertical tower that radiates its signal equally in all directions along the ground in a so-called nondirectional or omnidirectional pattern. A second purpose of an AM antenna system is often to concentrate the power in desired directions and to suppress it in other directions to protect the coverage of other stations sharing the same or closely-adjacent channels. This directionality may require a very complicated antenna system with several towers if the requirements are stringent.

The antenna is the last point in the system under the control of the broadcaster. The signals radiated from the antenna are propagated through space to each receiving antenna. The factors affecting the strength of the received signal include the strength of the signal radiated by the broadcasting station in a particular direction, the distance to the receiving site, losses incurred by the less-than-perfect conductivity of the ground along the propagation path, terrain obstructions, (large hills cast shadows even at AM frequencies) and, in the case of skywave transmission, the ionospheric conditions that determine how much of the radiated signal will be reflected back to each distant receiving location. Signal strength in a particular direction can also be affected by the presence of structures such as buildings or towers near the radiating system.

The polarization of the transmitted waves is also a factor; for standard broadcast stations vertical polarization is used because of its superior groundwave propagation and the simplicity of antenna design. The FCC has established maximum transmitter power limits for each of the three classes of AM channels (clear, regional and local) so the only variables available to the design engineer attempting to maximize the coverage of a radio station involve the antenna location, the pattern design, and a limited choice of power levels. These factors go hand in hand when designing a directional antenna system. Severe constraints are usually imposed on transmitter site selection because of aeronautical, zoning, environmental, and coverage requirements. The constraints encountered in the pattern design relate to the size and shape of the transmitter site, the extent to which the necessary signal suppression can be achieved at the desired transmitter power level and the cost of design, construction,

adjustment, and maintenance of multi-tower systems. The pattern design can also seriously affect the stability, efficiency, and bandwidth of the completed system. These factors will be discussed later.

RADIATION VERSUS FIELD STRENGTH

Two independent factors determine the signal strength at any given point within a station's service area. First is the strength of the signal radiated in that direction; second is the path attenuation between the transmitting and receiving antennas. Attenuation is determined by both distance and ground conductivity. It is customary to express the radiation in units of millivolts-per-meter at one mile (or one km), unattenuated. This is the field that would exist at one mile over perfectly conducting earth. In this case the field strength would be inversely proportional to the distance from the transmitting antenna; hence, the radiation is also described as the "inverse distance field". The unattenuated radiation cannot be measured directly but can be inferred with great accuracy if sufficient field strength measurements are made to determine the ground conductivity. Field strength measurements are always dependent on radiation, distance, and ground conductivity.

THE SINGLE TOWER NONDIRECTIONAL ANTENNA

Current and Voltage Distribution

The majority of single-tower antennas are neither top-loaded nor sectionalized and most of them are insulated from ground. For such simple towers, the current is a maximum 90 electrical degrees down from the top (or at the base if the tower is shorter than 90 degrees in height. A typical guyed tower that is 90 degrees high physically is about 95 degrees high electrically, because the velocity of propagation is less in the tower than in air and is a function of the tower cross-section, slowing down as the cross-section is increased. The approximate shape of the current distribution on a thin tower of uniform cross-section is given by

$$i_a = I_a \sin (G - y)$$

Where: i_a is current in amperes at height y
I_a is the maximum current in amperes
G is the tower height in degrees
y is the height in degrees of the current element i_a

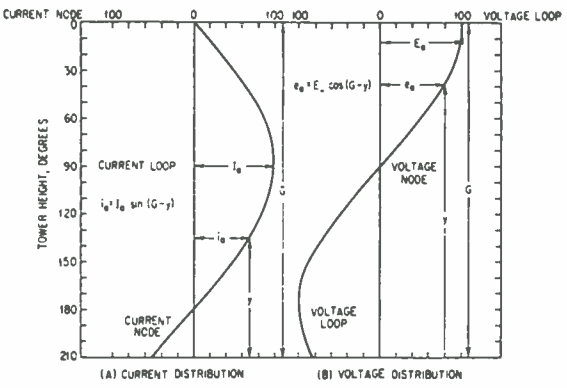


Fig. 1 Theoretical current and voltage distribution on a vertical radiator.

As an example, the general shape of the current and voltage distribution on a thin tower 210 electrical degrees high is as shown in Fig. 1. For shorter towers, the distribution would approximate that shown with the lower portions cut off; there always being a current node and a voltage maximum at the top of any such tower that does not employ top loading. It is important to visualize the shape of the voltage distribution along the tower because of the need of good insulators at the high-voltage points. Otherwise corona or arc overs may result to disrupt broadcasting service.

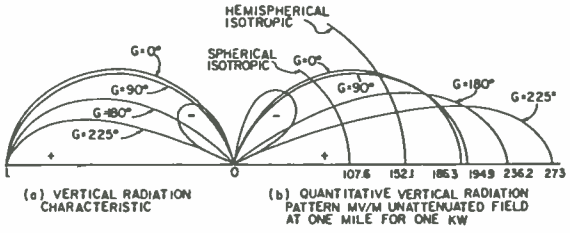
The tower current and voltage are not zero at the nodes shown along the tower. Rather, they reach minimum values and shift rapidly approximately 180 degrees in phase in traversing the node region. When towers considerably taller than 180 degrees in height are considered, the current near the base is in the opposite direction from that in the upper portion of the tower. Under these conditions, when viewed in the horizontal plane, the radiation from the lowest part of the tower is canceling a portion of the radiation from the part above the current minimum. Any increase in tower height above the optimum would actually reduce horizontal plane radiation.

Vertical Radiation Characteristics

Maximum groundwave radiation occurs for a tower 225 electrical degrees high (five eighths wavelength). The variations in tower current distribution with increasing tower height defines the shape of the radiation characteristic in the vertical plane. Fig. 2 shows the size and shape of the vertical plane radiation patterns for a single tower of various heights atop a perfect ground system is fed with one kilowatt of power.

Insulated Tower Base Impedance

The base impedance of a single nondirectional tower is determined principally by its electrical



$$f(\theta^\circ) = \frac{\cos(G^\circ \sin\theta^\circ) - \cos G^\circ}{(1 - \cos G^\circ)\cos\theta^\circ}$$

Fig. 2. Radiation characteristics in vertical plane.

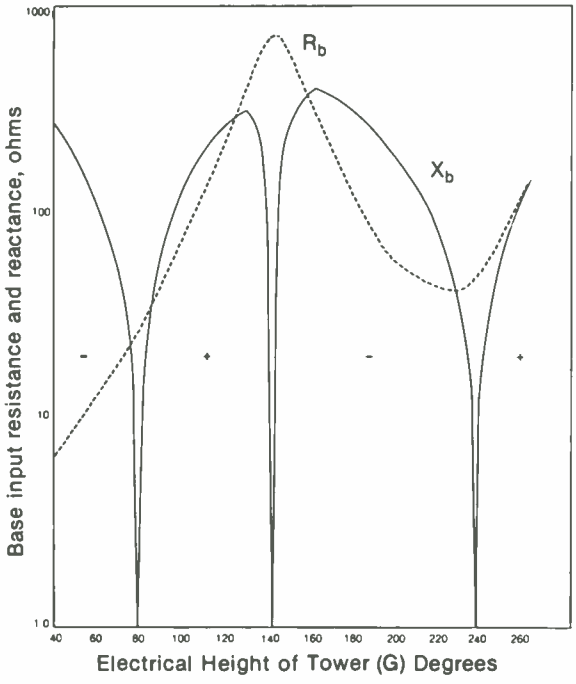


Fig. 3. Typical base input resistance and reactance of a uniform cross-section base insulated guyed tower.

height, its cross-section, the extent of the ground system, and the elevation of the feed point above ground. For typical guyed towers of uniform cross-section, which are base insulated and fed four or five feet above ground level, the resistive and reactive components of the base impedance approximate the values shown in Fig. 3. The base impedance of self-supporting towers departs radically from the values shown, not only because of their large and tapering cross-section, but also becuase of the capacitance of the base insulators necessary to support each leg of such towers.

Electrically short towers are inefficient radiators, not only because of the shape of their vertical radiation characteristics as shown in Fig. 2 but also because of proportionately higher ground losses. For example, with a tower 48 degrees high, having a base resistance of only 9 ohms, approximately 10% of the available power is wasted in the ground system resistance losses, which typically approximate one ohm.

Grounded Towers, Shunt Fed and Folded Monopole

Occasionally towers without insulated bases must be utilized as AM radiators. Such structures include FM or TV towers, water tanks, and ornamental flag poles. Although the impedance at the base of such a tower is necessarily essentially zero, the impedance rises with increasing height of the feed point. It is a simple matter to determine experimentally the height at which a shunt-fed tower must be driven to provide a desirable input impedance. A common technique is a "slant-wire" feed in which a wire is attached to the tower at a selected height above ground and brought down to near ground level at an angle approximating 45° to serve as the antenna input terminal. A slant-wire feed distorts the otherwise omnidirectional pattern of a single tower and tends to suppress radiation over the sector on the side where the slant-wire is attached. This effect can be avoided if, instead of the slant-wire, the feed conductors are insulated at the base and brought up outside of the tower and bonded to the tower, for example, 90° above ground to form a folded monopole. The conductors, in this concentric arrangement, in effect form the outer conductor of a coaxial transmission line with a short to the tower at the 90° point and an open at the base insulators. This quarter wave open circuit transmission line in effect puts an insulator at the tower base. The current up on the outer conductors and down on the tower essentially cancel so far as radiation is concerned. The tower with this insulated skirt performs like a base insulated tower. The concentric arrangement of conductors usually six, are tied together above the conductor base insulators and fed like a base insulated tower. There is a small amount of power loss in the 90° concentric transmission line shorted at the top and used to produce the open circuit at the bottom. The radiation current is up on the outer conductors, to where they are connected to the tower at the 90° point, and then on up to the top of the tower where the current is zero like on a base fed insulated tower.

Folded Conical Monopole

The folded conical monopole shown in Fig. 4 broadbands the input impedance and for a 90° tower the vertical radiation characteristic is that of a 75° tower but with an increased value of input resistance and reactance of about 50%. These results were obtained by applying the method of moments to compute the base impedance, current distribution and vertical pattern.

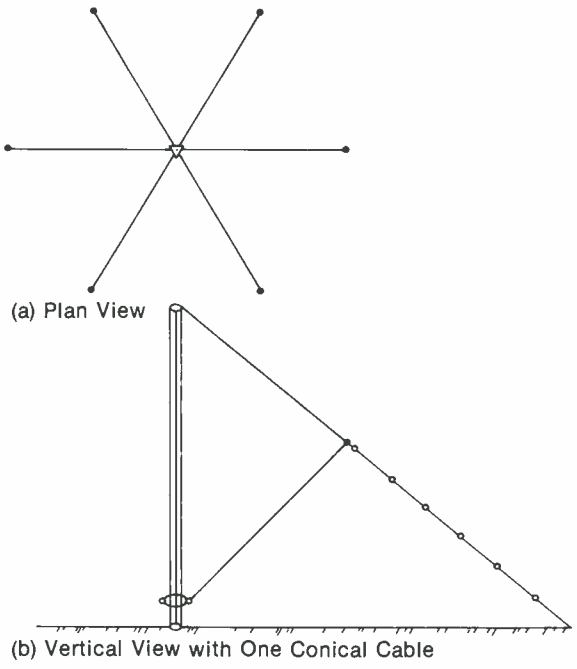


Fig. 4. Sketch of folded conical monopole antenna.

Top Loading

The performance of an electrically short tower (significantly less than 90 degrees) can be improved, both as to radiation efficiency and bandwidth by means of top loading. This consists of increasing the capacitance to ground from the top of the tower. This loading can take the form of either a flat more-or-less circular horizontal disk attached to the top of the tower (called a top hat) or as sections of guy wires bonded to the top of the tower and extending down a useful distance before encountering the first of the guy wire insulators. Many variations are possible. Some installations use 3, 6, or even 12 nonstructural guys for top loading that are very effective. By interconnecting the lower ends of the top loading cables the capacitive loading is increased some but this or spider web connections between the top loading cables increases the construction and maintenance problems. These problems can be eliminated by just increasing the top loading cables a small amount to give the same increase in capacity effect. Top loading is electrically less desirable than increased tower height, but is useful where towers must be electrically short due to either extremely low carrier frequencies or to aeronautical limitations. Top loading increases the base resistance and lowers the capacitive base reactance thus reducing the Q and improving the bandwidth on towers less than 90°. When the tower height is of the order of 130° top loading can be used to increase its electrical height to give maximum groundwave radiation and minimize skywave radiation.

Sectionalized Towers

A utopian vertical radiator would have a constant current throughout its height but in real life the current must ultimately reduce to zero at the tower top or at the end of the top loading cables. The current can be made to diminish less rapidly by inserting an inductance in series with the tower at a point part way up its height. This is the same technique as the familiar "loading coil" near the center of the vertical whips often used for mobile radio systems.

Top Loaded Sectionalized Tower

For a simple vertical radiator the radiation characteristic can be improved by increasing the tower height up to 225° for maximum ground wave or by top loading. This in effect raises the position of the current loop with respect to the ground. This principle can also be applied to the top section of a sectionalized tower.

The purpose of top loading a sectionalized tower is to provide a means of further controlling the current distribution on the lower section only. Considering efficiency and stability it is usually possible to achieve a more favorable radiation characteristic of the whole tower by employing top loading and sectionalization. See Fig. 5. In the case of tall towers used to support FM or TV antennas, it may not be practical to employ top loading.

Depending on the height of tower in wavelengths, the tower can be sectionalized at one or more points to accomplish the highest efficiency

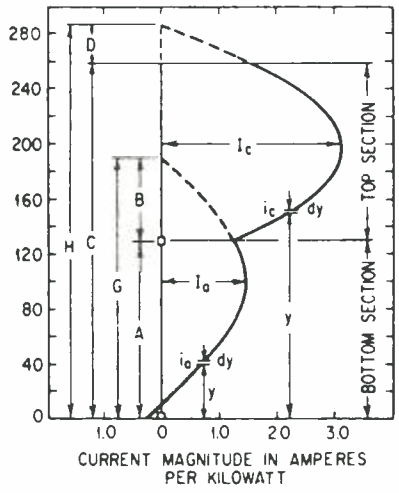


Fig. 5. Theoretical current distribution on top loaded sectionalized tower.

consistent with good operating stability. See Fig. 6.

Ground Systems

The current on a tower does not simply "disappear", rather it returns to earth through the capacitance between the earth and each incremental element of the tower or the top loading. For towers not exceeding 90° in height, the tower current is greatest at the base. For such towers the radial ground current is greatest near the tower and decreases with increasing distance from the tower. For single towers the ground currents are radial from the tower base. The ground losses are greatly reduced if the tower has a radial copper ground system so the ground current will be in the low-loss copper ground system rather in the earth which has a much higher resistance. A solid copper sheet of infinite radius would be the ultimate ground system, but experiments and experience have defined the dimensions of an adequate ground system. A system of 120 radial ground wires each 90 degrees long, 140 degrees is considered optimum and equally spaced out from the tower base constitutes a "standard" ground system. This is often augmented with an additional 120 interspersed radials 50 feet long or an expanded copper mesh ground screen 25 to 50 feet square centered at the tower. A superior ground screen material is the copperweld mesh ground mat often utilized by power companies for lightning protection under electrical substations.

Where the antenna site is too small to accommodate all the ground radials at full length a compromise often used, if easement can not be obtained beyond the property line, is to increase the number of radials by placing them 1 or 2 degrees apart rather than the standard 3 degree separation.

There is no magic in a "standard" ground system for non-directional towers; it simply represents a reasonable balance between cost and radiation efficiency.

The antenna system loss including the tower and ground system is normally assumed to be one ohm and is added to the tower base resistance.

Most ground systems under directional antenna arrays consist of the usual 120 radials per tower truncated and bonded to traverse copper straps where the radials from the several towers would otherwise intersect. Stability considerations may dictate larger than standard ground systems under critical directional antenna arrays; changes in soil conditions beyond the ground system can result in small changes in tower base impedance.

Ground system losses are minimized if the radial wires are placed above ground, thus the

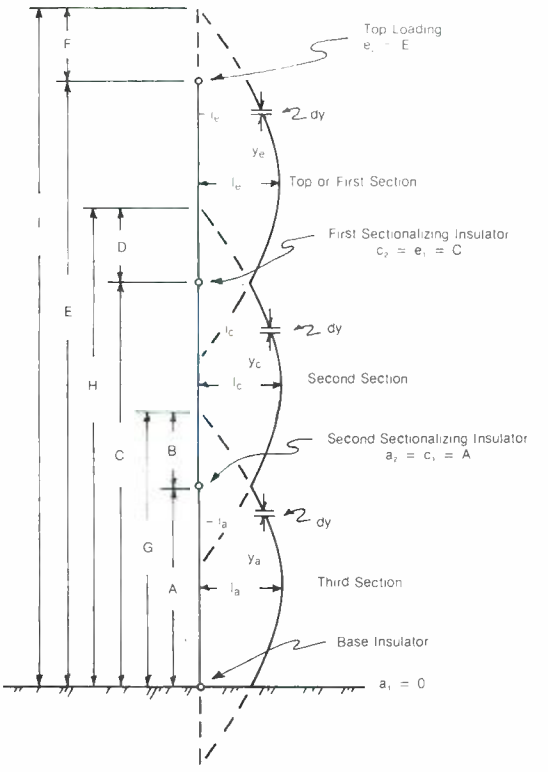


Fig. 6. Theoretical current distribution on three section top loaded tower.

E-field voltage from the tower and top loading cables terminate on these radial conductors so the H-field current can return to the tower base without penetrating the lossy earth. Ground radials are usually buried 6-8 inches for mechanical protection. Burial up to 24 inches is feasible where necessary to permit deep plowing for agricultural crops. However, the ground system should be very near the earth surface in the immediate vicinity of the tower. The earth losses are greater for the buried ground system. Ground systems laid on the earth surface, or tundra in the far north, has the highest loss and least stability of the base impedance. Changes in weather conditions change the dielectric constant and conductivity of any unshielded earth to the detriment of base current stability.

TWO TOWER DIRECTIONAL ANTENNA

Radiation Pattern Shape

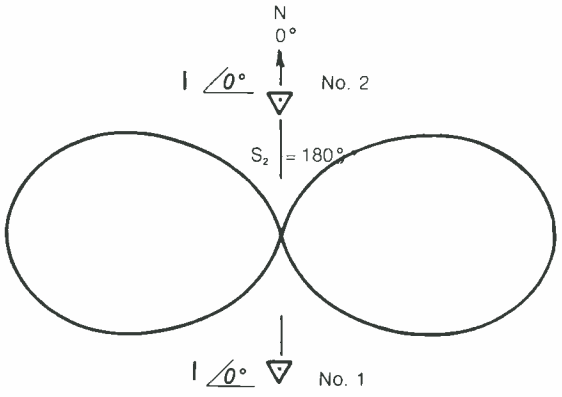
When a nondirectional antenna, with a given power, does not radiate enough field strength to serve the community of interest and/or protect other radio stations then it is logical to resort to a directional antenna system to achieve these ob-

jectives. FCC Rules spell out the protection requirements to be provided to the various classes of stations, both daytime and nighttime. These limits, which must be met in the directional antenna design, tend to define the shape and size of the most desirable antenna pattern. Since the distances and directions to the other stations requiring protection are rarely the same, most directional antenna patterns are tailored to meet the specific requirements. A directional antenna functions by carefully controlling the amplitude and phase of the radio frequency currents fed to each tower. The resulting field in any direction is the vector sum of the individual tower radiation components. To visualize the resulting pattern in the horizontal plane, one must consider the individual tower radiation components when viewed from distant points in different directions. The relative amplitudes from the individual towers remain unchanged but the relative phases shift with azimuth because the signal from the closest tower arrives first. In a directional antenna system, one tower is usually defined as the reference tower and the amplitude and phase of each other tower is measured relative to this reference. The reference tower usually has the greatest current, thus the ratio of the current in each other tower relative to the reference tower current is a fractional number often expressed as a percent of the reference tower current. The relative amplitude and phase of the tower currents is measured by means of an antenna monitor.

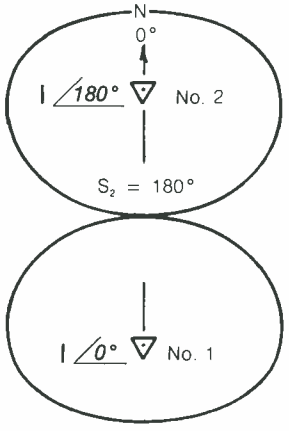
The phase of the field radiated by each tower relative to the reference tower has two components when viewed from any distant point of observation. The relative electrical magnitude of the current fed to the tower is one component and is adjustable. The second component is the phase which appears to lead or lag the reference tower by virtue of being more distant or closer than the reference tower to the point of observation. This is termed the space phase component and varies continuously for each tower in a sinusoidal manner as the observation point is moved in azimuth along a distant circle around the array.

Fig. 7 shows three simple directional antennas and their resulting patterns which are easy to visualize. Fig. 7(a) shows two towers arranged along a north-south line separated by 180 degrees and fed with equal currents in phase. When viewed from the east or west, the fields from the two towers are in phase and the maximum field strength results. When viewed from the north or south, the field from the more distant tower is delayed by the 180 degrees of additional distance, thus canceling the field of the closer tower so as to result in a minimum or null. The deepest minimum or null occurs only when the fields are exactly equal in amplitude and opposite in phase.

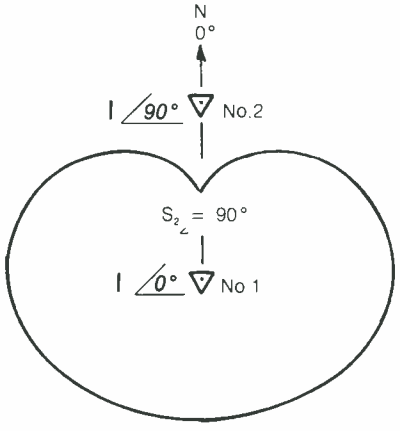
Fig. 7(a) is termed a broadside array because the maximum radiation is broadside to a line through the towers. Fig. 7(b) shows a similar arrangement, but with the phase of the current in the north tower shifted by 180 degrees. Then the fields from



(a) Broadside Array



(b) End Fire Array



(c) Cardioid Array

Fig. 7. Three simple directional antenna patterns.

the two towers cancel each other when viewed from the east or west but would produce maximum radiation north or south. This would be termed an end-fire array because maximum radiation coincides with a line through the ends of the array. Fig. 7(c) alters the spacing to 90 degrees and phasing to 90 degrees so as to produce a cardioid pattern. Other combinations of tower spacing and phasing can produce a great variety of pattern shapes. See Appendix B.

Multiplication of Two Tower Patterns

Perhaps the most widely used method of controlling pattern shape involves the multiplication of two tower patterns. This is illustrated in Fig. 8. When a two tower pattern such as pattern No. 1 with nulls at $\pm\phi_{n1}$ is multiplied by pattern No. 2 with nulls at $\pm\phi_{n2}$ the result is pattern No. 3 in a three tower array. The directions of all of the two tower array nulls are maintained in the three tower array. This is a very powerful design technique for protecting other stations and still serving a desired service area. In this special case the spacings S_2 and S_3 are equal resulting in an in line array with the fields of towers No. 2 and No. 3 being added in the center tower and the end tower of the three tower array is the multiplication of these fields as shown in pattern No. 3 of Fig. 8.

In the event that the protection directions are not symmetrically located, the two tower arrays can be placed on different azimuth angles as shown in Fig. 9 to produce a four tower parallelogram array. The nulls of the No. 1 pattern are maintained and the nulls of No. 2 pattern are maintained in the four tower parallelogram array. Furthermore, the spacing from No. 1 tower to No. 2 and No. 3 towers do not have to be the same. By this approach of using one or more parallelograms a wide variety of asymmetrical patterns are possible with relative simplicity of pattern calculations. However, modern computer techniques can optimize individual tower locations, currents and phases so as to produce an efficient pattern, frequently using fewer towers than required with the parallelogram approaches.

Systematization of Patterns

The pattern possibilities resulting from variations in spacing and phasing have been systematized and a sample of two-tower patterns is

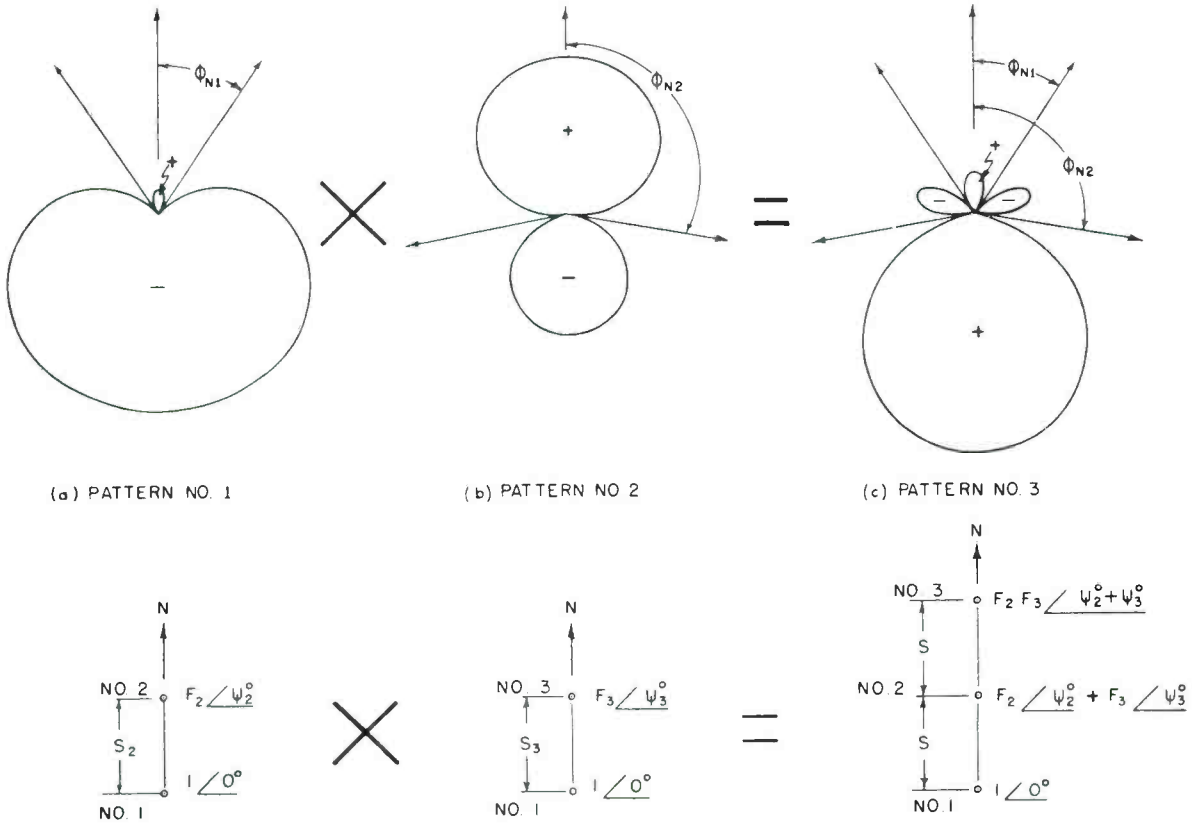
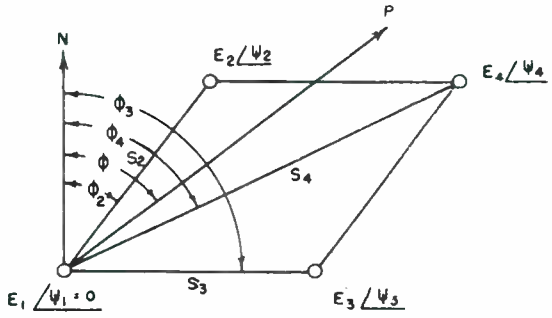


Fig. 8. Multiplications of patterns to produce a three tower in line array.



GENERAL FOUR TOWER CONFIGURATION

Fig. 9. Multiplication of two patterns to produce a four tower parallelogram array.

shown in Appendix B. See Reference 1 for 3-tower patterns.

Radiation Pattern Size

The pattern size is usually determined by integrating the energy flow outward through an imaginary hemispherical surface surrounding the directional antenna array. This method does not give information regarding the distribution of power radiated from the various towers of the directional antenna array, however, it is very useful for making comparisons of pattern size. This computation method is available in digital computer programs and is used by FCC.

There are other methods of determining pattern size such as the "Mutual Resistance Method" which employs Bessel Functions and the "Driving Point Impedance Method" which uses mesh circuit equations with self and mutual impedance information.

The "method of moments" is now available in large computer programs to determine; current distribution on towers and top loading cables, base driving point impedances and the vertical pattern of directional antenna arrays.

Driving Point Impedance

The input impedance of each tower in an array, called driving point impedance, is not that of the nondirectional tower. The driving point impedance contains the self impedance plus the mutual impedance multiplied by the current ratios that depend on the array as driven to produce the desired pattern. The driving point impedance will modify the self impedance depending on the array parameters and can even make the base resistance negative so that the tower draws power from the other towers and dissipates the power into a load resistor or delivers it back to the phasing system. Because the driving point impedance is affected by the currents in the other towers, it can only be measured by an operating bridge inserted in the tower feed point while the other towers are operating with essentially correct current magnitude and phase parameters.

Base Currents Versus Radiated Fields

In a directional array, the tower base current ratios will usually depart substantially from the calculated radiated field ratios when the pattern is correctly adjusted. This is caused by the mutual coupling between towers which distorts the sinusoidal current distribution otherwise assumed for each tower. Thus, the correct pattern is initially proved by means of a series of field strength measurements in significant radial directions from the station rather than by assuming that measurement of tower currents and phases can establish the correct pattern.

Near-Field Versus Far-Field Conditions

Theoretically a directional antenna pattern is not fully formed except at an infinite distance, where the separate towers can be considered as a point source. As a practical matter, near-field effects can persist as far as 20 miles from an antenna before far-field conditions prevail. This is especially true in the deep minimums of wide-space arrays; however, misleading measurement results can often occur under apparently innocent circumstances. Near-field calculations involve consideration of the actual inverse distance attenuation and the actual phase delay from each antenna element to a series of observation points along a radial.

Fig. 10 shows the results of such calculations on a minimum radial and the resulting analysis of field strength measurements. Line A is the inverse distance line for the theoretical unattenuated radiation at one mile. Line B is the result of the near-field calculations assuming only inverse distance attenuation, that is, no soil losses. It converges with the inverse distance line with increasing distance. Line C represents a soil conductivity of 10mmhos/m as drawn in the conventional manner from analysis of nondirectional measurements on the radial. Line D is a composite of Lines B and C. It includes the near-field calculations and is attenuated with distance in accordance with the soil conductivity previously established. This composite line converges with the near-field calculations at short distances where soil attenuation is negligible and converges with the soil conductivity line at great distances where near-field effects disappear. Since curve D accounts for both near-field effects and soil losses, it is the proper curve against which the directional field strength measurement data should be fitted.

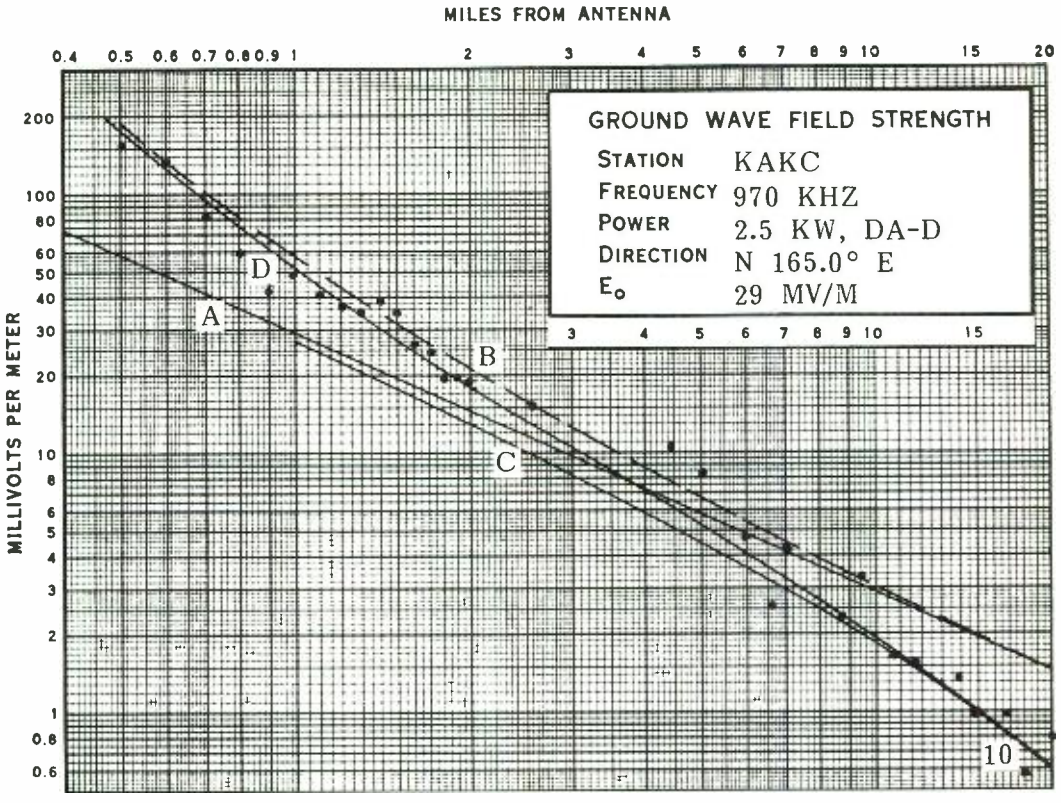


Fig. 10. Near-field effects.

Note the good fit to the measurement data, both close to the array and at distant points even though the first 19 measurement points fall considerable above the inverse distance Line A.

Pattern Size Versus Pattern Shape

The shape of a directional antenna pattern is determined by the adjustment of the phase and ratio parameters, whereas the pattern size is a measure of the power radiated and is affected by the transmitter power output and the losses within the phasing system and the ground system. Since pattern size and shape are essentially independent, it is most expeditious to adjust an array to get the correct shape before expending much concern on the size.

Field strength measurements on a previously-licensed directional antenna may appear to indicate a change in pattern shape or size when the change was in fact due to changes in soil conductivity. Such changes affect distant measurements more than close-in measurements. In some areas of the United States, the conductivity is typically higher during winter and spring months when the soil is more moist than in summer and fall months.

Seasonal conductivity variations are not observable in some portions of the country, yet are extreme in other areas. One well-documented case showed a seasonal doubling of signal strength at 20 miles in the main lobe of a correctly adjusted system operating on 1380 kHz. To avoid the misleading effects of seasonal conductivity changes that might appear to distort measured directional antenna patterns in size or shape, the FCC requires that all the field strength measurements in a directional antenna proof of performance be made under "similar environmental conditions".

Standard Patterns

Theoretical (also called calculated) patterns can have nulls wherein the radiation at specific azimuths goes completely to zero. In practice, it is not possible to prove by field strength measurements that a null exists. Reradiation and scatter from objects external to the array limit the depth to which a pattern minimum can be proven. Additionally, operational variations in phase and ratio parameters will increase radiation in any direction where the deepest possible minimum has been previously established. To accommodate these limitations, the FCC authorizes a "standard" pattern for each directional antenna station. Standard patterns exceed the theoretical pattern at all azimuths by specified and

easily calculated amounts. It is required that the radiation from a directional station not exceed its standard pattern. All U.S. stations employing directional antennas have FCC specified standard patterns. These supersede all earlier patterns based on theoretical calculations or on field strength measurements. The standard pattern radiation values are now used exclusively in all calculations of coverage and interference.

Augmented Patterns

Augmentation is applied to the standard pattern when the measured field strength is exceeded in discrete directions but does not cause interference to other stations. When augmentation is desired, it is achieved by applying Eq. (C-7) in Appendix C.

REFERENCES

1. *Directional Antenna Patterns*
2. *Theory and Design of Directional Antennas*
3. *Standard Broadcast Antenna Systems*
4. *Design and Operation of Directional Antennas*
5. Directional Antenna Pattern Shapes
6. *Radiation Characteristics of Transmitting Antennae (An Introduction to Directional Antenna Pattern Design)*
7. *Directional Antenna Design Example*
8. *Parasitic Reradiation*
9. *Introduction to Directional Antenna Systems*
10. *Instructions for Installation of Radio Broadcast Stations Ground Systems*
11. *Log Periodic Antenna Design Handbook*
12. *Radio Broadcast Ground Systems*
13. Stuart Ballantine, "On the Optimum Transmitting Wavelength for a Vertical Antenna Over Perfect Earth", Proc. I.R.E. Vol. 12, pp. 833-839; December, 1924.
14. Carl E. Smith and Earl M. Johnson, "Performance of Short Antennas", Proc. I.R.E., Vol. 35, pp. 1026-1038; October 1947.
15. Carl E. Smith, John R. Hall and James O. Weldon, "Very High-Power Long-Wave Broadcasting Station", Proc. I.R.E., Vol. 42, No. 8, pp. 1222-1235; August, 1954.
16. Ralph N. Harmon, "Some Comments on Broadcast Antennas", Proc. I.R.E., Vol. 24, pp. 36-47; January, 1936.
17. George H. Brown, "A Critical Study of the Characteristics of Broadcast Antennas as Affected by Current Distribution", Proc. I.R.E., Vol. 24, pp. 48-81; January, 1936.
18. Carl E. Smith, "A Critical Study of Several Antennas Designed to Increase the Primary Coverage of a Radio Broadcasting Transmitter", Professional Thesis at Ohio State University, Columbus, Ohio.
19. Carl E. Smith, "A Critical Study of Two Broadcast Antennas", Proc. I.R.E., Vol. 24, pp. 1329-1341; October, 1936.
20. Morrison, J. F., and P. E. Smith: *The Shunt Excited Tower*, Proc. IRE, vol. 25, pp. 673-696, June, 1937.
21. Jeffers, C. L.: *An Antenna for Controlling the Nonfading Range of Broadcasting Stations*, Proc. IRE, vol. 36. pp. 1426-1431, November, 1948.
22. Smith, Carl E., D. B. Hutton, and W. G. Hutton: *Performance of Sectionalized Broadcasting Towers*, IRE Trans., pp. 22-34, December, 1955.

APPENDIX A

DIRECTIONAL ANTENNAS FOR PATTERN SHAPE

Space Configuration

The plan configuration of the k[th] tower in an array is shown in Fig. A-1. A space view of the k[th] tower and observation point P is shown in Fig. A-2.

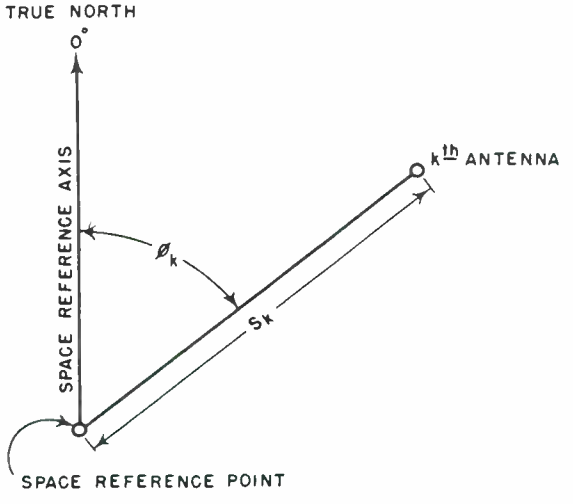


Fig. A-1. Plan view of space configuration of k[th] antenna.

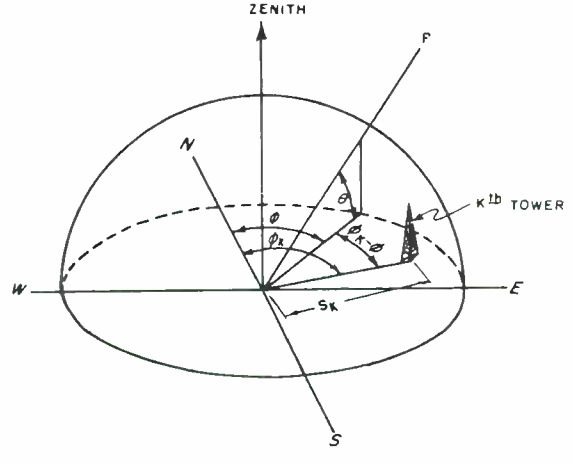


Fig. A-2. Space view of observation point P and the k[th] tower.

Vector Diagram

The field strength at the point P in space for the k[th] tower is shown in Fig. A-3. The space phasing in the horizontal plane is shown in Fig. A-4 and in the elevation plane the space phasing is reduced further as shown in Fig. A-5.

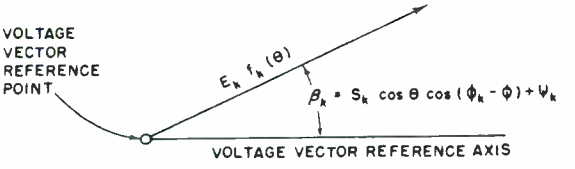


Fig. A-3. Voltage vector diagram for the k[th] antenna.

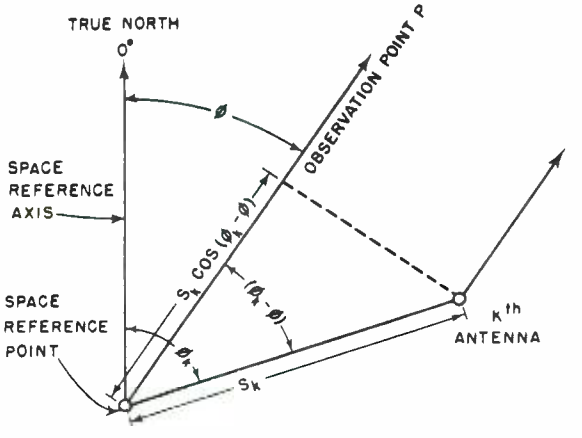


Fig. A-4. Plan view of k[th] antenna showing space phasing in the horizontal plane.

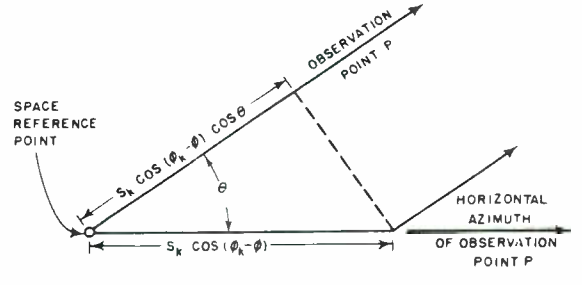


Fig. A-5. Elevation angle θ shortens the spacing S_k to the value of $S_k \cos\theta$.

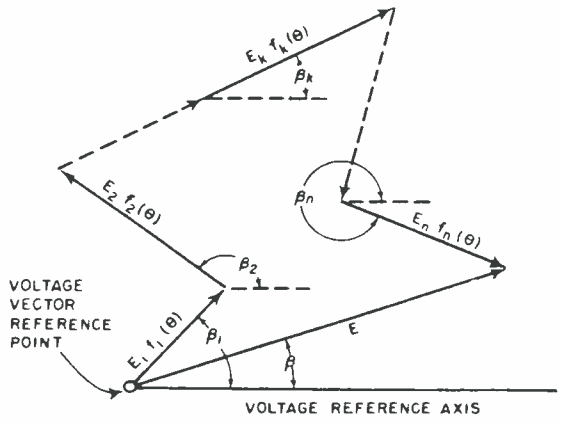


Fig. A-6. Summation of field strength vectors for n antennas in the directional antenna array.

Generalized Equation

The vector equation to express the vectors in Fig. A-6 is the generalized equation that can be used to express the pattern shape for a directional antenna array of n towers. The equation in condensed form is,

$$E = \sum_{k=1}^{k=n} E_k \; f_k(\theta) \; \angle \beta_k \qquad \text{[A-1]}$$

Where:

E = the total effective field strength vector at unit distance (P) for the antenna array with respect to the voltage vector reference axis. This vector makes the angle β with respect to this axis as shown in Fig. A-6.

k = the k^{th} tower in the directional antenna system.

n = the total number of towers in the directional antenna array.

E_k = the magnitude of the field strength at unit distance in the horizontal plane produced by the k^{th} tower acting alone.

$f_k(\theta)$ = vertical radiation characteristic of the k^{th} antenna as given in Eq. A-3.

θ = elevation angle of the observation point P measured up from the horizon in degrees.

$$\beta_k = S_k \cos\theta \cos(\phi_k - \phi) + \psi_k \qquad \text{[A-2]}$$

= phase relation of the field strength at the observation point P for the k^{th} tower taken with respect to the voltage vector reference axis. $S_k\cos(\phi_k - \phi)\cos\theta$ is the space phasing portion of β_k due to the location of the k^{th} tower and ψ_k is the phasing portion of β_k.

S_k = electrical length of spacing of the k^{th} tower in the horizontal plane from the space reference point.

ϕ_k = true horizontal azimuth, orientation of k^{th} tower with respect to the space reference axis.

ϕ = true horizontal azimuth angle of the direction to the observation point P (measured clockwise from true north).

ψ_k = time phasing portion of β_k due to the electrical phase angle of the voltage (or current) in the k^{th} tower taken with respect to the voltage vector reference axis.

The shape of any directional antenna pattern can be computed by applying the above equations, however, many directional antenna arrays can be designed by simplified versions of this equation.

For a vertical antenna having a sinusoidal current distribution with a current node at the top, the vertical radiation characteristic takes on the form

$$f(\theta) = \frac{\cos(G \sin\theta) - \cos G}{(1 - \cos G)\cos\theta} \qquad \text{[A-3]}$$

Where:

$f(\theta)$ = vertical radiation characteristic

G = electrical height of the antenna in electrical degrees

θ = elevation angle of the observation point measured up from the horizon in degrees.

The vertical radiation characteristics in Eq. [A-3] are graphed in Fig. A-7.

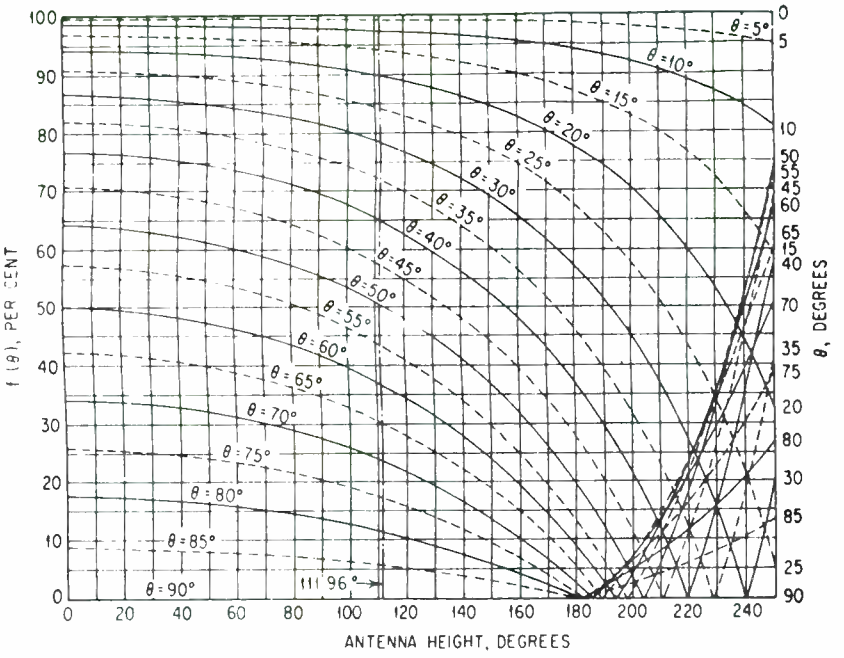


Fig. A-7. Vertical-radiation characteristic as a function of electrical tower height for various values of elevation angle.

For top-loaded tower the formula is,

$$f(\theta) = \frac{\cos B \cos (A \sin \theta) - \cos G - \sin B \sin \theta \sin (A \sin \theta)}{\cos \theta (\cos B - \cos G)} \qquad \text{[A-4]}$$

This is the vertical-radiation characteristic for a top-loaded tower of height A and top-loaded to a height of $G = A + B$.

For a two section top-loaded tower as shown in Fig. 5 the formula is,

$$f(\theta) = \frac{\cos B \cos (A \sin\theta) - \cos G + \dfrac{\sin B \cos (H - C) \cos (C \sin \theta)}{\sin (H - A)} - \dfrac{\sin B \sin \theta \sin (H - C) \sin (C \sin \theta)}{\sin(H - A)} - \dfrac{\sin B \cos (H - A) \cos (A \sin \theta)}{\sin(H - A)}}{\cos \{ \cos B - \cos G + [\sin B/\sin(H - A)](\cos \overline{H - C} - \cos \overline{H - A})\}}$$

This is the vertical-radiation-characteristic equation for a two-section sectionalized tower. The same procedure can be applied if more than two sections are involved, such as shown in Fig. 6.

Theoretical Self-loop and Base-radiation Resistance

It is useful to know the theoretical loop and base resistance of a vertical radiator. This information is presented graphically in Fig. A-8 along with the theoretical inverse field strength at 1 mile.

Mutual-impedance Curves

The value of mutual impedance for most tower heights and spacing is given in Fig. A-9. The loop mutual impedance between quarter-wave towers is shown in Fig. A-10.

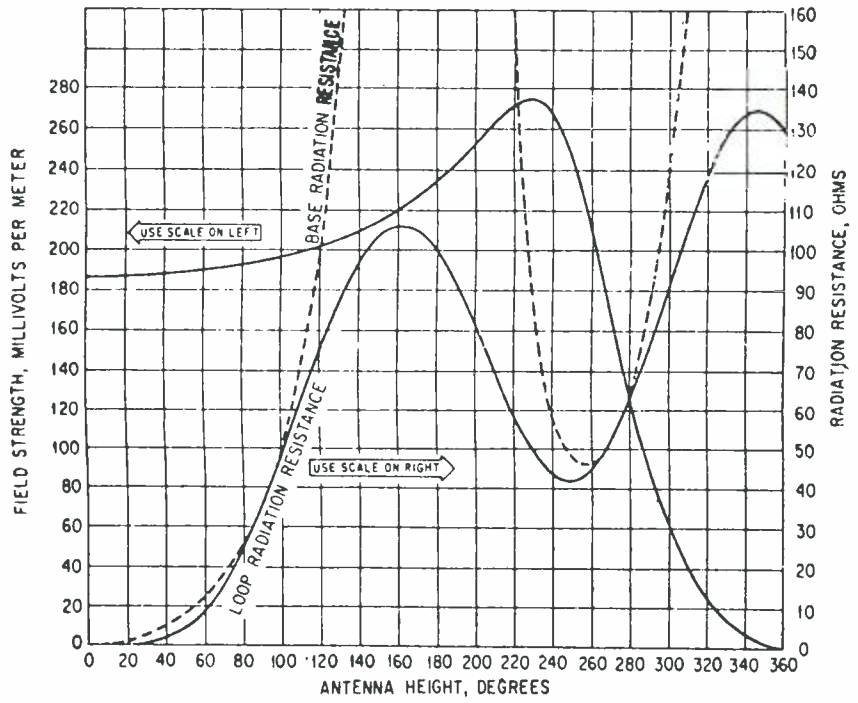


Fig. A-8. Inverse field strength at 1 mile for 1 kw, loop and base radiation resistance as a function of tower height over a perfectly conducting earth.

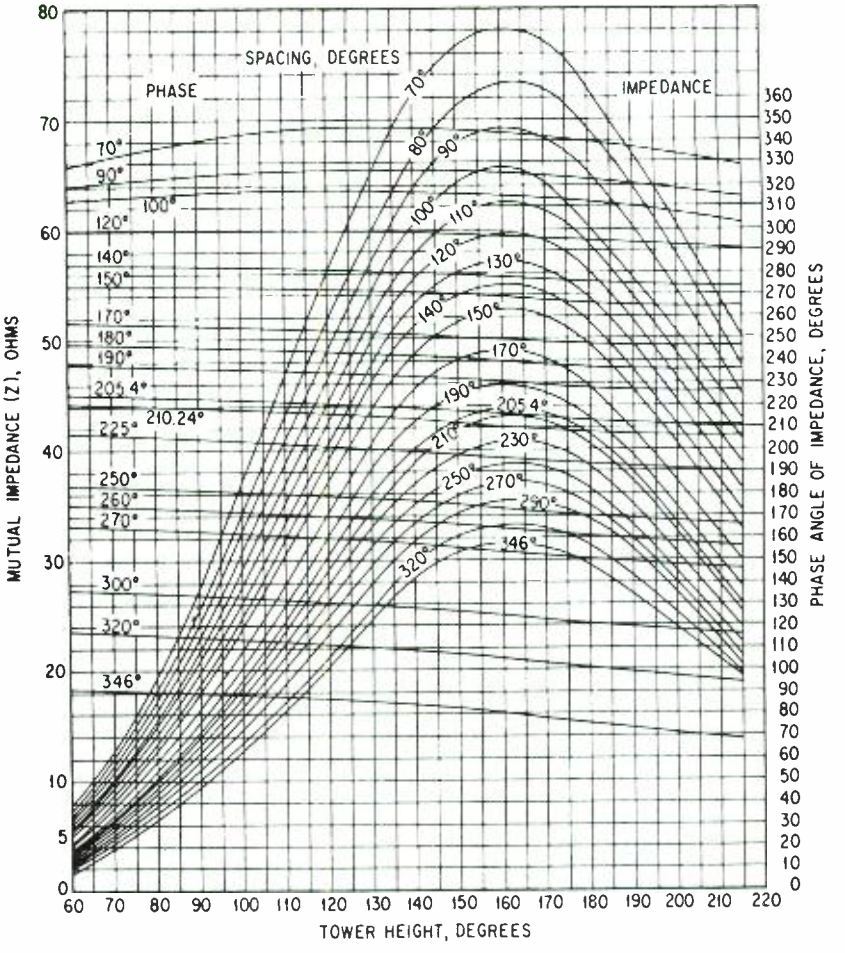


Fig. A-9. Loop mutual impedance and phase angle between two towers of equal height.

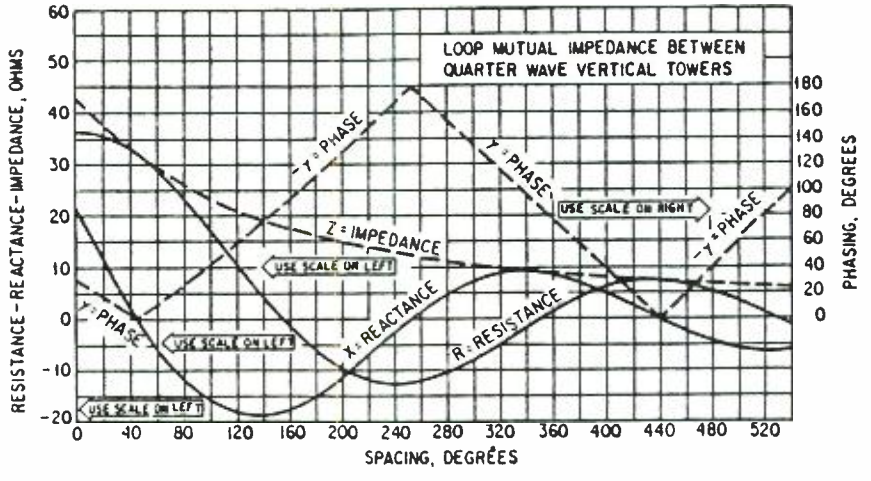


Fig. A-10. Loop mutual impedance between quarter-wave vertical towers.

Horizontal RMS Field Strength

The field-strength gain or loss of a two-tower array for various values of phasing and spacing is shown in Fig. A-11.

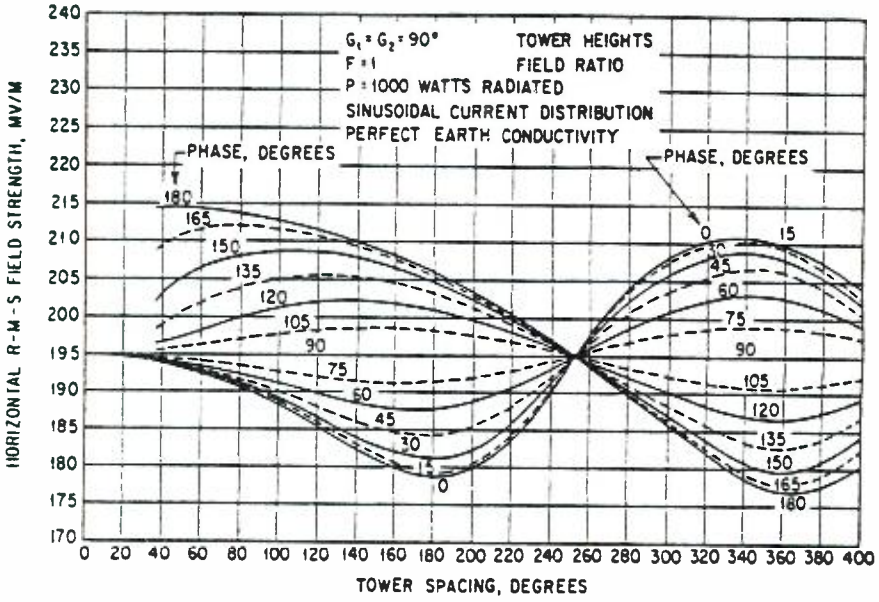


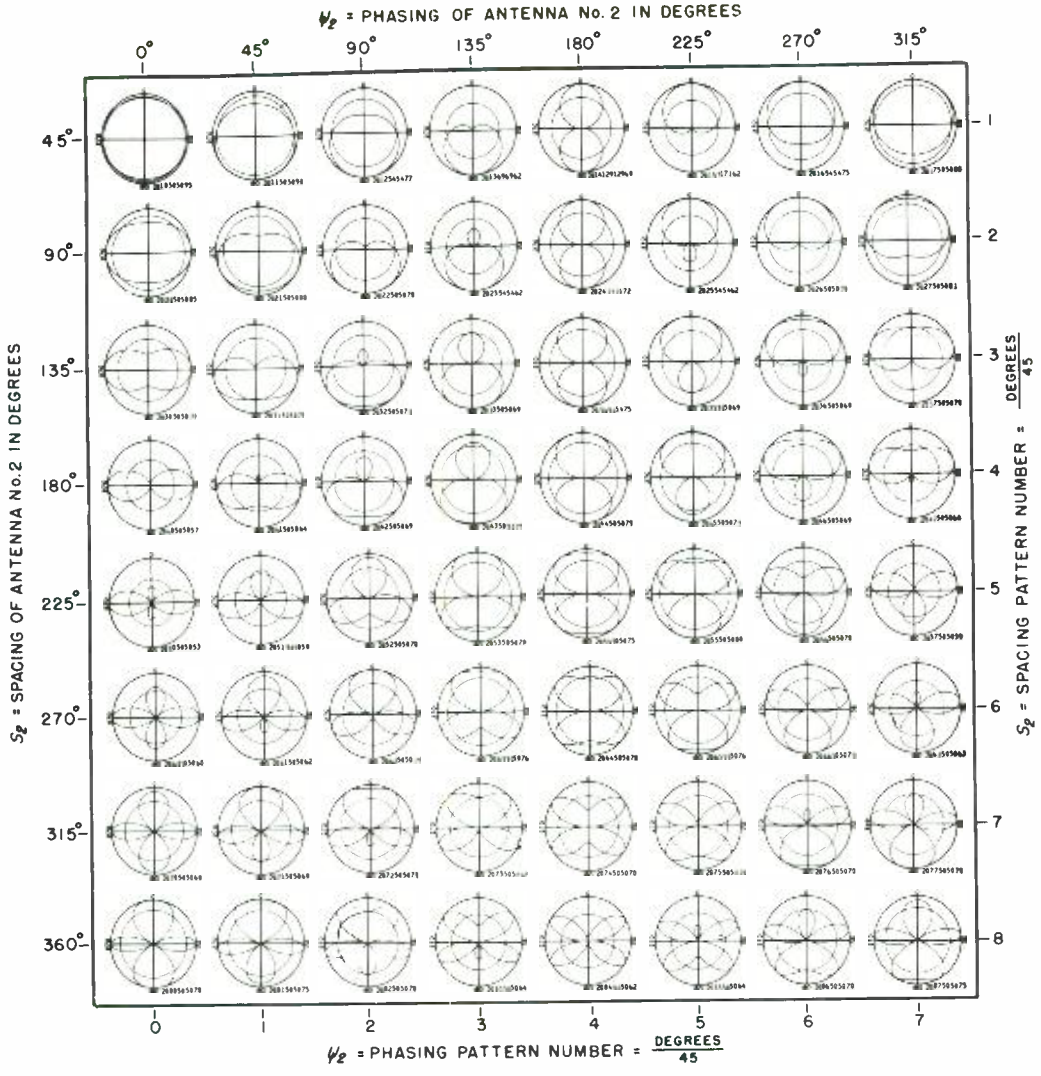
Fig. A-11. Horizontal rms field strength of two-tower directional antenna.

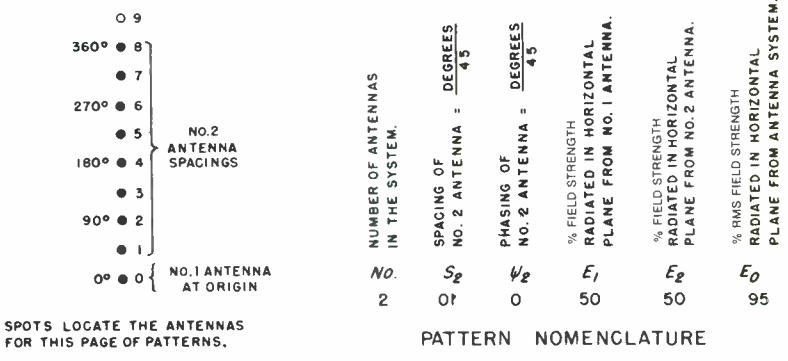
APPENDIX B

SYSTEMATIZATION OF TWO TOWER PATTERNS

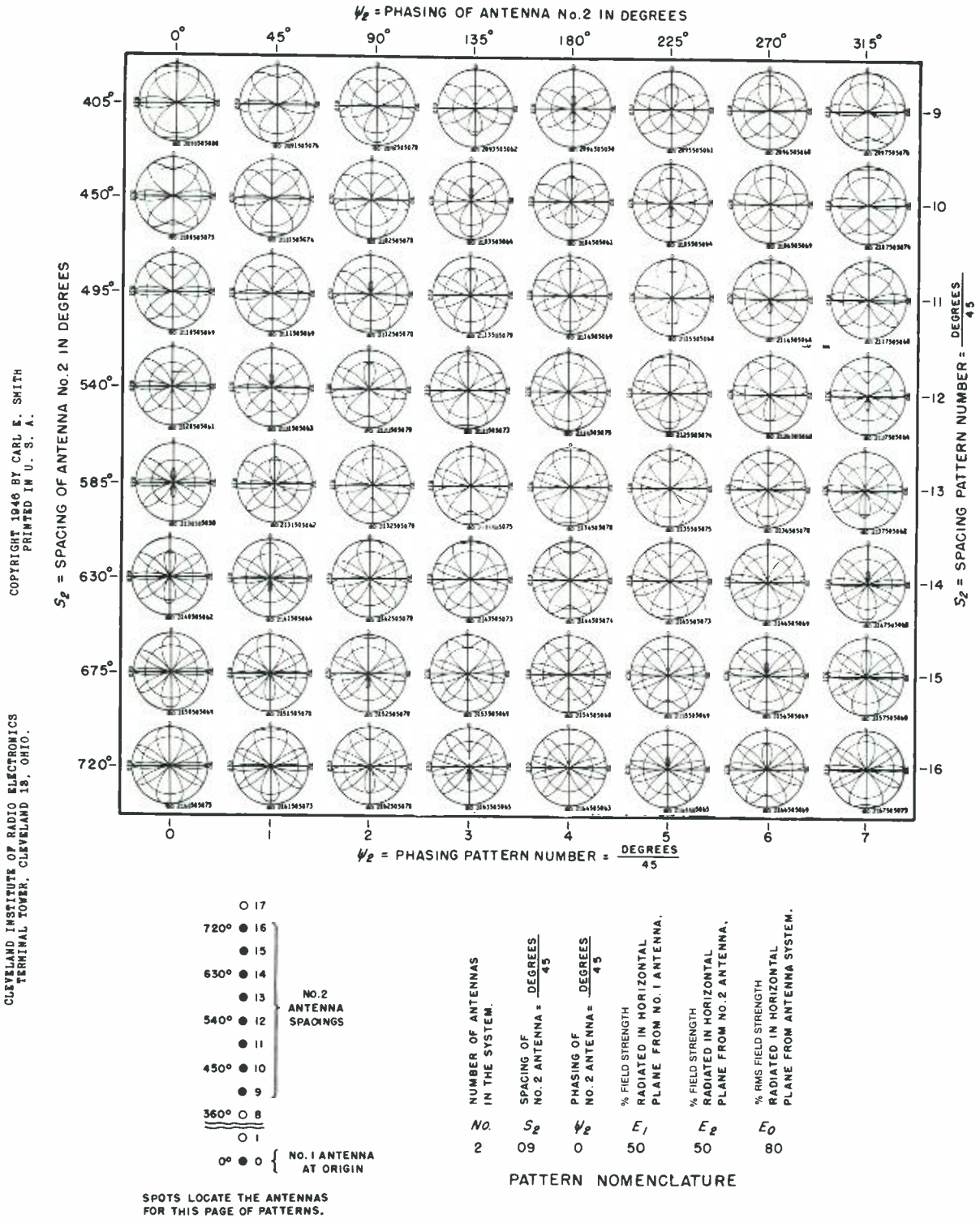
The pattern numbering system has been devised to furnish the antenna parameters in an orderly fashion as described at the bottom of each page. To simplify the numbering system the spacing and phasing of each antenna is shifted in steps of 45 degrees. The spacing varies from 45 degrees on page B-1 to 1440 degrees on page B-4 while the phasing varies from 0 degrees to 315 degrees on each page. The field strength of each antenna, E_1 and E_2 is expressed in percent of the maximum lobe field strength (50%) of the horizontal pattern and finally the last two digits specify in percent the RMS field strength in the horizontal plane of the two tower directional antenna array.

The detailed patterns on pages B-5 through B-10 are for spacings in steps of 15 degrees up to 360 degrees. The phasings are only presented from 0 degrees to 180 degrees since the same patterns, oriented 180 degrees, results for phasing from 180 degrees to 360 degrees.

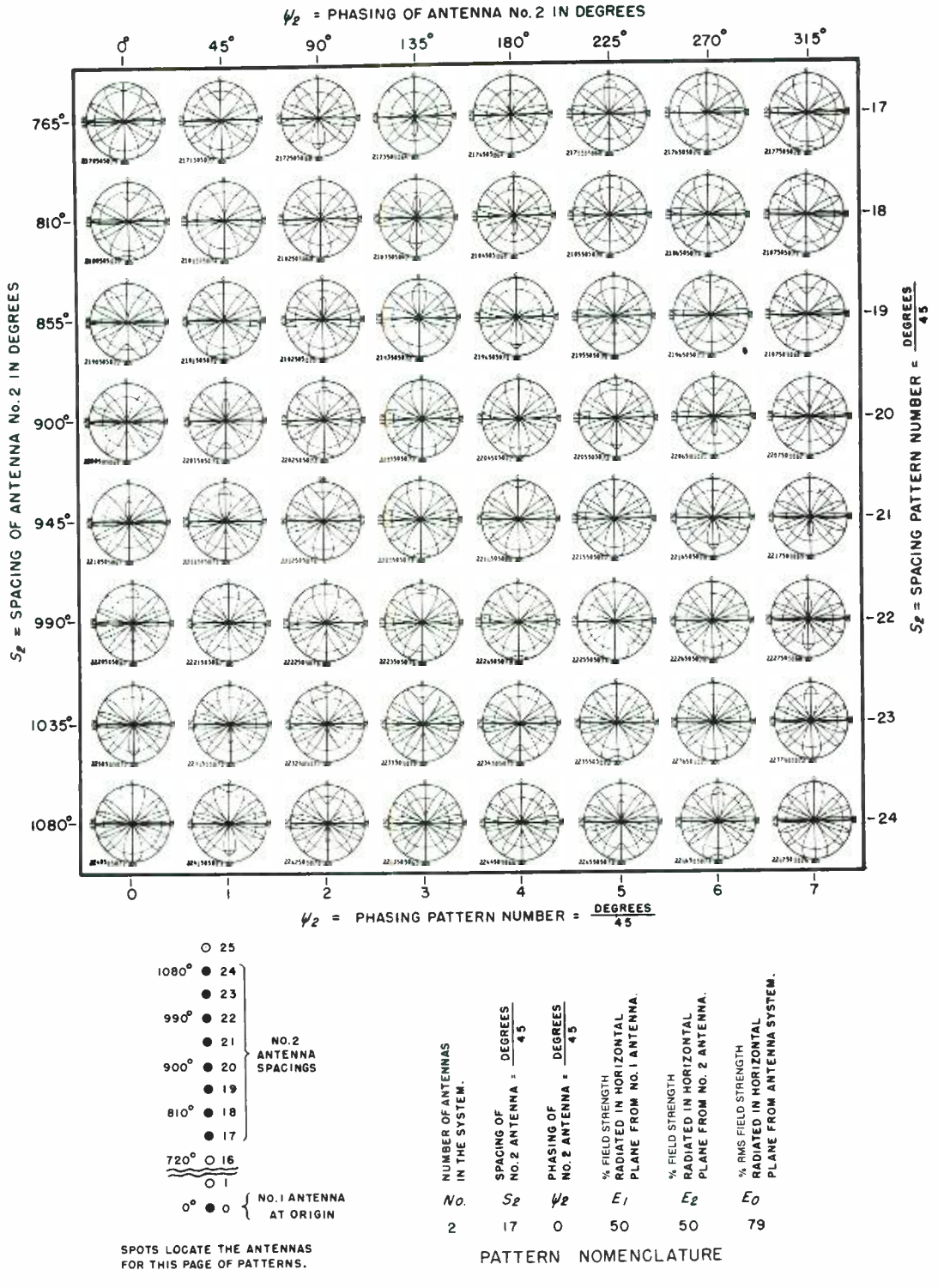

ψ2 = PHASING OF ANTENNA No. 2 IN DEGREES
0° 45° 90° 135° 180° 225° 270° 315°
S2 = SPACING OF ANTENNA No.2 IN DEGREES
45° 90° 135° 180° 225° 270° 315° 360°
S2 = SPACING PATTERN NUMBER = DEGREES / 45
0 1 2 3 4 5 6 7
ψ2 = PHASING PATTERN NUMBER = DEGREES / 45


9
360° 8
7
270° 6
5
NO.2 ANTENNA SPACINGS
180° 4
3
90° 2
1
0° 0
NO.1 ANTENNA AT ORIGIN
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS.
NUMBER OF ANTENNAS IN THE SYSTEM.
SPACING OF NO. 2 ANTENNA = DEGREES / 45
PHASING OF NO. 2 ANTENNA = DEGREES / 45
% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA.
% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA.
% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM.
No. S2 ψ2 E1 E2 E0
2 01 0 50 50 95
PATTERN NOMENCLATURE

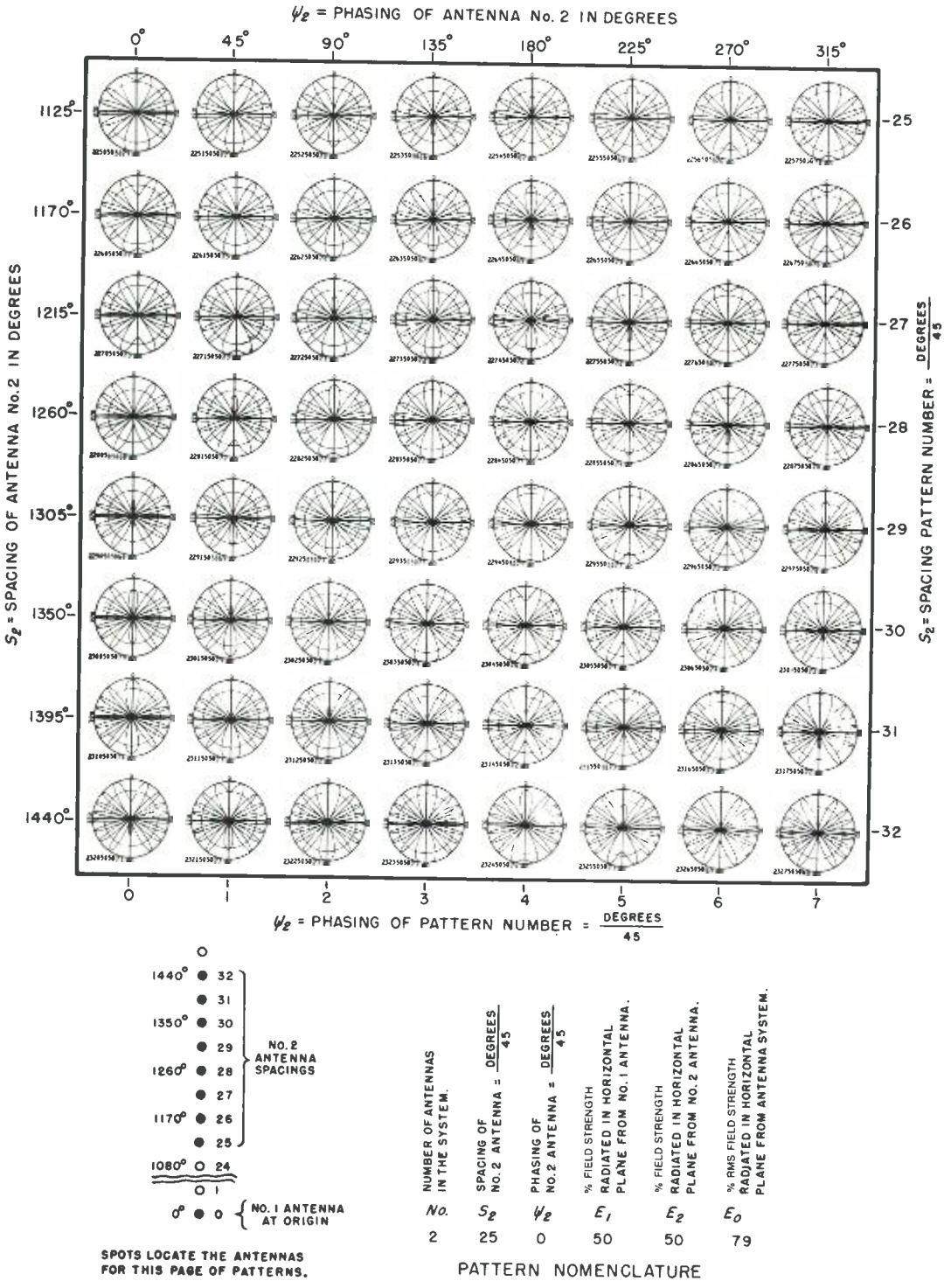
Appendix B-1.


ψ2 = PHASING OF ANTENNA No.2 IN DEGREES
0° 45° 90° 135° 180° 225° 270° 315°
405° 450° 495° 540° 585° 630° 675° 720°
S2 = SPACING OF ANTENNA No.2 IN DEGREES
-9 -10 -11 -12 -13 -14 -15 -16
S2 = SPACING PATTERN NUMBER = DEGREES / 45
0 1 2 3 4 5 6 7
ψ2 = PHASING PATTERN NUMBER = DEGREES / 45
COPYRIGHT 1946 BY CARL E. SMITH
PRINTED IN U. S. A.
CLEVELAND INSTITUTE OF RADIO ELECTRONICS
TERMINAL TOWER, CLEVELAND 15, OHIO.
O 17
720° ● 16
● 15
630° ● 14
● 13
540° ● 12
● 11
450° ● 10
● 9
360° O 8
O 1
0° ● 0
NO.2 ANTENNA SPACINGS
NO. I ANTENNA AT ORIGIN
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS.
NUMBER OF ANTENNAS IN THE SYSTEM.
SPACING OF NO. 2 ANTENNA = DEGREES / 45
PHASING OF NO. 2 ANTENNA = DEGREES / 45
% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. I ANTENNA.
% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO.2 ANTENNA.
% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM.
NO. S2 ψ2 E1 E2 E0
2 09 0 50 50 80
PATTERN NOMENCLATURE

Appendix B-2.


ψ2 = PHASING OF ANTENNA No. 2 IN DEGREES
0° 45° 90° 135° 180° 225° 270° 315°
765° 810° 855° 900° 945° 990° 1035° 1080°
S2 = SPACING OF ANTENNA No. 2 IN DEGREES
-17 -18 -19 -20 -21 -22 -23 -24
S2 = SPACING PATTERN NUMBER = DEGREES / 45
0 1 2 3 4 5 6 7
ψ2 = PHASING PATTERN NUMBER = DEGREES / 45
O 25
1080° ● 24
● 23
990° ● 22
● 21
900° ● 20
● 19
810° ● 18
● 17
720° O 16
O 1
0° ● 0
NO.2 ANTENNA SPACINGS
NO.1 ANTENNA AT ORIGIN
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS.
NUMBER OF ANTENNAS IN THE SYSTEM.
SPACING OF NO.2 ANTENNA = DEGREES / 45
PHASING OF NO.2 ANTENNA = DEGREES / 45
% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO.1 ANTENNA.
% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA.
% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM.
No. S2 ψ2 E1 E2 E0
2 17 0 50 50 79
PATTERN NOMENCLATURE

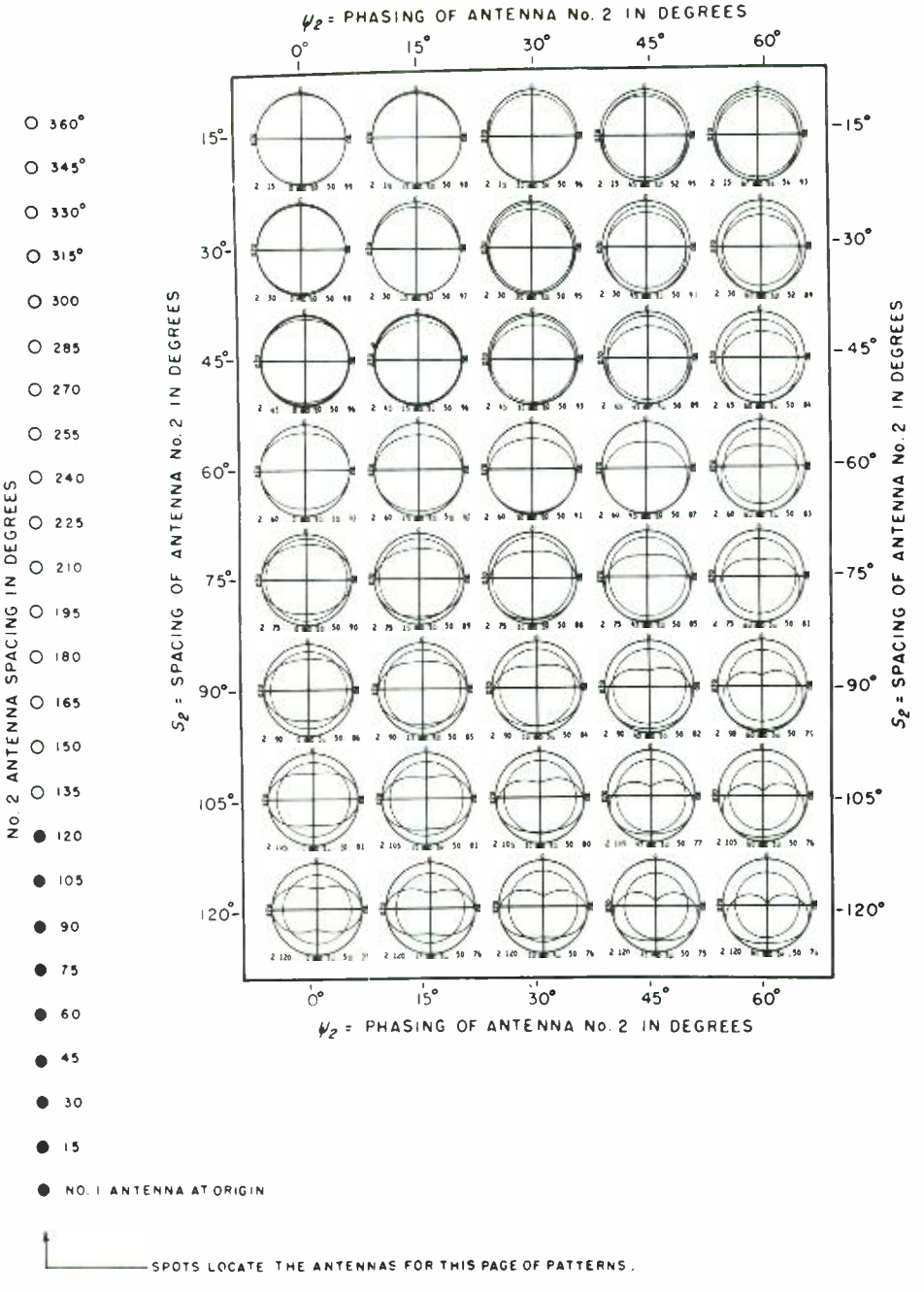
Appendix B-3.



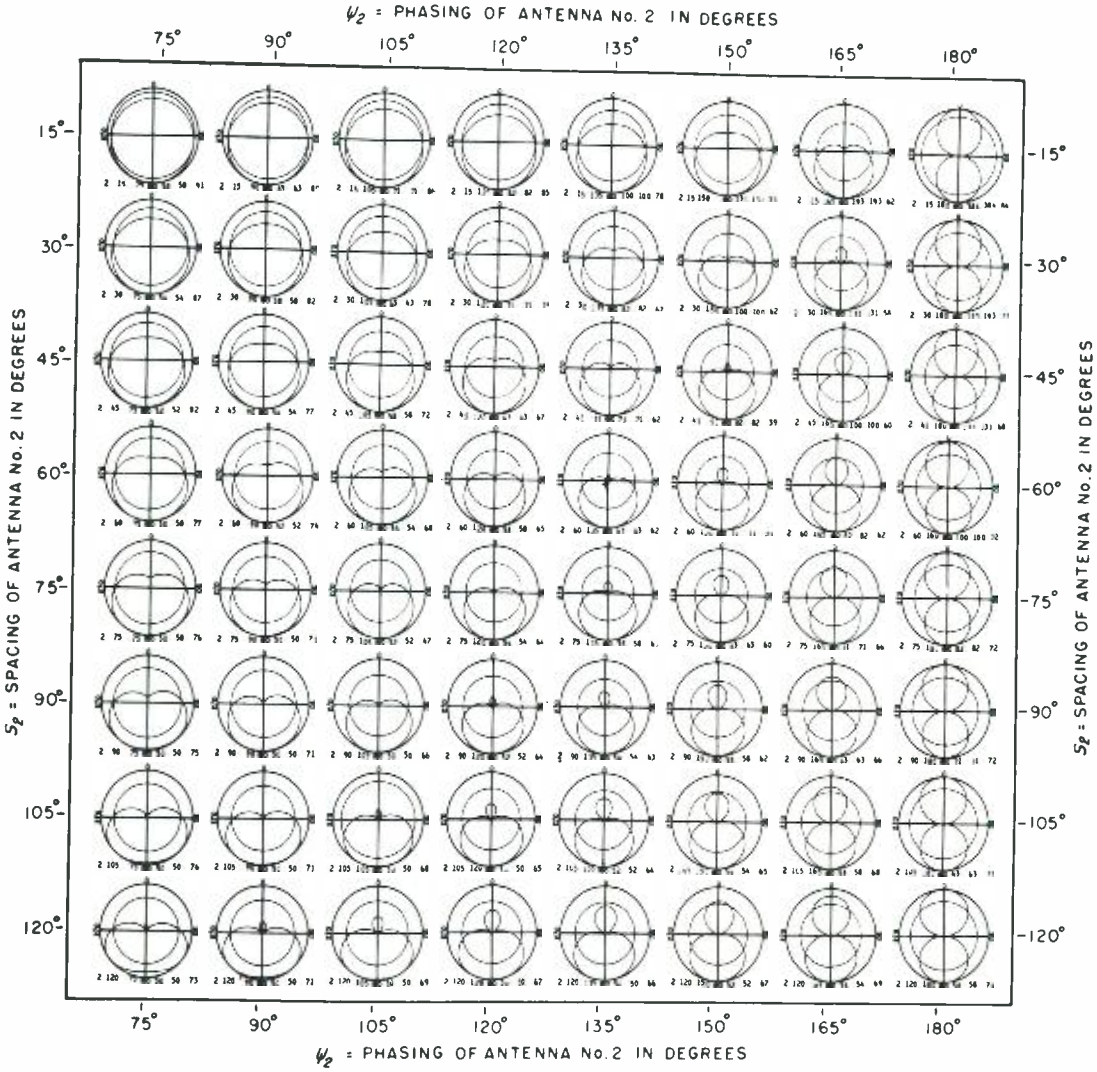
COPYRIGHT 1946 BY CARL E. SMITH
PRINTED IN U. S. A.

CLEVELAND INSTITUTE OF RADIO ELECTRONICS
TERMINAL TOWER, CLEVELAND 13, OHIO.

Appendix B-4.


ψ2 = PHASING OF ANTENNA No. 2 IN DEGREES
0°
15°
30°
45°
60°
S2 = SPACING OF ANTENNA No. 2 IN DEGREES
15°
30°
45°
60°
75°
90°
105°
120°
-15°
-30°
-45°
-60°
-75°
-90°
-105°
-120°
NO. 2 ANTENNA SPACING IN DEGREES
360°
345°
330°
315°
300
285
270
255
240
225
210
195
180
165
150
135
120
105
90
75
60
45
30
15
NO. 1 ANTENNA AT ORIGIN
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS.

Appendix B-5.



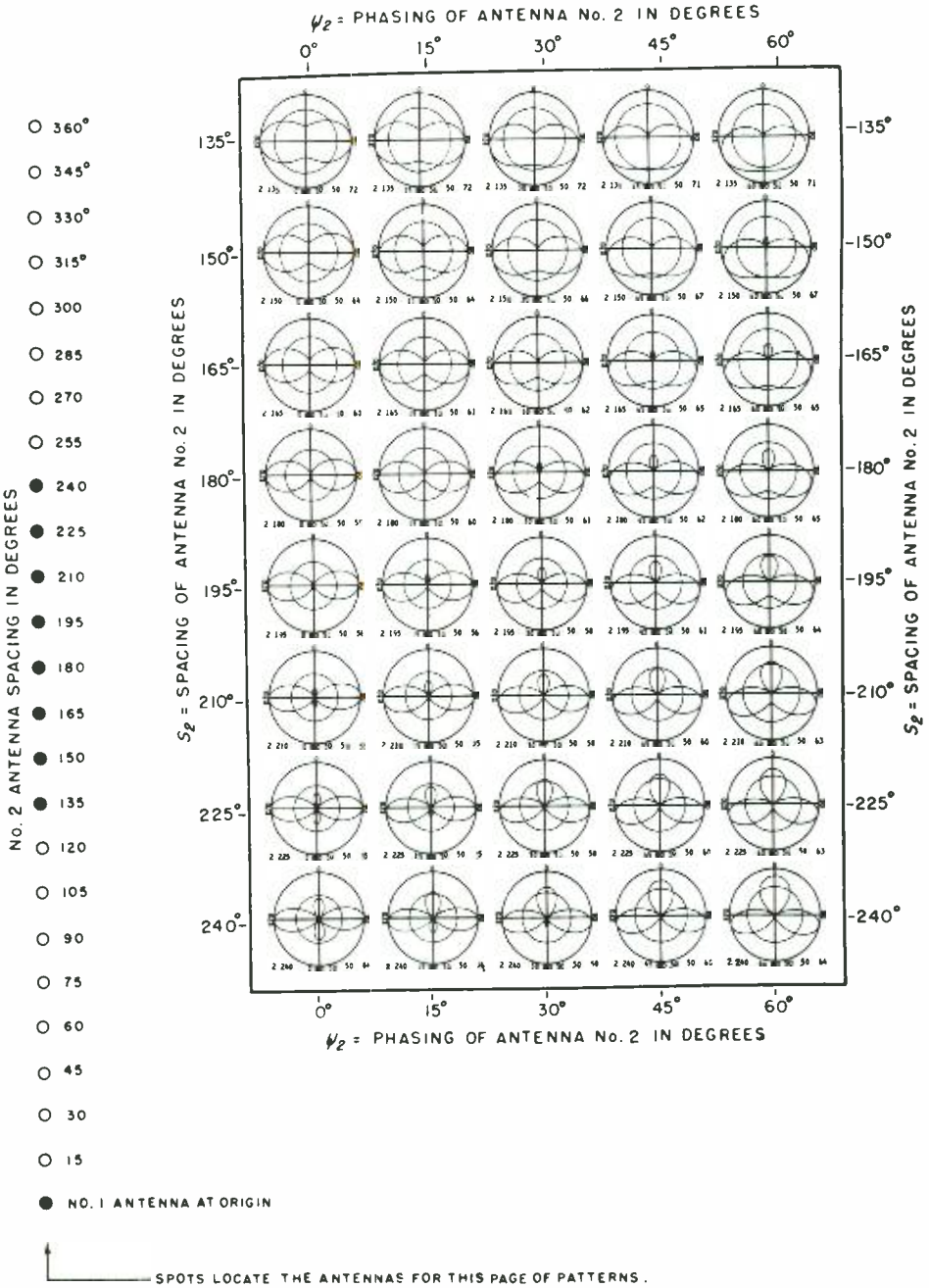
COPYRIGHT 1946 BY CARL E. SMITH
PRINTED IN U. S. A.

CLEVELAND INSTITUTE OF RADIO ELECTRONICS
TERMINAL TOWER, CLEVELAND 13, OHIO.

No.	NUMBER OF ANTENNAS IN THE SYSTEM	SPACING OF NO. 2 ANTENNA IN DEGREES S_2	PHASING OF NO. 2 ANTENNA IN DEGREES ψ_2	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA E_1	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA E_2	% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM E_0
2	15	75	58	58	91

PATTERN NOMENCLATURE

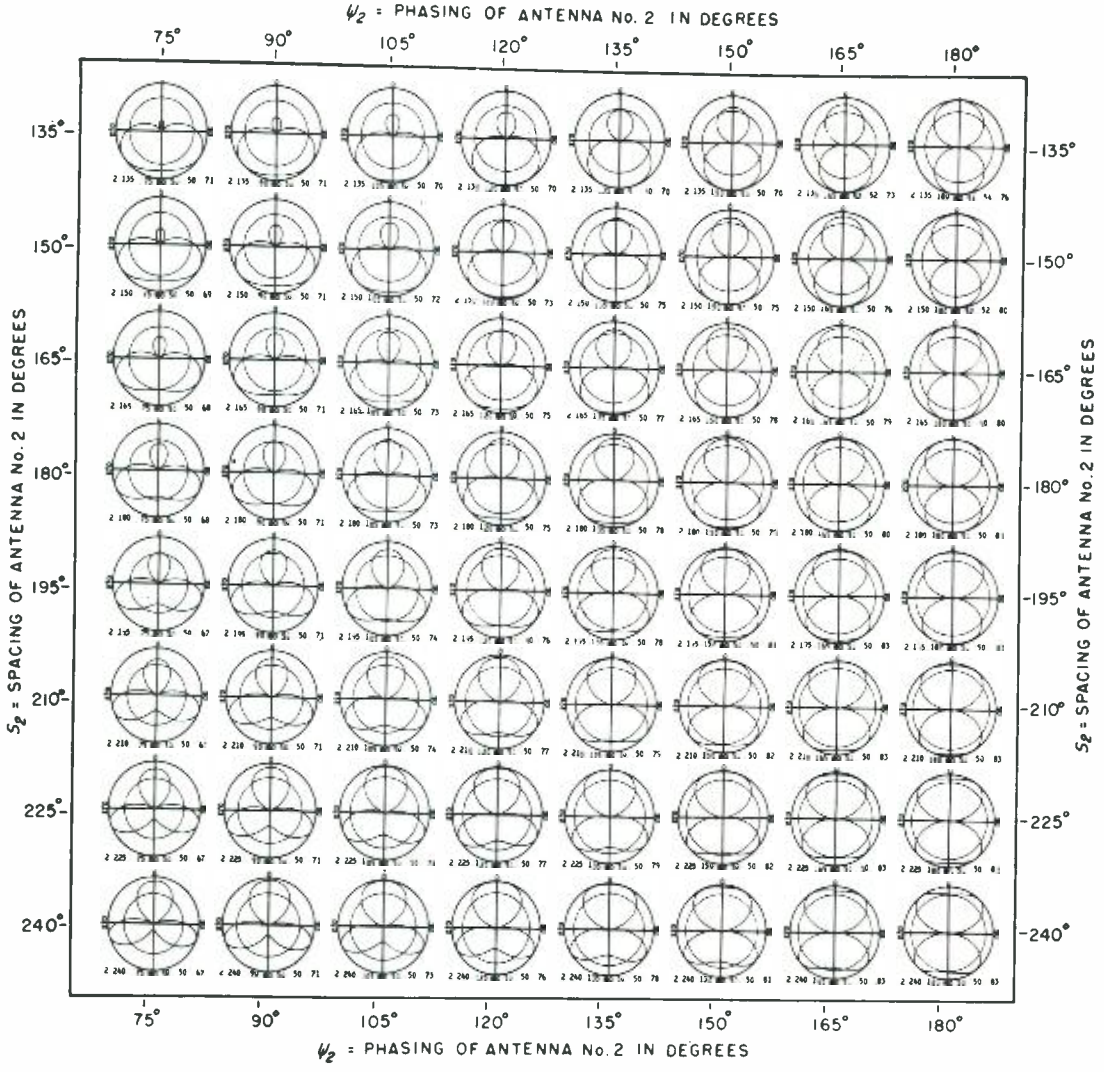
Appendix B-6.


ψ2 = PHASING OF ANTENNA No. 2 IN DEGREES
0°
15°
30°
45°
60°
135°
150°
165°
180°
195°
210°
225°
240°
-135°
-150°
-165°
-180°
-195°
-210°
-225°
-240°
S2 = SPACING OF ANTENNA No. 2 IN DEGREES
NO. 2 ANTENNA SPACING IN DEGREES
360°
345°
330°
315°
300
285
270
255
240
225
210
195
180
165
150
135
120
105
90
75
60
45
30
15
NO. 1 ANTENNA AT ORIGIN
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS.

Appendix B-7.

COPYRIGHT 1946 BY CARL E. SMITH
PRINTED IN U. S. A.

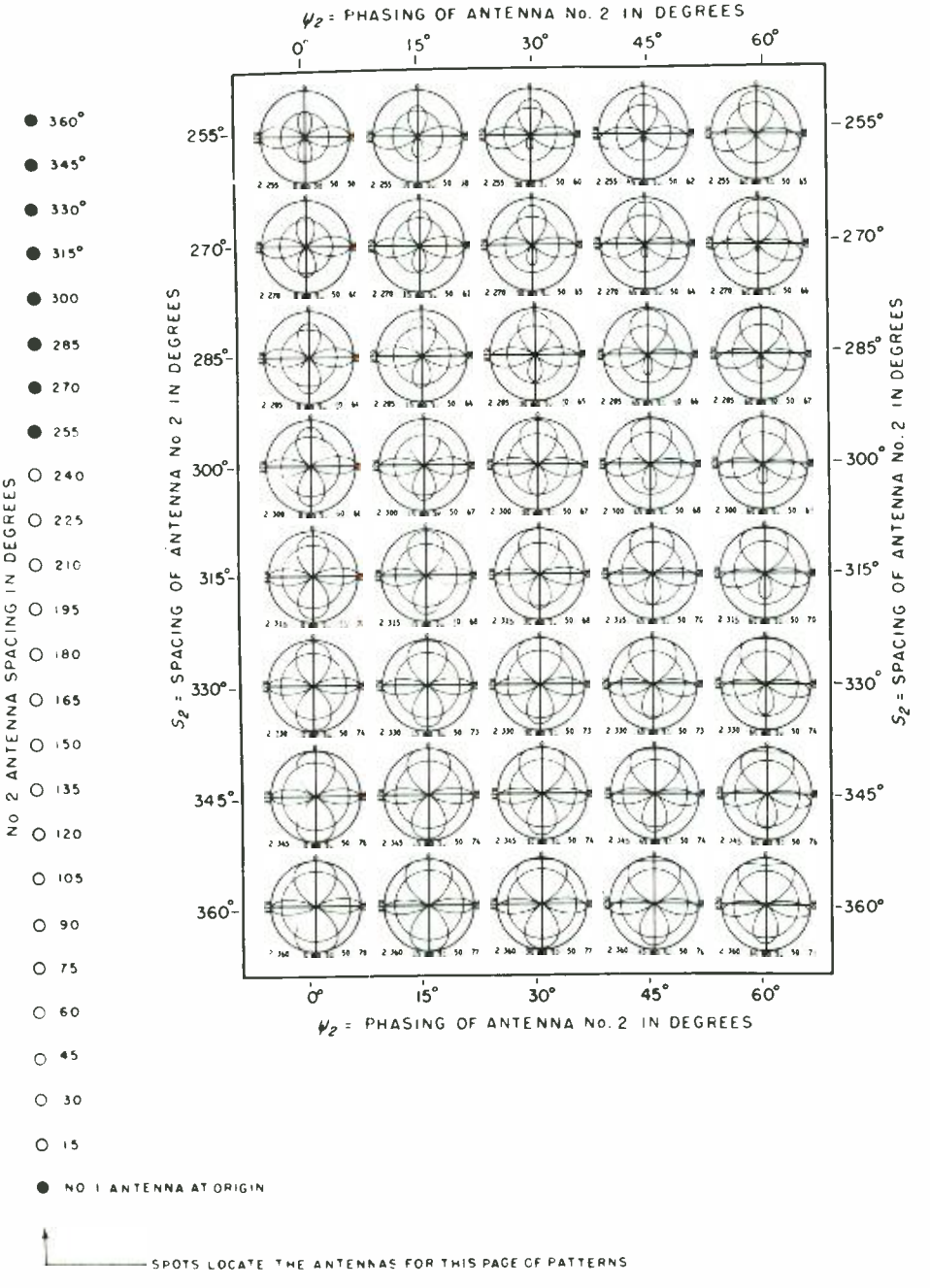
CLEVELAND INSTITUTE OF RADIO ELECTRONICS
TERMINAL TOWER, CLEVELAND 13, OHIO.



NUMBER OF ANTENNAS IN THE SYSTEM	SPACING OF NO. 2 ANTENNA IN DEGREES	PHASING OF NO. 2 ANTENNA IN DEGREES	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA	% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM
No.	S_2	ψ_2	E_1	E_2	E_0
2	315	75	50	50	71

PATTERN NOMENCLATURE

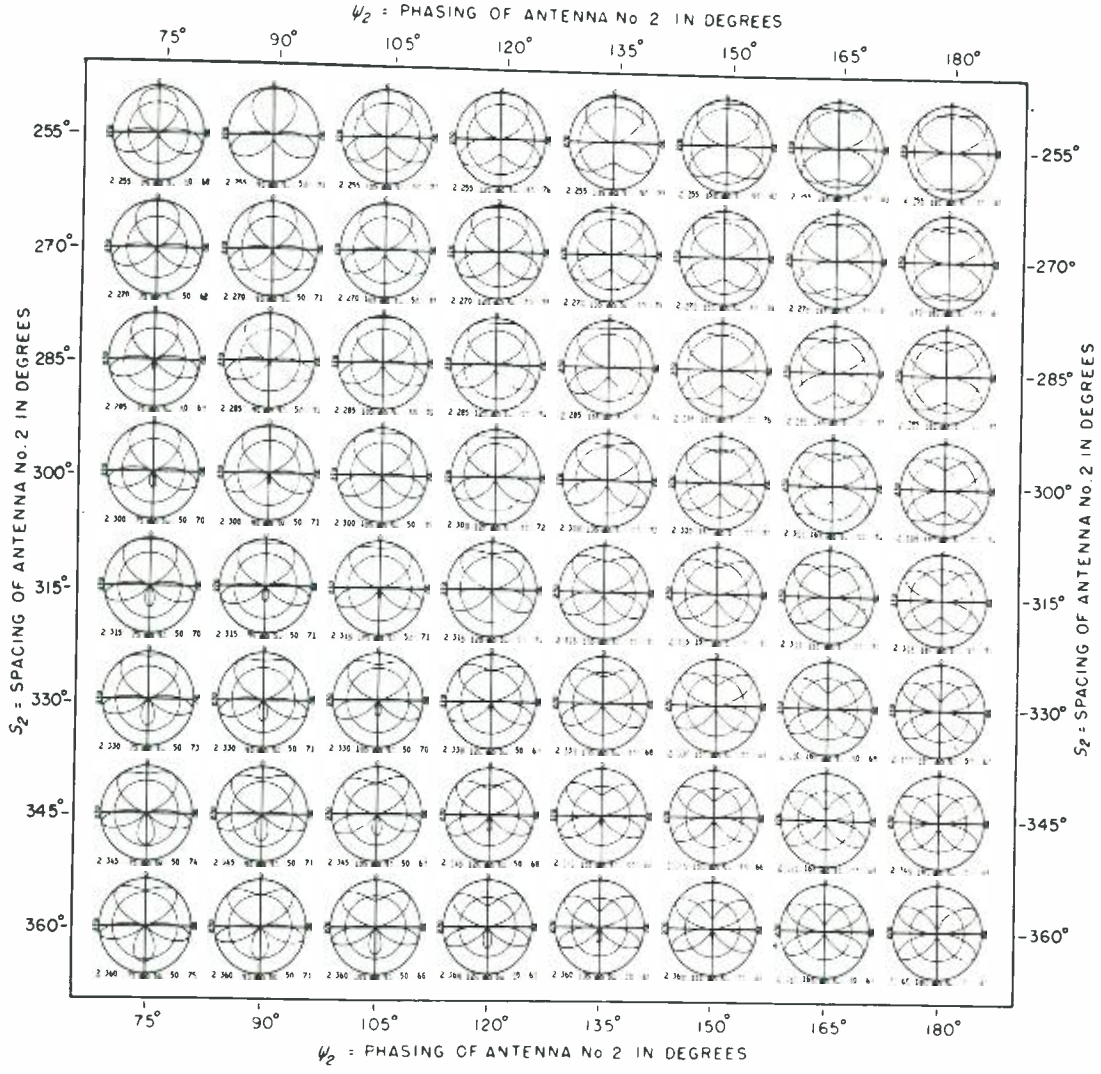
Appendix B-8.


ψ_2 = PHASING OF ANTENNA No. 2 IN DEGREES
0°
15°
30°
45°
60°
255°
270°
285°
300°
315°
330°
345°
360°
S_2 = SPACING OF ANTENNA No 2 IN DEGREES
S_2 = SPACING OF ANTENNA No. 2 IN DEGREES
No 2 ANTENNA SPACING IN DEGREES
360°
345°
330°
315°
300
285
270
255
240
225
210
195
180
165
150
135
120
105
90
75
60
45
30
15
NO 1 ANTENNA AT ORIGIN
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS

Appendix B-9.

COPYRIGHT 1946 BY CARL E. SMITH
PRINTED IN U. S. A.

CLEVELAND INSTITUTE OF RADIO ELECTRONICS
TERMINAL TOWER, CLEVELAND 13, OHIO.



No.	S_2	ψ_2	E_1	E_2	E_0
NUMBER OF ANTENNAS IN THE SYSTEM	SPACING OF NO.2 ANTENNA IN DEGREES	PHASING OF NO.2 ANTENNA IN DEGREES	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO 2 ANTENNA	% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM
2	255	75	50	50	68

PATTERN NOMENCLATURE

Appendix B-10.

APPENDIX C

DIRECTIONAL ANTENNAS PATTERN DEVELOPMENT

Theoretical Pattern Equation

The theoretical pattern equation of Appendix A can be written as follows by changing the k^{th} tower to the i^{th} tower to conform with FCC, thus

$$E(\phi, \theta)_{th} = \left| k \sum_{i=1}^{n} F_i(\theta) \angle S_i \cos\theta \cos(\phi_i - \phi) + \psi_i \right| \quad [C\text{-}1]$$

where k = multiplying constant which determines pattern size *Standard Pattern Equation*

The standard pattern equation is obtained from Eq. [C-1] by adding the quadrature Q term to fill minimums and increase the size by five percent, thus

$$E(\phi, \theta)_{std} = 1.05\sqrt{[E(\phi, \theta)_{th}]^2 + Q^2} \quad [C\text{-}2]$$

where:

Q is the greater of the following quantities:

$$0.025\, g(\theta)\, E_{rss} \quad [C\text{-}3]$$

or

$$10.0\, g(\theta)\sqrt{P_{kw}} \quad [C\text{-}4]$$

where:

$g(\theta)$ is the vertical plane distribution factor, $f(\theta)$, for the shortest element in the array (see Eq. [C-2] above; also see FCC Rules Section 73.190, Figure 5). If the shortest element has an electrical height in excess of 0.5 wavelength, $g(\theta)$ shall be computed as follows:

$$g(\theta) = \frac{\sqrt{\{f(\theta)\}^2 + 0.0625}}{1.030776} \quad [C\text{-}5]$$

$$E_{rss} = \sqrt{\sum_{i=1}^{n} E_i^2} \quad [C\text{-}6]$$

As an example, consider a two tower array, the theoretical pattern in Eq. [C-1] becomes,

$$E = E_1 f_1(\theta) \angle 0° + E_2 f_2(\theta) \angle S_2 \cos(\phi_2 - \phi) + \psi_2$$

Now for 5 kw with 90° towers for the following parameters:

Tower No.	Height G°	Field Ratio	Spacing 5°	True Bearing ϕ°	Phase ψ°
1	90	1.0	0	0	0
2	90	1.0	90	0	−90

the computer gives

E_{rss} (theoretical pattern) = 429.96 mV/m
Q (quadrature term) = 13.42 mV/m
E_{rms} (standard pattern) = 451.68 mV/m

A plot of the theoretical and standard patterns are shown in Fig. C-1.

The minimum horizontal field strength (at one mile) when the theoretical field strength goes to zero is given by Eq. [C-2] for a standard pattern along the ground, using Eq. [C-4] with g (θ) = 1.0. For 1 kw and under, the Q is 6 according to FCC Rules. For various FCC licensed values of power the minimum field strength values are as follows;

P_{kw}	Q	$E_{mV/m}$
0.25	6.0	6.3
0.50	6.0	6.3
1.00	6.0	6.3
2.50	9.49	9.96
5.0	13.42	14.09
10.0	18.97	19.92
25.0	30.00	31.50
50.0	42.43	44.55

The minimum field strength (at one mile) for any elevation of a standard pattern, by Eq. [C-5] is

$$g(\theta) = \frac{\sqrt{0 + 0.0625}}{1.030776} = 0.2425$$

Augmented Pattern Equation

The augmented pattern equation is obtained by adding an augmentation quadrature term to the standard pattern as given in the following equation,

$$E_{(\phi, \theta)\,aug.} = \sqrt{\{E_{(\phi, \theta std.}\}^2 + A\{g(\theta)\cos(180\frac{D_A}{S})\}^2} \quad [C\text{-}7]$$

where:

$E_{(\phi, \theta)\ aug}$ = Augmented Radiation Value at Azimuth/Elevation

$E_{(\phi, \theta)\ std}$ = Standard Pattern Radiation Value at Azimuth/Elevation

$A = \{E_{(\phi\ '\theta)\ aug}\}^2 - \{E_{(\phi\ '\theta)\ std}\}^2$

Augmentation Constant

$g(\theta)$ = lSame As In Standard Pattern [Eq. C-5]

S = Span of Augmentation In Degrees

D_A = Angular Distance from Center of Span

The principle of augmentation is illustrated in the cardioid pattern of Fig. C-2.

The FCC has converted all augmented directional patterns to a table for each station as shown in the example of Fig. C-3. In this case there were 6 augmentations as tabulated in Fig. C-4 and shown on the polar chart of Fig. C-5.

It should be noted that where the spans overlap Eq. [C-7] is applied repeatedly, once for each augmentation, proceeding clockwise from true north.

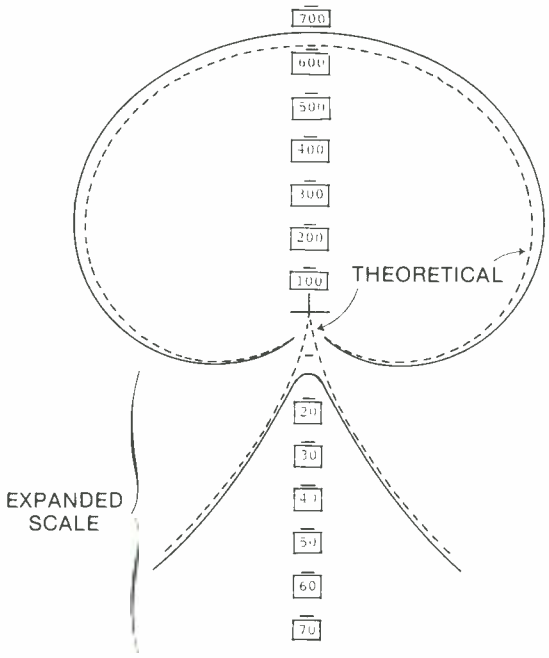


Fig. C-1. Theoretical and standard pattern.

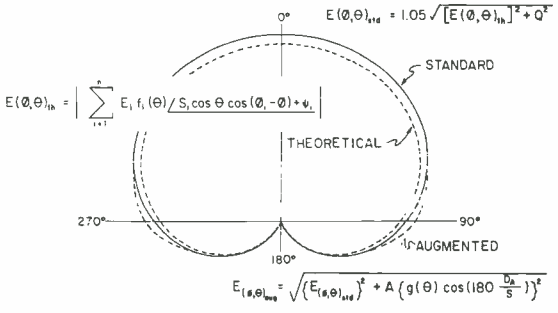


Fig. C-2. Theoretical, standard and augmented pattern.

TECHNICAL PARAMETERS RESULTING FROM CONVERSION
OF AM BROADCAST STATIONS TO STANDARD PATTERNS

STANDARD PATTERN CONVERSION NO.: 1280-22

FREQ. KHZ	CALL LETTER	CITY	STATE	PATTERN HRS.	PATTERN STATUS	CLASS
1280	WHVR	HANOVER	PA	N	LIC.	3

POWER KW	LATITUDE	LONGITUDE	PAT-MULT MV/M	TH-RMS MV/M	STD/AUG RMS-MV/M	PAT-RSS MV/M	Q-FACTOR
.500	39-49-11	77-00-25	131.27	143.00	150.54	185.65	6.0000

TOWER NO.	PHYS-HT (A)-DEG	TL-HT (B)-DEG	TOT-HT (C)-DEG	TL-HT (D)-DEG	FIELD RATIO	PHASE DEG.	SPACING DEG.	ORIENT DEG-TR	REF FLG
1	91.0	.0	.0	.0	1.000	149.5	.0	.0	
2	91.0	.0	.0	.0	1.000	.0	90.0	178.0	

----------AUGMENTATION DATA----------

CENTRAL AZIM. DEGREES TRUE	SPAN DEGREES	FIELD AT AZIM. MV/M
64.0	12.0	17.0
260.5	55.0	103.0
288.0	14.0	7.5
288.0	10.0	21.2
295.0	14.0	30.0
295.0	10.0	43.3

----------HORIZONTAL PLANE STANDARD/AUGMENTED RADIATION VALUES----------

AZ. DEG	FIELD MV/M	AZ. DEG	FIELD MV/M	AZ. DEG	FIELD MV/M	AZ. DEG	FIELD MV/M	AZ. DEG	FIELD MV/M	AZ. DEG	FIELD MV/M
0	136.8	60	29.1	120	174.0	180	239.4	240	163.9	300	42.2
10	132.8	70	9.0	130	196.3	190	237.0	250	136.2	310	71.0
20	123.1	80	43.5	140	213.5	200	231.2	260	104.7	320	95.4
30	107.5	90	80.0	150	225.9	210	221.4	270	69.3	330	114.4
40	86.3	100	115.0	160	234.0	220	207.2	280	31.3	340	127.7
50	59.8	110	146.7	170	238.4	230	188.0	290	20.4	350	135.1

CONSTRUCTION PERMIT LIMITS

AZIMUTH DEG.TRUE	PRESENT MV/M	NEW MV/M
64.0	17.0	17.0
231.0	179.0	185.8
288.0	33.0	21.2
352.0	131.0	135.9

--PATTERN MINIMA--

AZIMUTH DEG.TRUE	FIELD MV/M
68.5	6.8
284.5	17.3
290.0	20.4
299.0	40.9

--PATTERN MAXIMA--

AZIMUTH DEG.TRUE	FIELD MV/M
178.0	239.4
288.0	21.2
296.0	44.2
358.0	136.9

-FCC-

Fig. C-3. FCC method of specifying augmentation.

CENTER AZIMUTH OF AUGMENTATION	SPAN DEGREES	EXTENT OF SPAN	FIELD AT CENTER SPAN
64°	12°(±6°)	(58°-70°)	17.0
260.5°	55°(±27.5°)	(233°-288°)	103.0
288°	14°(±7°)	(281°-295°)	7.5
288°	10°(±5°)	(283°-293°)	21.2
295°	14°(±7°)	(288°-302°)	30.0
295°	10°(±5°)	(290°-300°)	43.3

Fig. C-4. Table of augmentation data.

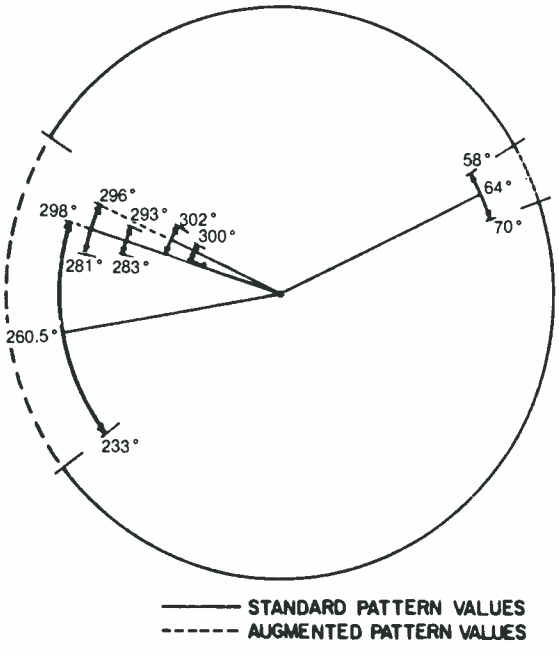


Fig. C-5. Augmented pattern flow chart showing overlapping spans.

2.4

AM Broadcast Antenna Systems

CHAPTER 2.4:
Part I: System Design
Part II: Phasing, Coupling
Part III: Maintenance

Part II: Antenna Coupling and Phasing Systems for AM Broadcast

Edward Edison, P.E.
Hammett and Edison, Inc.
San Francisco, California

AM broadcast antenna coupling and phasing systems consist principally of passive networks of coils, capacitors, transmission lines and of auxiliary components such as lightning gaps, meters, jacks, and relays. This equipment can range from simple (such as nondirectional station having the transmitter building located adjacent to the tower base) to complex (such as a multi-tower directional array requiring different patterns day and night). To understand antenna systems and their environment, we must consider the function of such systems and their performance objectives as well as the basic networks, power dividers, transmission lines, sampling systems, detuning systems, and transmitter load optimization.

THE FUNCTION OF A DIRECTIONAL ANTENNA PHASING SYSTEM

The function of a directional antenna phasing system is to distribute current to each tower with controllable phase and amplitude to generate the desired directional pattern. This function is accomplished typically by means of the following:

1. A network at each tower matches each tower load to its transmission line. (See Fig. 1) This network is typically in a box termed an antenna coupling unit or ACU. The remaining equipment, usually housed in one or more indoor cabinets, is termed a phasor.
2. Phasing networks provide control of the phase of each tower current (relative to the reference tower).
3. Power divider circuits control the relative current amplitude in each tower.
4. A common-point matching network adjusts the input impedance to a desirable resistive value without disturbing the phase or amplitude of the tower currents.

Fig. 1 shows a system with only two towers; each additional tower requires its own antenna coupling unit, transmission line, and phasing network, as well as additional components in the power divider.

PHASOR PERFORMANCE OBJECTIVES

The essential performance objective is to have both the phasor input impedance and the directional antenna radiation pattern remain essentially constant at all frequencies within the channel. The performance may be disappointing if the design process proceeds by a piecemeal block-by-block approach, where the networks are independently designed for each of the functions as illustrated in Fig. 1 and then merely connected together. A

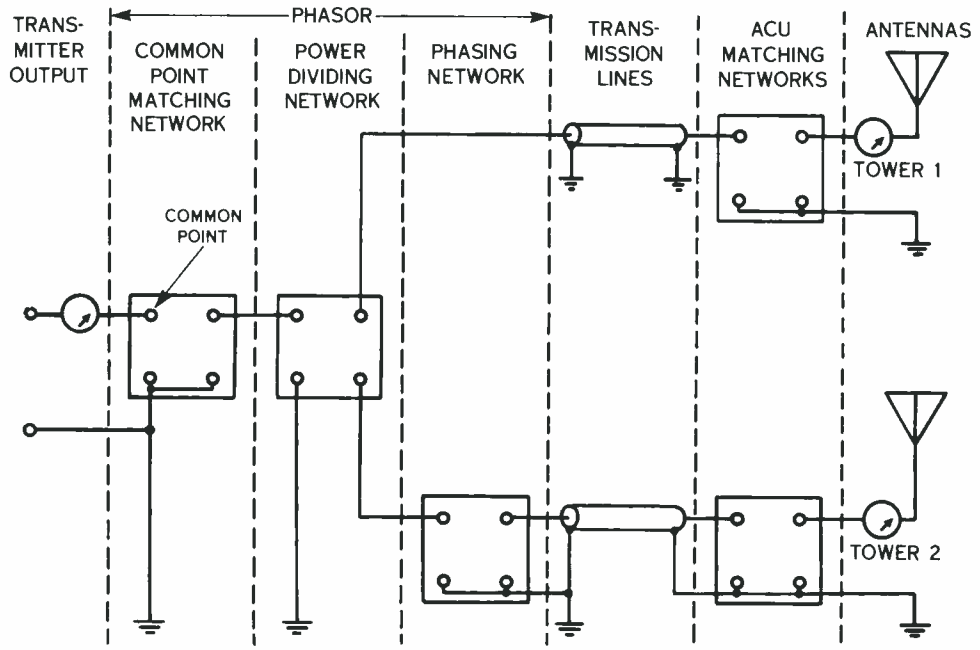


Fig. 1. Block diagram of a directional antenna system.

better approach is to use a systems design that considers the entire collection of components between the transmitter and the towers as a whole rather than by the "building block" approach implicit in Fig. 1.

Phasor Input Impedance

An ideal phasor would present a load to the transmitter that is purely resistive and unchanging at all sideband frequencies. However, phasors consist of coils and capacitors, whose reactance varies with frequency; therefore, this ideal cannot be achieved. The term "impedance bandwidth" is used to describe the degree of constancy of the phasor input impedance across the entire range of sideband frequencies. A useful figure-of-merit to express the impedance bandwidth as a single number is the worst-case voltage standing wave radio (VSWR) existing at either of the two 10 kHz sideband frequencies when the system is perfectly matched at the carrier frequency. This approach yields a VSWR number that is related to antenna performance just as television and FM transmitting antenna performance is described by VSWR limits at various sideband frequencies.

Bandwidth requirements change greatly across the broadcast band. At 1600 kHz, a total bandwidth of 20 kHz corresponds to about one percent of the center frequency, whereas at 540 kHz, 20 kHz corresponds to nearly four percent of the center frequency. Comparatively, an AM station at the lower frequencies has a more stringent bandwidth requirement than is needed for acceptable visual transmitter performance on television channels 7 through 13 or on any of the UHF channels.

The VSWR at 10 kHz above and below carrier often is better than 1.1 to 1 in good phasor designs. Poor designs can be worse than 2 to 1. Poor phasor designs manifest themselves by poor audio quality, which is most obvious in the minimum radiation sectors of the antenna patterns of stations on the lower-frequency channels. The sideband VSWR can be determined by analysis of common-point impedance measurements. The resistance and reactance at each sideband frequency of interest are expressed as a percentage of the measured carrier frequency resistance and are then plotted on a Smith Chart. (A Smith Chart depicts the relationship between the load impedances at sideband frequencies and the matched load established at the carrier frequency.) The distance from the center of the chart for each sideband frequency is a measure of the VSWR at that frequency.

Radiation Pattern

An ideal phasor would produce an antenna radiation pattern that remains unchanged across the channel. Any variations in the phase and ratio of tower currents at the sideband frequencies can result in changes in the location and depth of the intended pattern minimums. The frequencies for which the pattern remains useful describe the "pattern bandwidth". Pattern bandwidth cannot

be described by simple numbers, but the concept is useful in comparing alternative designs.

The example of poor pattern bandwidth below (Fig. 2) shows the three-tower daytime pattern of an actual station at its carrier frequency and at the 10 kHz sideband frequencies. The sideband patterns were calculated from the actual measured ratios and phases of tower currents at both sideband frequencies. This directional antenna system did not adequately protect an adjacent channel station even though conventional field strength measurements indicated proper operation. A spectrum analyzer displaying the received signal confirmed the extreme sideband asymmetry in critical directions.

BASIC NETWORKS

The networks used for matching impedances or for shifting phase are typically "T" or "L" configurations. "Pi" networks having shunt elements at the input and output and a central series element can be made electrically identical to any T network; but T networks are easier to adjust.

The networks at the left in Fig. 3 offer large phase shifts, while the configurations on the right offer small phase shifts. Intermediate between these two conditions are L networks which can be considered as T networks with one zero-reactance arm. L networks do not permit independent adjustment of impedance match and phase shift; however, the resulting phase delay or advance can be calculated easily, with the result often being a desirable value compatible with the overall phasor design. The formulas for these networks are all based on matching into resistive loads.

Antenna tower loads usually have a reactive component; therefore, the output arm of the matching network is modified to cancel the tower reactance. When this modification is made, the output arm will occasionally assume the opposite reactance sign as shown in the parentheses in Fig. 3.

T Networks

The reactances of the input, output, and shunt arms of a T network can be calculated quickly, once the desired input and output resistances and the phase shift (β) are specified, by using the formulas shown in Fig. 4. The formulas are equally applicable for leading ($+\beta$) and lagging ($-\beta$) networks.

L Networks

Conventional L networks can provide a match between any two resistance values. The formula for such networks is shown in Fig. 5, which presumes a non-reactive load. If an L network is used to match a tower to a transmission line, the reactive component of the tower impedance must be considered. If the tower resistance is lower than the line impedance, the series arm of

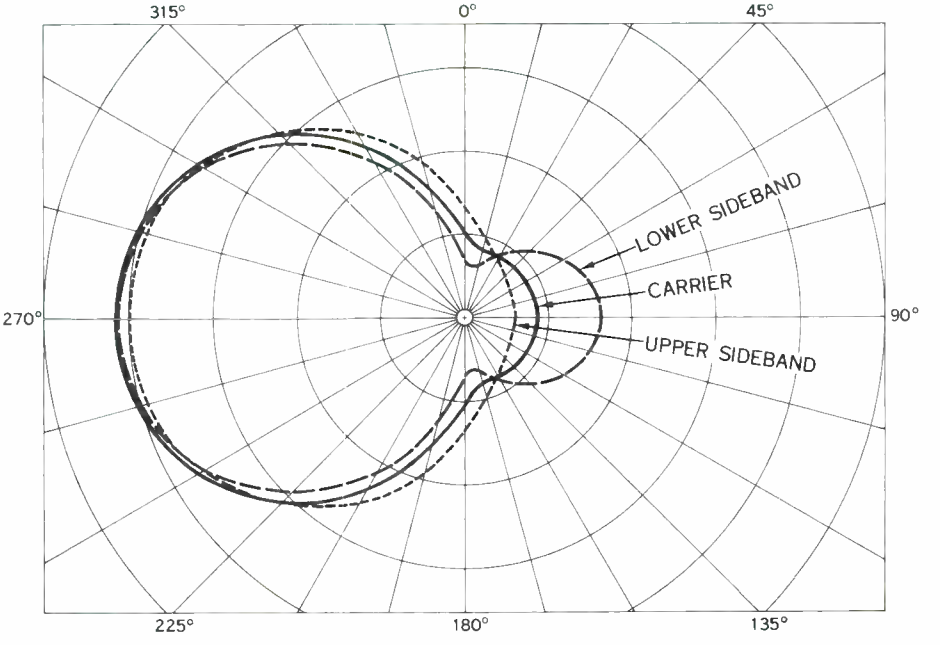


Fig. 2. Example of poor pattern bandwidth.

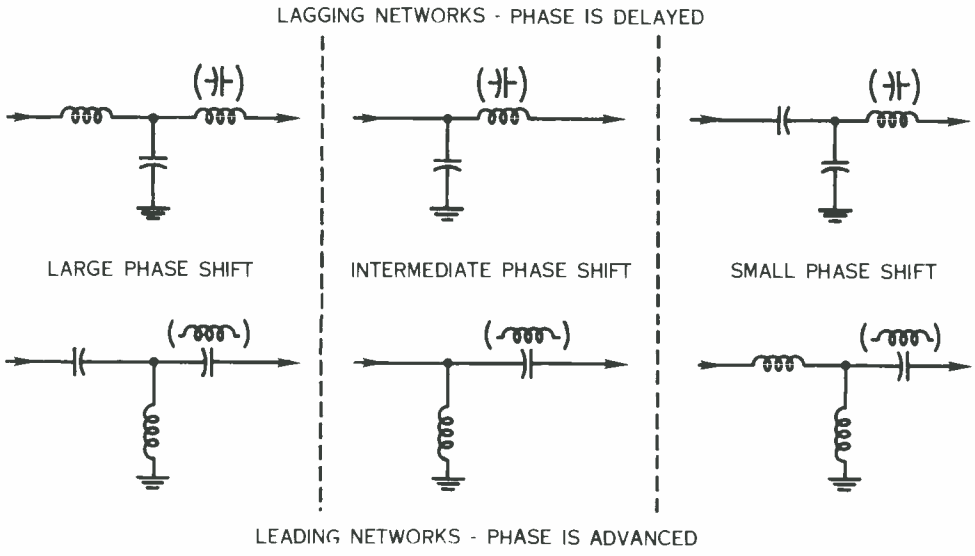
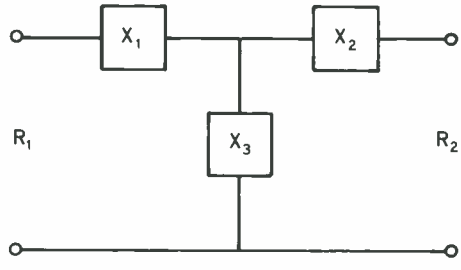


Fig. 3. Conventional "T" and "L" networks.

the L network is connected to the tower. This arm can then be modified from the value calculated by the formula so as to also cancel the tower reactance.

An L network can also be used to match a tower having a resistance higher than the transmission line impedance, but in this case the formula in Fig. 5 does not apply unless the tower impedance contains no reactance. In the usual case, where the tower impedance is reactive, an L network cannot be so easily calculated. The shunt arm (which is in parallel with the reactive tower load) must be one which makes the resistive component of the parallel combination equal to the transmission line impedance. Then the resulting reactance of the parallel combination is cancelled by the series input arm of the L network. Such networks are easy to adjust; the shunt arm of the L network is adjusted to make the input resistance match the transmission line characteristic impedance, and the series arm is then adjusted to cancel the resulting reactive component. The two adjustments are substantially independent of each other. If the tower is one element of a directional array, an operating impedance bridge (hot bridge) at the network input must be used and the phase and ratio parameters must be approximately correct in order for the tower operating impedance to be that which will exist when the directional antenna array is operating normally.

When the tower resistance is higher than the line impedance, there are two different values of shunt arm reactance (one capacitive and one inductive) that can satisfy the conditions necessary for a match with an L network. If the shunt arm



$$X_3 = \frac{\sqrt{R_1 R_2}}{\text{SIN } \beta}$$

$$X_2 = \frac{R_2}{\text{TAN } \beta} - X_3$$

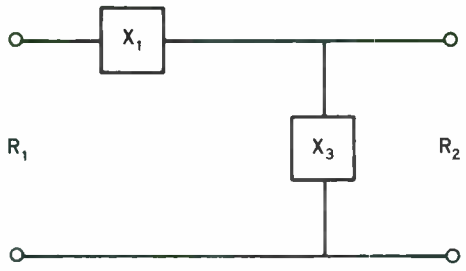
$$X_1 = \frac{R_1}{\text{TAN } \beta} - X_3$$

R_1 = INPUT RESISTANCE

R_2 = OUTPUT (LOAD) RESISTANCE

β = PHASE SHIFT BETWEEN INPUT AND OUTPUT

Fig. 4. "T" network formulas.



$$X_1 = \pm \sqrt{R_1R_2 - R_1^2}$$

$$X_3 = \mp \frac{R_1R_2}{X_1}$$

$$\beta = \cos^{-1} \sqrt{\frac{R_1}{R_2}}$$

R_2 MUST BE GREATER THAN R_1

X_1 IS INDUCTIVE (+ J) FOR LAGGING NETWORK

X_1 IS CAPACATIVE (-J) FOR LEADING NETWORK

X_3 MUST HAVE SIGN OPPOSITE TO X_1

Fig. 5. "L" network formulas.

is of the same sign as the tower reactance, the required series arm will be of opposite sign and the phase shift will be small. If the shunt arm is opposite in sign to the tower reactance, the required reactance in the series arm will have the same sign as the tower reactance and the phase shift will be large.

An alternative way to design such L networks (rather than by calculating the shunt arm reactance necessary to produce the desired resistive component for the parallel combination), is to think of them as T networks in which the output arm is represented by the reactive component of the tower load. As such, these networks can be described as "Phantom T Networks".

Phantom T Networks

A phantom T network utilizes the tower reactance itself as the output arm (X_2) of the network. It is electrically similar to a conventional T network but requires one less circuit element. Because it has only two adjustable elements, the phase shift of a phantom T cannot be independently selected but two choices are possible, corresponding to T networks with small and large phase shifts. When the input resistance and reactance are properly adjusted, the resultant phase shift is then defined. Phantom T networks can be calculated quickly by the T network formulas and cut-and-try variation of the phase shift until X_2 exactly equals the tower reactance. The phantom T networks with small phase shifts, exhibit excellent bandwidth. Those with large phase shift are only slightly poorer.

POWER DIVIDERS

In most phasors, separate components are used to accomplish the power-division function; but the same networks that control phase shift can also control the division of power, if desired. It is important to remember that the power delivered to a tower bears no direct relationship to the base current. A high current tower having a very low base resistance may consume very little power (I^2R) because the resistance is so low. The actual power division is defined by the required base-current ratios and the base resistances. An example of power-division calculations is shown in Fig. 6.

Tank-Type Divider

In a tank-type power divider, as shown in Fig. 7, roller coils L2 and L3 (termed "jeep" coils in this configuration) adjust the power; the combination of L1, L2, and L3 is tuned close to resonance by capacitors C1 and C2. The input tap on L1 adjusts the common point resistance; L4 adjusts the common point reactance. This system is no longer popular because it is difficult to adjust and the bandwidth is limited by the excessive stored energy.

Ohms-Law Divider

A common type of divider is the "Ohms-Law" design shown in Fig. 8, which uses several adjustable (roller) coils in parallel, each of which controls the current to an individual tower. The reactance of the L1, L2, L3 combination is then tuned to resonance with C1. Component values are selected so that the impedance at point A is in order of 400 ohms. A conventional T network then matches this load to the desired common point impedance. This design is easy to adjust; however, the rollers on the variable coils may tend to bind and develop intermittent contacts after several years of use.

Given: Total power is 1000 watts with base current ratios and resistances as shown. I = Current in Tower 3.

Tower No.	Base Current Ratio	Base Resistance	Power
1	0.20	25 ohms	$(0.20\ I)^2 \times (25) = 1.0\ I^2$
2	0.70	130	$(0.70\ I)^2 \times (130) = 63.7\ I^2$
3	1.00	40	$(1.00\ I)^2 \times (40) = 40.0\ I^2$
4	0.50	10	$(0.50\ I)^2 \times (10) = 2.5\ I^2$

$107.2\ I^2 = 1000$ watts;
$I = 3.054$ amps

Tower No.	Base Current	Base Power
1	0.20 x 3.054 = 0.611 amps	$(0.611)^2 \times (25) = 9.3$ watts
2	0.70 x 3.054 = 2.138	$(2.138)^2 \times (130) = 594.2$
3	1.00 x 3.054 = 3.054	$(3.054)^2 \times (40) = 373.1$
4	0.50 x 3.054 = 1.527	$(1.527)^2 \times (10) = 23.4$
		1000.0 watts

Fig. 6. Example of power division calculations.

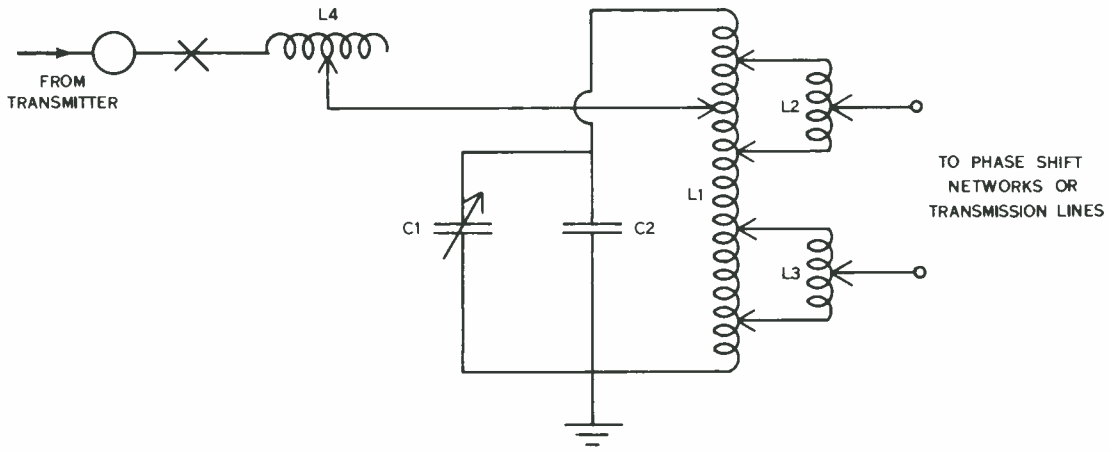


Fig. 7. Typical tank-type power divider.

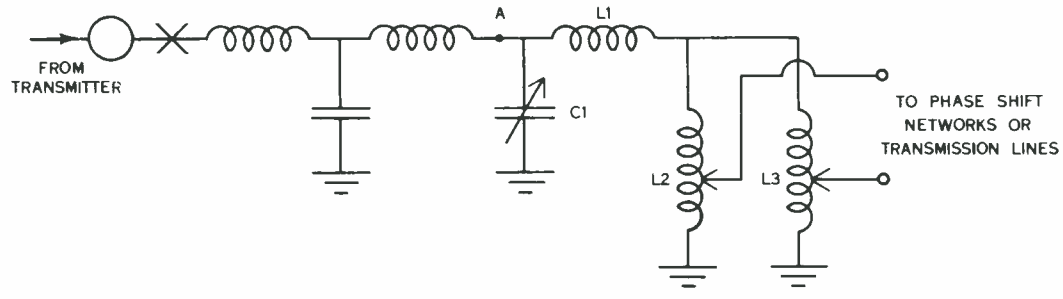


Fig. 8. Typical Ohms-Law power divider.

T Network Power Division

A phasor can be designed to exploit the input impedance of conventional T networks to achieve control of both power division and phase, as shown in Fig. 9. In such a system, each T network presents a load to the input junction which is appropriate to divert the required power to its corresponding tower.

Once such a phasor is properly adjusted, the small changes in phase and ratio that may later be required to maintain an array within tolerances are easily accomplished with very small adjustments in only the input and shunt arms of each individual tower network in the phasor. Although the phase and ratio adjustments interact (as with all phasors, due to the mutual coupling between towers), the shunt arms tend mostly to control power division, whereas the series input arms tend mostly to control phase. By noting which parameters are farthest out of tolerance, it is a simple matter to make small adjustments in the networks, observe the results of each change, and expeditiously restore such a phasor to the desired parameters.

Simplified Power Division

For two-tower directional systems, some very simple configurations can permit adjustment of both power division and phase shift with only two circuit elements. One such simplified system is a so-called "back-to-back" phasor; an example is shown in Fig. 10.

Components "C" and "L" are connected "back-to-back" at the output of the common-point matching network. In this example (which assumes matched transmission lines with resistive inputs), reducing L to zero would yield a current into transmission Line 2 that is in phase with the applied voltage, Eo. As L is increased, the current into Line 2 diminishes and lags the applied voltage. As L is varied from zero to infinity, the locus of all possible Line 2 currents is the semicircle on the lower half of the diagram. Similarly, as Capacitor C is reduced, the amplitude of the current in Line 1 is reduced and its phase is advanced relative to the applied voltage. The locus of all possible currents into Line 1, as C is varied from infinity to zero, is the upper semicircle of the vector diagram. The ranges of adjustment of C and L need only be sufficient to reach the desired phase and ratio parameters, not the entire semi-circular gamut.

Independence of adjustment of phase and ratio is completely lacking in a back-to-back design; yet the phasor is easy to adjust. If one wants to change the ratio, an arbitrary change is first made in either component, phase is restored to the initial valve by adjustment of the opposite component, and then the direction of ratio change is noted. It becomes a very simple cut-and-try process, not unlike that required to maximize transmitter plate efficiency by adjusting transmitter plate tuning and loading.

It is not always necessary to employ one coil and one capacitor in a back-to-back phasor.

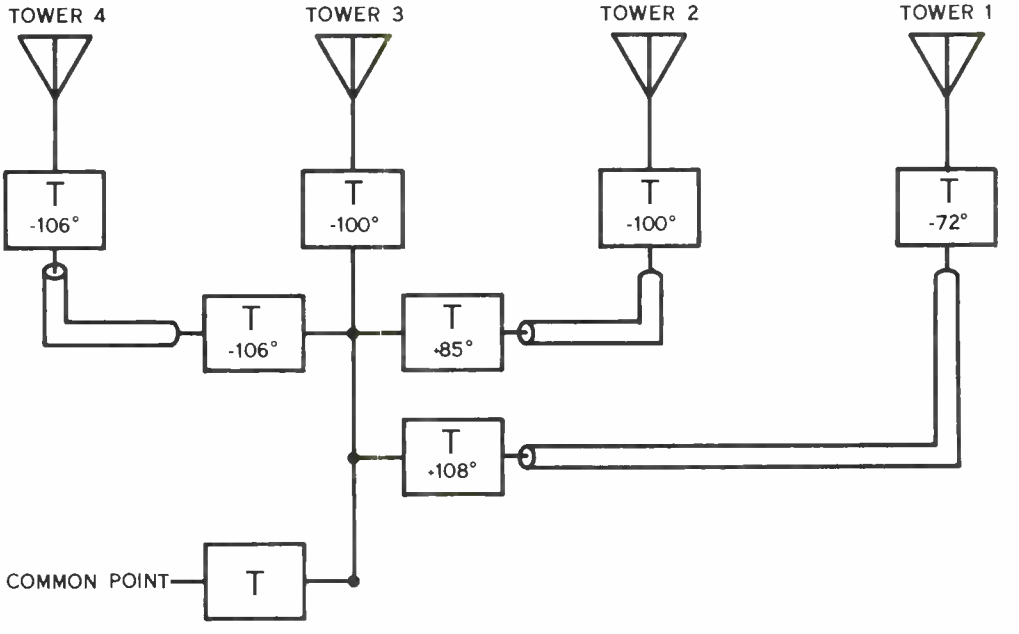


Fig. 9. Typical phasor with "T" net power division.

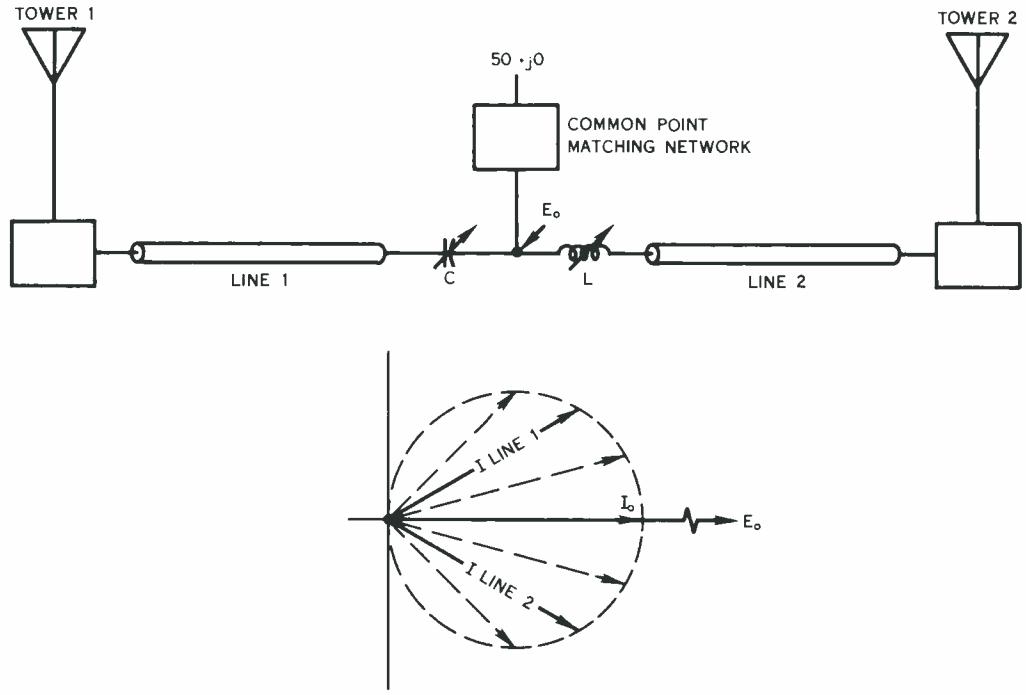


Fig. 10. Example of back-to-back phasor.

Often, the phase shift in the transmission lines and ACU networks can be tailored to provide the desired parameters with a series capacitor on the input to each line, rather than one capacitor and one coil. This arrangement permits a two-tower phasor in which both power division and phase adjustment are accomplished by only a pair of variable vacuum capacitors offering excellent stability and resetability. This arrangement also provides excellent impedance bandwidth.

TRANSMISSION LINES

Some of the requirements for AM broadcast transmission lines differ from those used in FM and TV installations; the similarities and differences are discussed below.

Line Losses

The losses in transmission lines at AM broadcast frequencies are largely in the copper, not in the dielectric. For this reason, and for mechanical convenience, semi-flexible foam-filled lines are the most popular. Air dielectric lines are needed only when power levels exceed the ratings of available foam-filled lines.

Jacketing

All lines should include a black polyethelene outer jacket. Unjacketed lines can result in inadvertent poor contacts to other metallic conductors, which can be a source of minute arcs that can cause spurious emissions. Jacketed lines are particularly suitable for direct burial. Burying the lines greatly reduces the daily and seasonal temperature extremes they encounter, yielding greater stability relative to above-ground installations.

Characteristic Impedance

A characteristic impedance of 50 ohms is the industry standard for transmission lines. Such lines can be expected to be more easily available than other impedances in future years, should a replacement line be needed. The velocity of propagation in transmission lines is less than the velocity in air. Therefore, the electrical length of any line is somewhat greater than its physical length. This increase must be considered in any phasor design. Typical values of transmission line velocity constants are listed below:

Obsolete solid-dielectric flexible lines	68%
Original foam-filled lines	79%
Low-density foam (LDF) lines	88%
Semi-flexible air dielectric lines	90-93%
Modern rigid copper lines	99.8%

Phase-Stabilized Line

In its first year, a new directional array will usually experience small drifts in phase and ratio parameters in directions that will not be repeated seasonally thereafter. This initial drift is caused by the minor mechanical stresses remaining in the

line following manufacture and installation; these stresses are slowly relieved with temperature cycling. The result following installation is a small initial change in characteristics that will not be repeated. "Phase-stabilized" lines, which will reduce the initial drift, are available. Such lines have been temperature-cycled in an oven to relieve residual mechanical stresses. Within a year following installation, no observable difference in characteristics exists between regular lines and those that were initially phase-stabilized.

Transmission Line Fittings

All modern transmission lines can be equipped with EIA-standard flanged fittings to mate with connecting equipment. Although the impedance continuity of such fittings is essential at FM and TV frequencies, such fittings are unnecessary for antenna feeds at AM broadcast frequencies. However, adequate electrical bonds are essential between the transmission line conductors and the adjoining equipment.

Line Mismatch

At AM broadcast frequencies, the effects of a transmission line mismatch are quite different from the electrically-long transmission lines used for FM and television antennas, where mismatches can be reflected into a transmitter and cause crosstalk or ghosts. At broadcast frequencies, transmission lines are rarely longer than a wavelength. A mismatched transmission line yields an input impedance that is dependent on both the load impedance and the length of the line. Thus a transmission line can act as a simple impedance transformer and can be designed to exhibit a desired input impedance through proper choice of load impedance.

Perfect transmission line matches are not critical to overall system bandwidth. As long as the transmission line matches do not yield an input VSWR greater than approximately 1.5:1 at carrier frequency, the additional line losses due to the mismatch are usually trivial and the effect on overall system bandwidth is negligible. An exception occurs when the mismatch is on an unusually long line handling the greater part of the total power.

ANTENNA MONITOR AND SAMPLING SYSTEM

A directional antenna sampling system consists of current sampling transformers or sampling loops on each tower to provide a sample of the tower current, the transmission lines which return the samples, and an antenna monitor which measures the amplitude and phase of each sample relative to that of the reference tower.

Sampling Loops

A sampling loop consists of a rigid single-turn coil permanently attached to each tower. Because sampling system stability is essential, the loops are typically made of galvanized angle iron or rigid copper water pipe. The loops must be at least ten feet above ground and may be insulated from the tower and kept at ground potential. However, it is more common practice to use loops at tower potential and return the sample to ground potential through an isolation coil (iso coil) formed by coiling up the sampling coax so as to form a high impedance across the tower base insulator while not disturbing the current sample carried within the coax.

Sampling Transformers

An alternative method of obtaining tower current samples is to use shielded sampling transformers. These have much to recommend them if the tower heights do not exceed approximately 130 degrees. Although a transformer will sample both the current going up the tower and a lesser component that flows to ground through the base insulator capacitance, the sampling error is usually inconsequential. The advantages to using sampling transformers are extreme stability, a sampling device that is protected inside the ACU instead of being exposed to the weather, and the elimination of the iso coils that are otherwise usually required at each tower.

Sampling Lines

The transmission lines in sampling systems are usually cut to equal length and are buried. The surplus line from the closer towers is also buried so that a uniform environment for all lines minimizes the effects of temperature variation. Most sampling systems employ 3/8" diameter semi-flexible foam transmission lines. Although smaller diameter line is available, it is usually thought to be not sufficiently rugged for the hazards of direct burial and the wear and tear to be expected on those portions above ground.

Sampling System Stability and Accuracy

Sampling system stability is vital, but accuracy is not critical because the proper directional antenna pattern is determined by means of field strength measurements. The sampling system is required to detect changes from the original adjustments of indicated phase and ratio. The accuracy of a sampling system in measuring the absolute amplitude of radiation from each tower

is inherently poor. Even though the sampling loops may be carefully adjusted so that each has exactly the same area in its single-turn coil and all are mounted at the same height, the samples will not be a measure of the relative radiation from each tower. The mutual impedances between towers seriously distort the sinusoidal current distribution which would otherwise exist throughout the height of each tower. Thus the indicated antenna monitor ratios are not an absolute measure of the relative radiation from each tower. The monitor ratios may also differ substantially from the base current ratios, particularly when the loops are a considerable distance above ground level. The indications of phase from a good monitoring system are relatively more accurate than the ratio indications.

DETUNING AND DECOUPLING SYSTEMS

Tower Sectionalization

Occasionally when it is necessary to use a tower that is too tall, sectionalization of the tower is

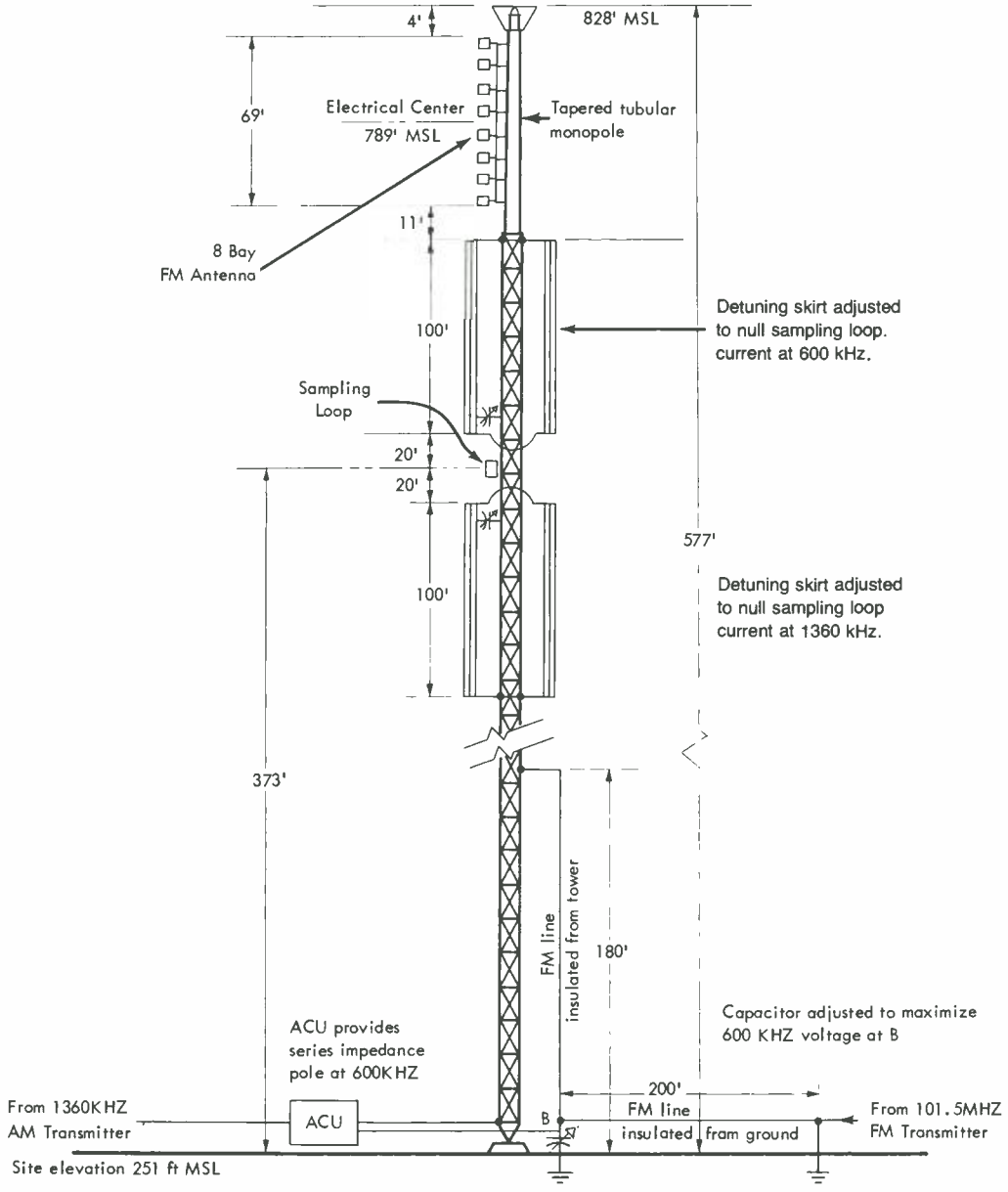


Fig. 11. FM tower sectionalized to make an efficient 1360 kHz radiator simultaneously detuned at 600 kHz.

required. For example, it may be desired to share an FM tower with an AM station. If the overall tower height were to exceed about 225 degrees at the AM frequency, the tower would be a poor radiator, putting more AM signal up into the sky than along the ground. The preferred solution for such a tall tower is to include insulators in the tower legs (and an isocoupler in the FM feedline at the same height) so as to open-circuit the tower at the height needed to make it a good AM radiator. A parallel resonant circuit (an impedance pole) across the insulators can then resonate the insulator and stray capacitances to effectively decouple the upper portion of the tower. In certain cases where structural considerations prevent the sectionalizing of a tower by means of insulators, a workable solution can be to use detuning "skirts" to decouple the top portion of the tower (Fig. 11).

A tower skirt, which is an insulated wire cage outside a tower, can be thought of as a shorted quarterwave coaxial transmission line which is slightly foreshortened and loaded with a capacitor at its open end for easy adjustment. The center conductor of the transmission line is the tower itself, with the outer conductor comprised of the skirt wires. All skirt wires are bonded to the tower at one end and can be connected in parallel at the other end so as to be tuned with a single capacitor. Adjustment of the skirt tuning places a high impedance at the open end of the skirt with the result that the tower is effectively open-circuited at the elevation.

The effectiveness of such a tower skirt in open-circuiting the tower is determined by the characteristic impedance and the losses in the transmission line section formed by the tower and the skirt wires. The most effective skirt will necessarily have a high Q, which will best decouple the top of the tower only at or near the carrier frequency. As a result, the tower base can exhibit a steep impedance versus frequency characteristic which can seriously impair the bandwidth.

Detuning Power Lines

The detuning techniques described above can also be applied to steel power line towers or to other tall metallic structures in order to reduce the radio-frequency currents in them, currents that would otherwise cause reradiation and distort the desired directional antenna pattern of a nearby radio station. Fig. 12 shows such an arrangement with each skirt wire on each tower leg separately tuned. In effect any radio frequency currents flowing up the power line tower are effectively balanced by the currents that are on the length of the skirt section and the number, diameter, and spacing of the skirt wires.

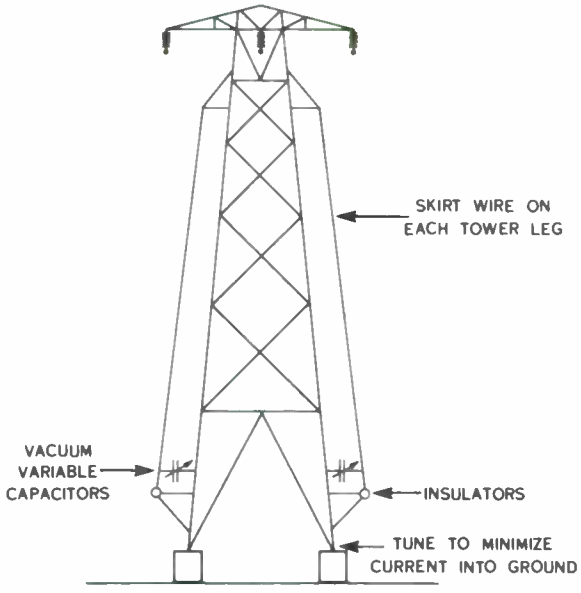


Fig. 12. Skirts used to detune power-line towers.

Floating Unused Towers

When stations operate with different tower combinations day and night, any unused towers must be placed in a nonradiating (floating) condition. If not adequately detuned, these towers will be parasitic radiators. Unused, insulated guyed towers a quarterwave high or less, can often be adequately detuned by simply disconnecting them at the base. More critical situations

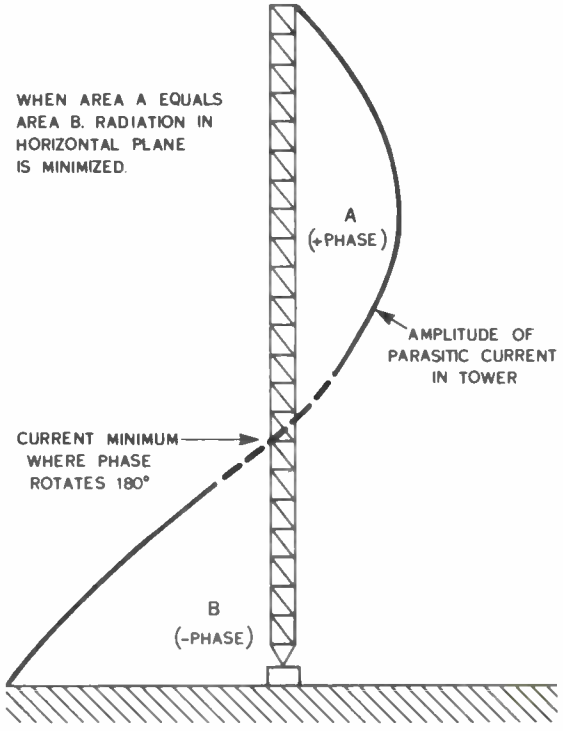


Fig. 13. Current distribution on detuned tower.

require a detuning inductance across the base to cancel the current to ground through the capacitance of the base insulator. Towers of any height can be effectively detuned (for reradiation in the horizontal plane) by placing a reactance across the base to achieve a tower current distribution as shown in Fig. 13.

Because there is a phase reversal at the elevation of minimum current, it is simply necessary to position a current minimum on the tower so that Area A equals Area B. In the horizontal plane, the radiation from the portion of the tower above the minimum will then cancel that from the portion below the minimum. Such a detuning method may still leave substantial amounts of reradiation departing the tower at high elevation angles. The most practical way to eliminate almost all reradiation is to subdivide the tower height into insulated sections (or skirted sections), each considerably less than 90 degrees high.

Filter Systems

If it is necessary to control the current distribution on a tower at a different frequency in order to avoid disturbing the pattern of a nearby directional station, a filter system is needed to permit control of the impedance shunting the tower base at the other station's frequency. The control should be independent of routine phasor adjustments. Such an arrangement is shown in Fig. 14 for each tower of a station operating on 630 kHz. The 630 kHz station must control tower current distribution at 950 kHz in order to protect the directional antenna operation of the nearby station on that frequency.

For filters in series with antenna feeds (such as the C3/L7, C4/L8 combination) it is important to provide an impedance zero at the pass frequency as well as the impedance pole at the reject frequency. Even when the pass and reject frequencies are widely separated, failure to provide the impedance zero with a reasonably low L/C ratio often results in excessive losses and impaired bandwidth.

Tower Current Minimums

For reasonably thin guyed towers of uniform cross-section, the required location of a current minimum on the tower to minimize reradiation (detune) in the horizontal plane can be calculated. Fig. 15 shows the proper null location to detune guyed towers of various heights. Placing current nulls at the proper height on towers to be detuned is a more straightforward process than attempting to achieve a detuned condition through analysis of field strength measurements.

Intermodulation

Filters to control spurious emissions resulting from intermodulation products generated within the final stage of a transmitter can have the same configuration as filters used to control tower-current distribution for a nearby station. Before such filters are designed, a knowledge of the frequencies that generate the intermod is essential. The second and third harmonic frequencies of a station can be involved in intermod products even though these harmonics themselves are suppressed to acceptably low levels when measured at the transmitter output. In the general case, an unwanted incoming signal from some other station can be coupled into the final amplifier through the antenna system to produce a spurious output frequency.

Effective filters can take the form of either traps to prevent an unwanted signal from getting

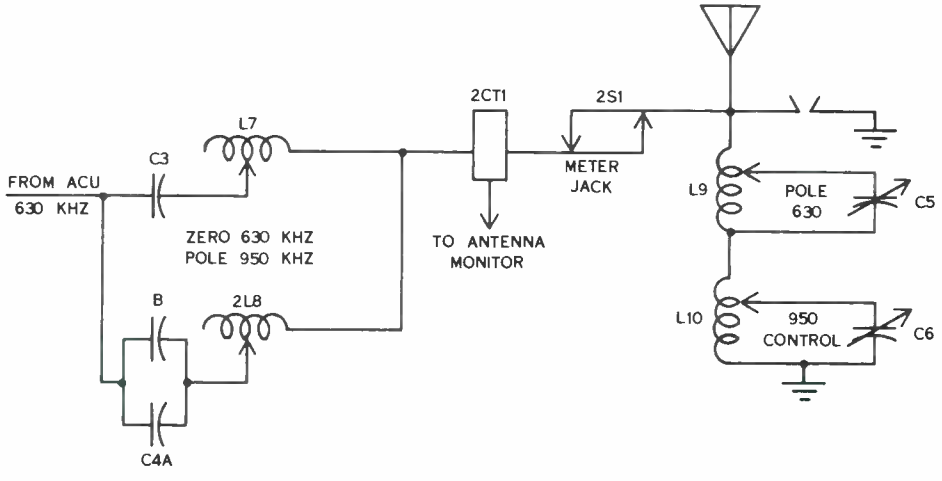


Fig. 14. Independent control of tower current distribution at a second frequency.

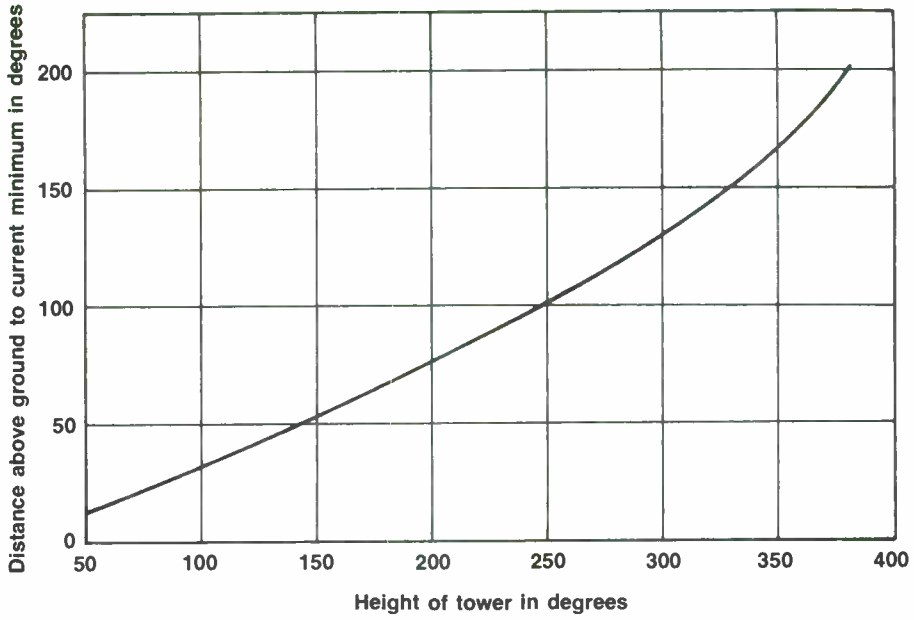


Fig. 15. Approximate height of required current minimum to detune guyed towers.

into the transmitter or traps to prevent the resulting spurious emission from getting out (or both). Filters can be series-resonant shunt elements that short the unwanted incoming signal (or the spurious emission) to ground, or they can be parallel-resonant elements in series with the transmitter output to present a high impedance to either the unwanted incoming signal or the spurious emission.

One clever and expeditious arrangement, when a single spurious frequency must be eliminated, is to modify the shunt arm of the common point matching network to consist of a series-resonant L/C circuit that simultaneously has a low impedance at the undesired frequency and the proper reactance at the station carrier frequency.

TRANSMITTER LOAD OPTIMIZATION

A transmitter will deliver equal power to both sidebands only if the sideband load resistances are equal. If the transmitter load VSWR at ±10 kHz from carrier is rather good (perhaps 1.2:1 or better), further adjustments to improved load symmetry may not be warranted. However, if the ± kHz sideband loads are rather poor (e.g., 1.5:1 or greater) sideband load symmetry can become a critical matter. Symmetry is achieved by adjusting the phase shift in the common-point matching network so that the load resistances at the ±10 kHz sideband frequencies are equal and the reactances are equal but opposite in sign as measured at the anode of the transmitter output stage.

Because different manufacturers use different output circuitry with different phase shifts and many have not published information as to optimum load orientation at the transmitter output terminal, the necessary measurements usually must be made on the load seen by the final amplifier plate. Fig. 16 shows the Smith Chart orientation for the two conditions that satisfy symmetrical loading requirements. The lower curve shows equal sideband resistances which are higher than at carrier; this orientation tends to emphasize the high frequency response. The upper curve also shows equal sideband resistances, but these are lower than at carrier; this orientation tends to show reduced 10 kHz distortion. Either of the two conditions is preferable to the intermediate conditions that yield asymmetrical load resistances at the two 10 kHz sideband frequencies.

DIPLEXERS AND MULTIPLEXERS

Two, three, or more AM stations can be combined on a single tower provided sufficient frequency separation exists between the channels and the electrical height of the tower is not unreasonably short or tall at any of the channels. Depending upon the transmitter characteristics, only 40 dB of isolation or less is typically required between the transmitters to avoid generation of spurious emissions and to permit completely independent operation. Diplexer adequacy is assured when each station

1. Has no objectionable spurious emissions.

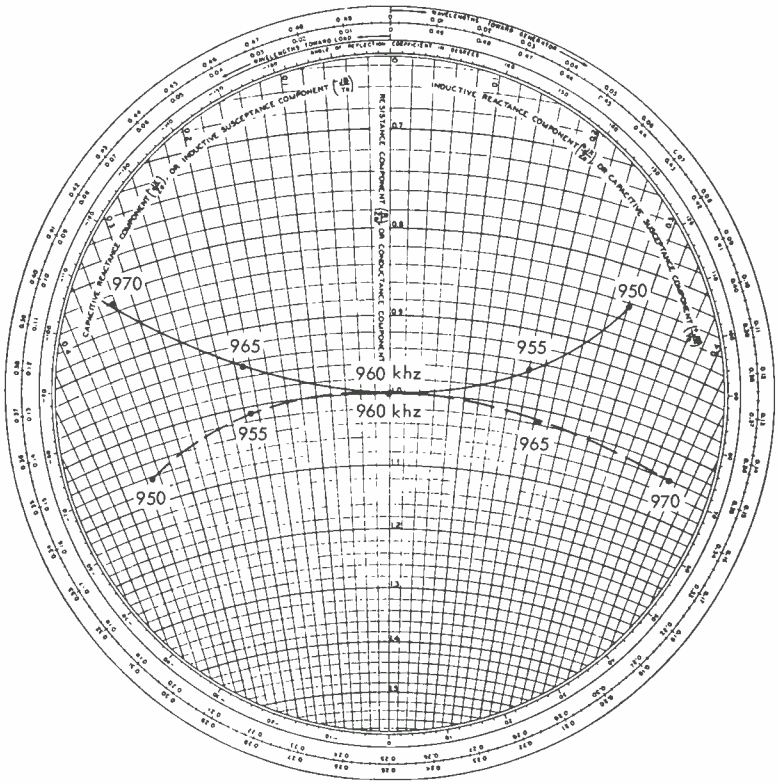


Fig. 16. Proper load impedance at final amplifier plate.

2. Can conduct an acceptable audio proof, including distortion and noise measurements, while the other station is in operation, and
3. Has no observable change in its indicated antenna current when the other station's transmitter is turned on and off.

The losses in diplexing and multiplexing filters can become crucial to a successful design. Since the tower impedance and required tower current at each frequency are known, the losses can be calculated with good accuracy. Capacitor losses are negligible. Coil losses can be calculated using an assumed coil Q of 200, which is a reasonable approximation for typical silver-plated RF inductors in shielded enclosures. Diplexer losses can be minimized if the reactive component of base impedance can be eliminated by means of shunt networks connected directly across the tower base. Then the shunt elements in the diplexing filters operate at lower voltage levels.

OVERALL SYSTEM PERFORMANCE

Directional antenna pattern design and phasor design go hand in hand. Given a poor pattern design, no amount of clever circuit design in the phasor can provide an excellent system. Following are considerations that can lead to an excellent antenna system.

In the Pattern Design

1. Avoid broadside minimums without ample spacing between towers; otherwise the driving point impedances can become very low.
2. Check to see that the individual tower radiation vectors add in-phase (or very nearly in-phase) in the pattern maximum; otherwise excessive circulating currents, poor bandwidth, and pattern instability can result.
3. Choose tower heights in the range of 100 degrees to 130 degrees when possible. Shorter towers exhibit lower driving point resistances and poorer bandwidth. Taller towers may require excessively large impedance transformations in the ACU networks; this condition can add another bandwidth limitation.

In the Phasor Design

1. Minimize reactive power (I^2X) in the phasor components. This will avoid high Q circuits

with their attendant frequency selectivity that limits bandwidth.

2. Avoid excessive use of series (trim) coils to adjust the reactance of fixed capacitors. Such coil/capacitor combinations necessarily have a steeper impedance versus frequency characteristic than a capacitor alone of the proper reactance exhibits.
3. Consider alternative phasor designs. The design with the fewest parts usually has the best bandwidth unless specific broadbanding circuits are incorporated.
4. Derate coil current ratings by 40 percent and mica capacitor current and voltage ratings by 50 percent. Remember that RF currents under heavy asymmetrical modulation can exceed 125 percent of the unmodulated current and that peak voltages can exceed 350 percent of the unmodulated RMS voltages. Vacuum capacitors are self-healing and need no derating.

A SIMPLE BANDWIDTH TEST

A simple test can evaluate the performance of the individual towers in an existing directional antenna system. The object is to determine the amplitude of each high-frequency sideband component as radiated by each tower. This test is possible with any common field strength meter because the selectivity of such meters is just sufficient to resolve sideband components that are 10 kHz removed from the carrier. The procedure is as follows:

1. Keep the sampling lines terminated into the antenna monitor, but add "T" connectors to bridge off samples into a field strength meter operating as a linear tuned voltmeter. Be certain the samples do not exceed the safe voltage input for the field strength meter.
2. Modulate the transmitter 50 percent with 10 kHz sinewaves. In a perfect system, this would result in sideband amplitudes equal to 25 percent of the carrier level in each tower.
3. For each tower sample, first adjust the field strength meter gain so as to set the carrier level full scale (100 percent). Then tune in each sideband in turn and log each sideband amplitude as a percent of full scale.
4. Repeat the process for each tower.

In the best antenna systems, all 10 kHz sideband components will range between 23 percent and 27 percent with 50 percent modulation at 10 kHz. Poor systems have been observed to have individual tower sideband components as low as 5 percent or as high as 40 percent in this test.

In the main lobe of a directional antenna pattern, deficient 10 kHz sideband amplitudes do not usually result in measurable distortion because the radiation components from the individual towers add approximately in phase and the sideband deficiencies of any one tower are masked by the sum total of radiation from all of the other towers. However, the test is useful in pinpointing limitations in existing systems.

SAMPLING SOURCE TO FEED A MODULATION MONITOR

The indications of a modulation monitor may be inaccurate at high modulation frequencies if its modulation sample is taken from a less than perfect antenna system. In an antenna system with a high VSWR at the 10 kHz sidebands, the voltage sampled for the modulation monitor may be higher or lower at the 10 kHz sidebands than at low modulating frequencies.

The best measure of 100 percent modulation is at a remote point in the main lobe of the antenna pattern. Various sampling points within the transmitter or phasor can be tried until a sample source is found that matches the percentage modulation at high modulating frequencies observed in the far field of the main lobe.

CONCLUSION

When the complexities in the design of directional antenna patterns and circuitry are considered together, the need for specialists in this field is evident. However, these chapters should have increased the reader's understanding of the complexities and thus assisted in the design and construction of excellent AM directional antenna systems.

2.4

AM Broadcast Antenna Systems

CHAPTER 2.4:
Part I: System Design
Part II: Phasing, Coupling
Part III: Maintenance

Part III: Maintenance of AM Broadcast Antenna Systems

Edward Edison, P.E.
Hammett and Edison, Inc.
San Francisco, California

Many stable directional arrays, being electrically passive devices, operate for 10 or more years without any readjustment. However, maintenance attention will be needed to overcome the normal effects of age and deterioration (routine maintenance), to restore proper operation after catastrophic failures (such as caused by lightning), and to cope with new sources of reradiation that may develop within the environment in which the antenna system operates. Infrequently, readjustment and relicensing with new pattern parameters may be required.

ROUTINE MAINTENANCE

Routine mechanical and electrical maintenance is required to offset the effects of age and deterioration. Mechanical maintenance includes the attention necessary to keep the moving parts functioning and the tower painted and in good repair. Electrical maintenance may involve replacement or recalibration of base current meters; checks on the continuing proper performance of the phasor components, transmission lines, and ground system; and infrequent readjustment of the antenna phase and ratio parameters as necessary to assure operation within licensed limits and to maintain the proper directional antenna pattern.

Mechanical Maintenance

The moving components within an antenna system may include RF relays, meter switches, dial drives, and the rollers on variable coils.

The contacts on RF relays that carry substantial currents may eventually wear out and require replacement. It is vital that such relays be interlocked so they cannot be switched while transmitter power is applied. Relay maintenance problems are greatly reduced when vacuum relays are employed.

Meter switches that disconnect thermocouple-type ammeters from the circuit when not being read are subject to considerable mechanical wear and tear. Occasional lubrication and tightening of the components are necessary if the parts are to function properly. Replacement of thermocouple ammeters with modern transformer-type meters eliminates the need for RF meter switches and their associated maintenance requirements.

Dial drives on variable coils and capacitors, once properly adjusted, require little attention except infrequent lubrication. The thrust bearings on vacuum variable capacitors are factory lubricated and do not require maintenance attention. However, the rollers on variable coils are often a source of mechanical difficulties (particularly in older coils) and periodic maintenance is required if they are to operate smoothly and without arcing. Networks that are designed to utilize

variable capacitors instead of variable coils are superior in this regard.

Electrical Maintenance

Thermocouple RF ammeters that measure base currents and common-point currents are a frequent problem due to failure or changes in calibration. If such meters cannot be replaced with modern transformer-type units, an intermediate improvement can be effected by substituting make-before-break meter jacks at the base of each tower (in lieu of the original permanent thermocouple meters and associated protective switches). The meters can then be stored in a dry environment and taken to the towers only when base current readings are required. The effects of calibration errors are reduced if the same meter is used to measure all base currents (provided all currents fall within an acceptable range on the meter scale).

Thermocouple ammeters can be calibrated with 60 Hz current. A useful procedure is to remove all such meters from the system and connect them in series for testing. A high-quality dynamometer or soft-iron-type meter should also be included as a calibration standard. A filament transformer having adequate secondary current rating can be used to drive current through all of the meters connected in series. Current amplitude is easily controlled by supplying the filament transformer from an adjustable ac supply such as a Variac.

Modern current-transformer RF ammeters cannot be calibrated with 60 Hz and, if defective, must be returned to the manufacturer for repair and recalibration. The transformer, meter, and interconnecting cable are calibrated as a unit. The cable length should not be changed without recalibration by the manufacturer.

Occasionally loose connections or deteriorating phasor components will produce abnormal heating. Failures from these causes can be anticipated by simply feeling all RF connections and components for warmth immediately after sign-off.

Transmission Lines

Air or foam dielectric lines in continuous lengths rarely develop troubles, but pressure must be maintained on air dielectric lines in order to prevent the accumulation of moisture. Breaks in the outer conductor of foam-filled lines that are buried may cause obscure symptoms and prove difficult to locate. In extreme situations, a time-domain reflectometer is the best tool to pinpoint the problem.

Ground System

Significant deterioration of a ground system can manifest itself in two ways. The first indications may be unusual changes in the phase and ratio parameters between wet and dry conditions. These changes depend upon the nature of the directional array and the character of the ground. When ground systems are installed in shallow tidewater or saltwater marshes, the inherent ground conductivity is so good that even drastic changes of the ground system may produce negligible effects.

A second, more obvious symptom of a deteriorating ground system is a reduction in antenna radiation and a reduction in base currents. It is not uncommon in older arrays to find that the absolute value of each base current has fallen off since the time of the initial installation, even though the base current ratios remain correct. With the available common-point power remaining constant, any increase in ground system losses must necessarily reduce the base currents.

It is essential that all joints in a ground system be made by brazing or silver soldering. Soft solder consisting only of lead and tin deteriorates quickly when buried.

The existence and continuity of buried ground radials is best checked by using an underground cable locator of the type used by utility companies to locate buried cables and pipes. These devices consist of a transmitter, which can be located at the tower base to place a modulated low-frequency signal on all connected ground wires, and a receiver that detects the unique modulation. While in use, the receiver can be carried in a circle with a radius of 100 feet or more about each tower, so that the radial wires that are intact can easily be detected and counted.

Alternatively, if a cable locator is not available, a shielded pick-up loop held near the ground and connected to the external input of a field strength meter may suffice to detect the current in individual radial ground wires. Even when a radial is broken, the current beyond the break tends to concentrate in the wire instead of the adjacent earth. A most definitive check is to uncover the distant ends of adjacent radials and check for continuity between them with a dc ohmmeter.

Towers

Towers require occasional attention to assure their structural integrity. Periodic inspections by an experienced tower contractor are desirable. Guyed towers should be checked to confirm that they are straight and plumb and that the guy tension is correct. Towers with tubular legs can rust from the inside out; a close inspection is necessary to detect this condition while repairs are still feasible. Towers with solid legs avoid the hazards of internal rust. Galvanized towers must be painted only if required for aeronautical safety. Nongalvanized towers should be avoided, not only be-

cause rusting makes the maintenance problem more severe but also because of their inferior electrical conductivity.

Lightning strikes and target shooters may destroy guy-wire insulators. Such failures can usually be discovered with the aid of field glasses or a telescope. The electrical field gradient can be very high adjacent to a tower, particularly near the top. Arc-overs and corona can be avoided by cascading guy-wire insulators (johnny balls) immediately adjacent to the tower. Under severe conditions, fiberglass rod insulators or dielectric guy cables are a preferred solution. In an existing system with marginal insulation, any dirt or salt deposits on the insulators may cause corona and arc-overs. Washing the insulators and coating them with silicone grease may provide a temporary remedy.

SUDDEN COMPONENT FAILURES

The most common cause of component failure in a well-designed antenna system is lightning damage. Ideally, lightning which strikes a tower should be conducted directly to ground through the ball gap that is typically part of each tower installation. However, lightning has been known to destroy components in what appear to be well-protected systems. Such components can most usually be located by a careful visual inspection.

Lightning currents flowing through adjacent coil turns tend to collapse them; therefore, coils should be inspected to confirm that all turns are in their original uniform alignment. The forces generated by lightning traveling through the coil strap and clip on a ribbon coil may dislodge the clip and leave the strap hanging in nearly its original position. Careful visual inspection is needed to locate dislodged coil clips.

Although vacuum capacitors are usually self-healing if subjected to minor over-voltages that cause internal arcing, the extemely high currents from a lightning strike can melt the plates together and short the capacitor, necessitating replacement.

If lightning damage is a recurring problem that warrants additional protection, the following steps are suggested:

1. Check the ball gap at the tower base. The balls should be arranged side-by-side so that dirt and water will not bridge the gap with the first rain of the season. The balls should be on the same radial line through the tower axis because towers tend to twist in high winds; this twisting

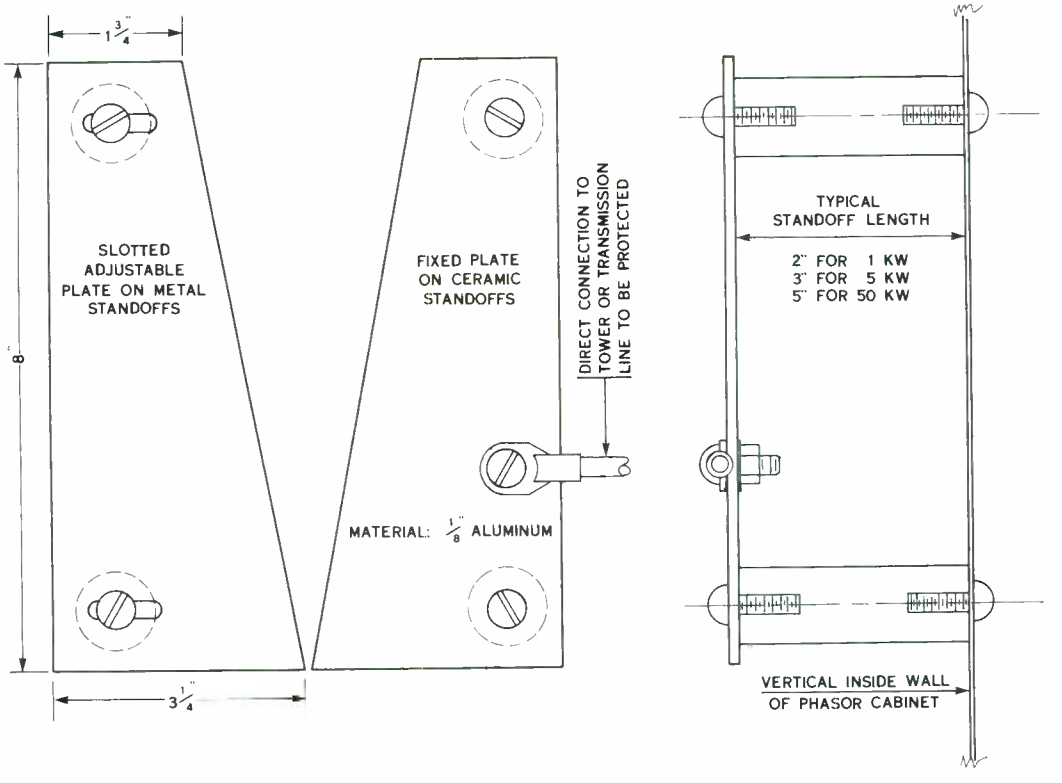


Fig. 1. Suggested lightning gap design.

could otherwise change the gap between the balls. The gap should be as narrow as possible.

2. Provide a two-or-three turn choke coil in the RF feed from the antenna coupling unit (ACU) to the tower if one is not already installed. The coil can be from 3 to 10 inches in diameter depending on the station power level and the feedline size. Its function is to present a high impedance to lightning strikes so they will jump the ball gap rather than enter the ACU. Readjustment of the output arm of the matching network will be required to offset the added lightning choke inductance.
3. Provide a horn-type lightning gap within the ACU similar to the design shown in Fig. 1. The relatively clean, dry, and insect-free environment inside the ACU permits a tighter gap setting and increased lightning protection than can be accomplished with an exterior gap. The path for lightning currents from the tower to the gap within the ACU should be very direct with minimum inductance and no sharp bends.
4. Lightning gaps, similar to those described in Step 3, can be installed at both ends of all transmission lines to help prevent lightning currents from getting into the phasor.
5. Adjust each gap individually by reducing the spacing until it arcs on the heaviest modulation peaks. The spacing should then be doubled for the permanent adjustment. This will be a much smaller gap spacing than is usually encountered on external gaps at the tower base.
6. Check to see that there is a dc path from each tower to ground, either through a phase sampling isolation coil, a separate static drain, a spare winding on a tower lightning choke, or the network circuitry within the ACU itself. Without a static drain, static charges may build up on a tower and will then discharge with small arc that may be sufficient to trip protective circuits and take the transmitter off the air.

ENVIRONMENTAL CHANGES

The ideal environment for a directional antenna system is a flat plane of high conductivity with no tall structures in the general vicinity, such as buildings, power line towers, water tanks, or oil wells. Such structures (or any metallic objects of substantial vertical dimension) will have currents induced in them, currents which are dependent upon the size and shape of the structure, the frequency, and the ambient field with which they are illuminated. The currents in such objects make them parasitic antennas. The resulting reradiation can distort the pattern of a directional antenna array.

Reradiating objects located in the main lobe of an antenna pattern are of greater consequence than those located in or near pattern minimums where their illumination is substantially less. The reradiation from reasonably slim electrically short objects (where the overall height is substantially less than a quarter wavelength) can be calculated with useful accuracy by means of the approximate formula shown in Fig. 2.

If feasible, a more accurate assessment of the reradiation can be obtained by measuring the RF current flowing in the reradiating object. If the object is reasonably thin (such as a guyed communications tower, a cable television headend tower, or the four individual legs of self-supporting power line towers) measurement of the current flowing from the tower to ground is not difficult. For this measurement, a toroidal pickup coil formed by the spiral steel wire in a length of clothes-dryer exhaust hose (or even better, some types of vacuum-cleaner hose) is useful. The hose section should be long enough to encircle the tower or current-carrying conductor to be measured and to have its ends attached to a field strength meter operating as a linear voltmeter. Such a pickup coil can be calibrated by encircling a conductor carrying a known current, such as the base of a radio tower.

It is not necessary to measure the current distribution throughout the height of electrically short objects. The current distribution can be assumed to be triangular, decreasing to zero at the top of the tower if it is freestanding; or the current can be assumed to be uniform throughout the entire height of the tower as a worst-case assumption where power-line towers exhibit heavy toploading due to the capacitance to ground of the conductors they support. Once the current is measured the reradiation can be calculated by relating the "ampere-feet" of current in the reradiator to the ampere-feet of current in a quarterwave tower at the same frequency which typically produces an unattenuated radiation of about 300 mV/m at one kilometer with one kilowatt of power.

The techniques for detuning reradiating objects are the same as those described in the previous chapter for detuning unused towers within a two-pattern directional array.

READJUSTING AN ARRAY

Any readjustment of a directional antenna array should be undertaken only by personnel who have a basic understanding of directional antenna theory and practice. At the minimum, the

$$E_r = E_i \frac{\cos G - 1}{\cos G} \Big/ 6{,}282 \left(ln \frac{2h}{a} - 1\right)$$

Where: E_r = Reradiated field in mV/m at 1 km
E_i = Incident field in mV/m at location of raradiator
G = height of reradiator in electrical degrees
h = height of reradiator in meters
a = effective radius of reradiator in meters
ln = natural logarithm

Fig. 2. Approximate formula for calculating reradiation

material in the preceding two chapters should be read and understood. Before any array adjustments are attempted, considerable information needs to be collected and analyzed.

Four conditions to proper array performance are explained below. All of these conditions should be met simultaneously in normal operation.

1. The antenna monitor indications should be within the FCC tolerances of five percent for tower current ratios and three degrees for phase. A special case is a "critical" array which has been assigned tighter tolerances by the FCC.
2. Changes in base current ratios should be consistent with changes in antenna monitor ratios. Although the base current ratios and antenna monitor ratios are rarely in exact agreement (and will differ greatly in arrays with unequal height towers), these ratios should change by essentially the same percentage for incremental changes in the actual base current ratios. In other words, when the monitor indications match those shown in the license or the most recent proof, the base current ratios should also match what is shown in the same license or proof. Discrepancies are an indication of changes in the sampling system or in the base current metering and should be investigated.
3. The reradiation environment must be essentially unchanged from that in which the array was last in proper adjustment. Any substantial structures such as power-line towers or steel-frame buildings constructed recently in the vicinity of the array, particularly in the main lobe of the pattern, can cause trouble. Grounded structures a quarterwave high can distort critical antenna patterns even if located one or two miles away in the main lobe of radiation.
4. The monitoring points should be within the limits shown on the station license. A high monitoring point may result from a changed environment due to the construction of buildings or power lines near the monitoring point. If a high monitoring point does not correlate with observed changes in antenna monitor parameters, the point is suspect and should be checked by measuring and analyzing 10 or more of the other points on the same radial that had been measured and recorded in the most recent proof or partial proof. Readjustment to reduce excessive radiation is indicated only if the analysis of 10 or more points confirms that the radiation is in fact in excess of the standard pattern limit.

Soil Conductivity

The analysis of a radial may be misleading due to changes in soil conductivity. Increased soil conductivity during wet seasons may cause substantial increases in signal strength at distant measuring points when compared to the same measurements during dry seasons. This phenomenon varies with distance, with season, and differing geographical regions. These effects may not exist in some regions, but in extreme cases may show 2:1 changes in field strength at a distance of 20 miles. Soil conductivity variations can be eliminated by comparing the present ratio of directional to nondirectional field strength at each measurement point to the same ratio in previous complete or partial proofs.

Because new nondirectional measurements may be needed at a future date, it is highly desirable to incorporate in the phasing system at least some

simple manual switching capabilities to permit reversion to nondirectional operation at those stations which do not normally have a licensed nondirectional mode.

Readjustment Data and Analysis

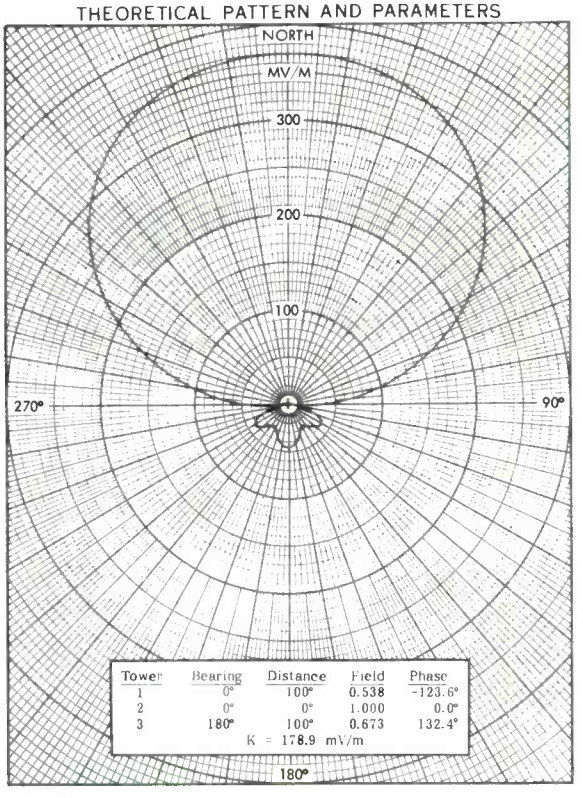
Directional antenna arrays vary so much in pattern shape, suppression requirements, and phasor circuitry that precise readjustment instructions cannot be described. If possible, the consulting engineer who adjusted the array before its last proof of performance should be consulted on the problem. The following guidelines should prove helpful:

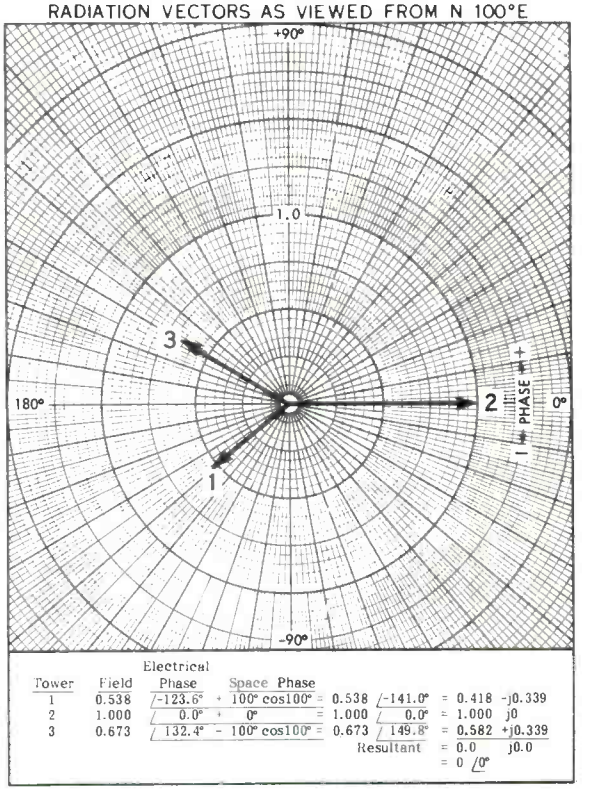
1. Carefully log all dial settings and all coil tap locations before making any changes.
2. Keep in mind what you are trying to accomplish before twisting any knobs or changing any coil taps.
3. Make changes only in small increments, typically never more than about one degree or one percent in phase or ratio.
4. Keep a step-by-step record of each change as it is made so that the array can be restored to initial conditions, if necessary.
5. Remember that even small adjustments of phase or ratio can have a measurable effect on the common-point resistance. The power fed to the antenna system is only correct if the common-point resistance and current are essentially correct. A permanently installed common-point operating impedance bridge is a convenience not only for keeping track of the common-point impedance during adjustments but also for continuing confirmation of the licensed common-point value in day-to-day operation.
6. Construct vector diagrams for each important direction. Samples of such diagrams are shown in Fig. 3. The phase relationships must include both the electrical phase of the currents fed to the towers and the space phase component for each tower relative to the reference tower as viewed in each direction. Such diagrams will assist in visualizing what effect any contemplated changes in phase or ratio for any tower will have on the resultant field in each direction. The vector diagram amplitudes may be in terms of the individual tower field ratios (such as in Fig. 3) or in terms of the theoretical unattenuated radiation. The theoretical unattenuated radiation from each tower (expressed in millivolts-per-meter at one kilometer or one mile) is obtained by multiplying the theoretical pattern field ratio for each tower by the pattern constant K, which is also usually shown in each theoretical pattern.
7. If the pattern includes essentially zero minimums (which need to be as deep as possible), make "talkdown" adjustments at a series of the most distant points on the null radial from which adequate two-way communications can be obtained. At each talkdown location, adjust the phasor for any combination of tower currents and phases that gives the deepest possible minimum. (A deep minimum can usually be confirmed by rotating the field strength meter 90 degrees on a vertical axis and noting that the signal received from scattered reradiators is stronger than that received from the station when the meter is in its normal measurement orientation.)

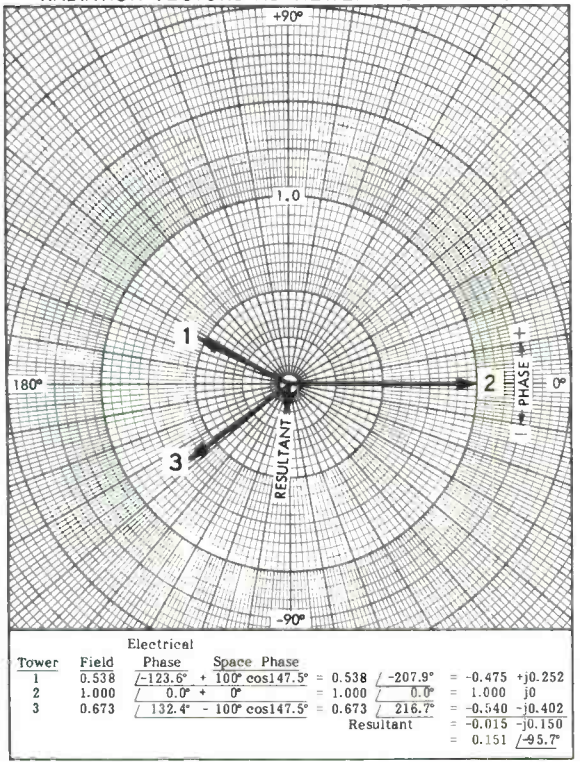
   Construct the vector resultant for each talkdown on a vector diagram similar to that shown in Fig. 3, but use the antenna monitor indications of phase and ratio instead of the theoretical parameters. The vector resultant will probably not be zero because of errors in the antenna monitoring system, non-sinusoidal current distribution on the towers, and reradiation from objects external to the array. However, the resultants so plotted from a series of talkdowns along a radial will enclose an area in which the optimum adjustment has its vector resultant at its center. Knowing the desired resultant for each critical radial direction, one may then be able to infer a set of phase and ratio parameters to satisfy all conditions simultaneously.

For simple arrays, a more pragmatic, although less scientific approach (but one that often yields effective results), is to station observers with field strength meters at each of the several monitoring points or other critical directions. By using a two-way radio to learn the effect on field strength, cut-and-try adjustments of the phasor can yield a set of phase and ratio parameters that satisfy all conditions simultaneously.

Following readjustment, if any of the new phase and ratio parameters exceed the three degree phase and five percent ratio tolerances permitted by the FCC when applied to the parameters shown on the current station license, a partial proof-of-performance will be required before the FCC will license the new parameters. If the new parameters are within tolerance of the licensed values, a partial proof and application for changed parameters may still be desirable in order to avoid long-term operation uncomfortably close to the tolerance limits.







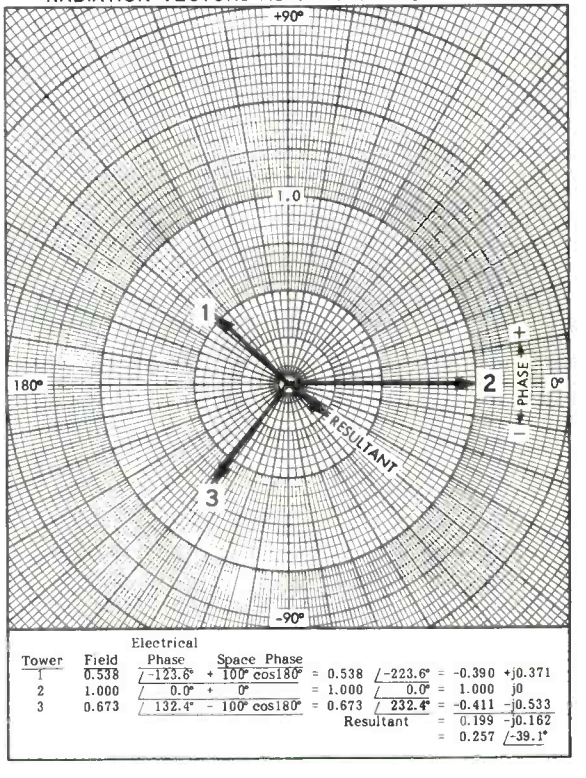


Fig. 3. Tower radiation vectors as viewed from different azimuths.

2.5

Antennas For FM Broadcasting

Peter K. Onnigian, PE
Consulting Antenna Engineer
Sacramento, California

This chapter is dedicated to broadcast engineers, technicians, and station managers who must make important decisions regarding FM transmitting antennas. To insure the best possible signal strength in the station's service areas, the site location, antenna height, antenna type and propagation conditions must all be considered.

FM broadcasting was first authorized in the United States in 1940 by the Federal Communications Commission (FCC). The first FM station began operation in 1941. In 1945 the FM service was assigned to the 88 to 108 MHz band and divided into 100 channels, each 200 kHz wide. The projection is that by the first of January, 1986, there will be 5,600 FM stations in the United States, not counting over 1,000 FM translator stations.

About 99 percent of their antennas are nonsymmetrical, that is they are mounted on one side of a steel supporting tower or pole. FM antennas outside the western hemisphere on the other hand are usually symmetrical, that is installed on all faces of a tower. Both methods are capable of providing excellent onmidirectional azimuth patterns.

Antennas for FM broadcasting use horizontal polarization (Hpol), vertical polarization (Vpol) or circular polarization (Cpol)*. Cross polarization is used as a means to prevent co-channel interference in some European countries but not in the western hemisphere. Cpol together with its special form, elliptical polarization (Epol) was introduced in the United States in the early 1960s as a means to provide greater signal penetration into the many different forms of FM receiving antennas, which are now found in the service area. As of this writing, Hpol is standard in the United States, but Cpol or Epol may be used if desired.

Receiving antenna types have proliferated as have receivers. In the 10 year period between 1973 and 1983 there were 276 million FM radios sold in the United States, of which 54 million were automobile AM-FM radios.[1]

Antennas for FM broadcasting must be chosen carefully, in order to cover the service areas properly, with adequate level and quality signals. For economic and technical reasons effective radiated power (ERP) should be produced with a proper balance between antenna gain and transmitter power. It is the purpose of this chapter to provide sufficient technical information for the broadcaster to achieve this.

The height of the antenna over the service area, distances to areas of population, the ERP, and the economics are items that must be considered.

*Hpol, Vpol, Cpol and Epol are unofficial abbreviations used for clarity & brevity in this chapter.

[1]EIA Consumers Electronics Annual Review, 1983. Electronics Industry Association, 2001 Eye Street, N.W. Washington, D.C. 20006.

Antennas currently available in the United States differ considerably from those to be found in Europe. The various American types are discussed so that the engineer will be informed on the subject. Considerable advances have been made in recent years in the design and fabrication of FM antennas. These improvements provide greater penetration of signals into automobile FM radios as well as popular small FM transistor radios of all kinds.[2] The newer FM broadcasting antennas must meet the more stringent requirements for FM stereo and quadraphonic broadcasting.[3]

Circular polarization for FM broadcasting has come of age. About 98 percent of United States FM stations are now using Cpol antennas, while an estimated 75 percent in Latin America use this type.

PROPAGATION

FM broadcasting has some distinct advantages over AM (medium wave) broadcast service. These advantages stem from the propagation characteristics of FM frequencies as well as the modulation system.

There is essentially no difference between day and night FM propagation conditions. FM stations have relatively uniform day and night service areas. FM propagation loss includes everything that can happen to the energy radiated from the transmitting antenna during its journey to the receiving antennas. It includes the free space path attenuation of the wave and such factors as refraction, reflection, interference, diffraction, absorption, scattering, Fresnel zone clearances, grazing and Brewster angle problems.

Propagation is dependent upon all these properties out to approximately 40 miles (65 km). Some additional factors enter the picture with longer service ranges. Radio wave propagation is further complicated because some of these propagation variables are functions of frequency, of polarization, or both, and many have location and time variations.

The technical intent of the broadcaster is to put a signal into FM receivers of sufficient strength to overcome noise and to provide adequate limiting for at least 20 dB signal to noise ratio, which will provide at least 30 dB of stereo separation. The required RF signal level varies from about 2 uV/m (microvolt per meter) for high sensitivity FM stereo tuners in the suburbs to about 500 uV/m for less sensitive transistorized portables, as well as most automobile receivers in urban areas.

FM antenna manufacturers do not guarantee coverage. They supply antennas which radiate a signal meeting certain specifications, including power gain. This is indicated as a free space value for 1 kW of input power and assumes an omnidirectional radiation pattern. These free space values are shown in the catalogs for reference purposes and are achieved in practice only when measured on a good antenna test range.

Some manufacturers in the United States provide azimuth pattern adjustment service to insure a horizontal plane pattern circularity of ± 3 dB when mounted on the side of a specific tower or pole. It must be pointed out that this radiation pattern and gain are for free space conditions with no obstructions to propagation. Such conditions are rarely found in actual installations.

The radiation pattern and propagation are two distinctly separate parameters. They should not be confused as one and the same. They are not.

The pattern is the radiation which is transmitted by a given antenna, without any propagation limitations, as measured on a good antenna test range. Propagation depends on conditions existing between the transmitting antenna and the receivers.

The actual service area signal strengths are based upon two probability factors. Contours are not solid signal areas as we would believe. For example, the FCC signal coverage charts are based upon a probability of 50 percent of the locations, 50 percent of the time. This means that at any one given location the signal has a 50 percent chance to measure up to the predicted contour level. Furthermore, half the time at that location, it may reach the level predicted while at other times it may be lower or higher in strength. Signal level prediction is not a fine art.

These FCC charts (FCC Rules, Sec. 73.333) are based upon the assumption that excellent propagation conditions exist. One or more of the conditions mentioned in the second paragraph under this heading may reduce the measured signal strength from those predicted values.

Propagation Loss

The power radiated from a FM transmitting station is spread over a relatively large area, somewhat like an outdoor, bare light bulb on top of a tall pole. The power reaching the receiving antenna is a very small percentage of the total radiated power.

At 100 MHz and a distance of 30 miles (48 km) the figures indicate the free space path loss to

[2] Onnigian, Peter: "A Study Into the Effects of Vertically Polarized Radiation in FM Broadcasting" Technical monogram. Jampro Antenna Company, now a division of Cetec Corp. 1965.

[3] National Quadraphonic Radio Committee, report to the FCC, Nov. 1975. EIA, 2001 Eye Street, N.W. Washington, D.C. 20006.

be 106 dB.[4] Doubling the distance increases the space loss by exactly 6 dB. The path loss does not attenuate the signal with distance as much as some other factors. Path loss between an earth station and a satellite is a classic text book example of a 6 dB loss every time the distance is doubled. But a typical FM station signal travels through a nearly perfect dielectric (air) and over the imperfect earth's surface (ground). Herein lies the FM radio propagation loss problem.

Between the transmitting and the receiving antennas there may occur in the propagation path refraction, diffraction, and reflection from scores of objects such as hills, and buildings. These, along with absorption, scattering, lack of Fresnel zone clearances, and other factors, all reduce the signal strength.

Signal loss due to foliage has been well known to UHF TV broadcasters for many years.[5] This same condition exists to a lesser degree for FM broadcasting. Trees, shrubs, and other foliage on hills or smooth terrain affect the reflected as well as the lateral signal loss with distance. With average values of permittivity and conductivity in both foliage and ground, a loss of about 2.5 dB was found to exist in a ten mile path, at FM frequencies.[6] The height gain factor is increased with heights above the foliage. Considerable depolarization takes place because the transmission through or reflections from ground foliage is a diffracted field contribution.

Multi-path Problems

The ideal reception condition is a strong direct single source signal. When energy from two or more paths (due to reflections) reaches the receiver, a condition called multi-path reception occurs. Poor reception is experienced when there is insufficient strength difference between the direct and the reflected signals.

Nothing is more important in the way of broadcasting facilities than the location of the transmitting antenna. Great care must be exercised to find a suitable site. Poor selection of the transmitter point can result in very unfavorable signal propagation and negate the entire project. One very serious result of poor site selection is multi-path propagation in some directions.

As an example, the transmitter should not be located so that strong reflections take place from nearby hills or mountains. This can happen when

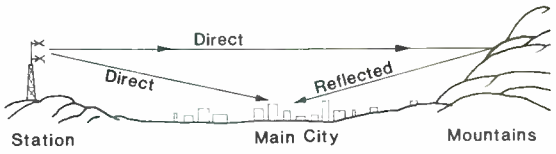


Fig. 1. Example of poor station location causing severe multi-path conditions due to delayed reflections from mountains on the right. Not to any scale.

the transmitter is placed on one side of a large city and the other side of the city has a high mountain range. Radiation into the city directly from the transmitting antenna, as well as reflections from the nearby hills and mountains will create two or more signal paths to many receivers. These reflections can be so strong that only a 10 dB difference may exist between the direct and the reflected, a condition which causes severe multi-path problems.

A TV station at this same location would experience un-usable signals due to heavy ghosting, even with directional receiving antennas, which exhibit moderate signal pickup from their back. This is illustrated in Fig. 1 where a mountain range causes reflections back into a large city.

The multi-path example shown in the sketch was an actual case. The site was chosen by the FM broadcaster, without proper engineering guidance, simply because the hill had a tower, building, power and the road was in. In fact it later developed that the broadcaster learned why the TV people had abandoned the site: the TV station had failed due to extremely heavy ghosting into the principal city.

A much better FM transmitting site was located on the hills between the high mountain range and the city. Using a directional transmitting antenna with very little radiation towards the high mountains, reflections were satisfactorily reduced; and the FM station is now operating successfully.

Multi-path reflections are very easy to identify. On an automobile radio, the signal will drop out, sometimes abruptly, as the car moves. This effect may be rhythmic with distance while traveling slowly. It is sometimes called picketing as it acts like a picket fence alternately blocking and letting the signal pass. A field strength meter will usually reveal great variations of signal when moving, say, 100 feet (30 m) in a line with the transmitter. Cyclic variations over quite uniformly spaced intervals on the ground as great as 40 dB have been observed by the author.

This variation in signal levels is caused by the reflections adding and substracting from direct and reflected signals. This is indeed caused by propagation problems existing in the path between transmitter and receiver. It really has

[4]Freeman, Roger: "Telecommunications Transmission Handbook" John Wiley & Sons, New York. pp 180-186 1975.

[5]Head, Howard: "Influence of Trees on TV Field Strengths" Proceedings of the IRE, Vol. 48, pp 1016-1020, June 1960.

[6]Armstrong, A.: "Study of Electromagnetic Wave Propagation at 112 MHz." Proceedings of IREE Australia, pp 105-110, April, 1969.

nothing to do with the qualities of the transmitting antenna. It is a function of site selection. This should not be confused with a similar effect observed near the base of the tower supporting a high gain antenna. Nulls produced by stacking bays for gain are found near the antenna and may be filled-in if a problem (see "Null Fill" in this chapter).

Ground Reflections

In the elevation plane between transmitter and receiver nearly all FM signal coverage lies within 10° below the horizon. Generally the higher the transmitting antenna above the service area the greater will be this angle. Called the grazing angle, it lies between the horizontal plane and the earth's surface.

The angle of incidence and reflection are not the same, as shown in Fig. 2. The depression angle and the grazing angle are not equal as would be the case for a flat earth. Reflections from these angles play an important part in the strength and the quality of the signal in FM broadcasting with Cpol.

It is quite difficult to predict accurately the reflection co-efficient (efficiency), which varies considerably as a function of polarization, frequency, grazing angle, surface roughness, soil type, moisture content, vegetation growth, weather and the season. There are complex formulas for predicting the ground conductivity at the frequency of interest. For 100 MHz, a value of 10 millimhos per meter ground conductivity is often used, with a permittivity of 25, as being about the average for the continental United States.[6]

The ground which causes reflections at these grazing angles does not treat Hpol and Vpol in the same manner. The Vpol is attenuated considerably more than the Hpol as shown in

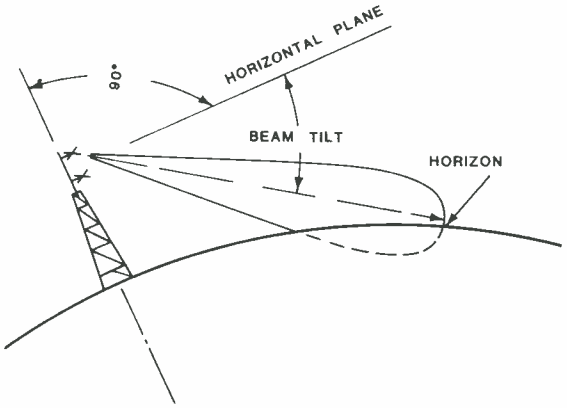


Fig 2. Beam tilt to radiate maximum ERP at the horizon. Not to any scale and exaggerated for illustration.

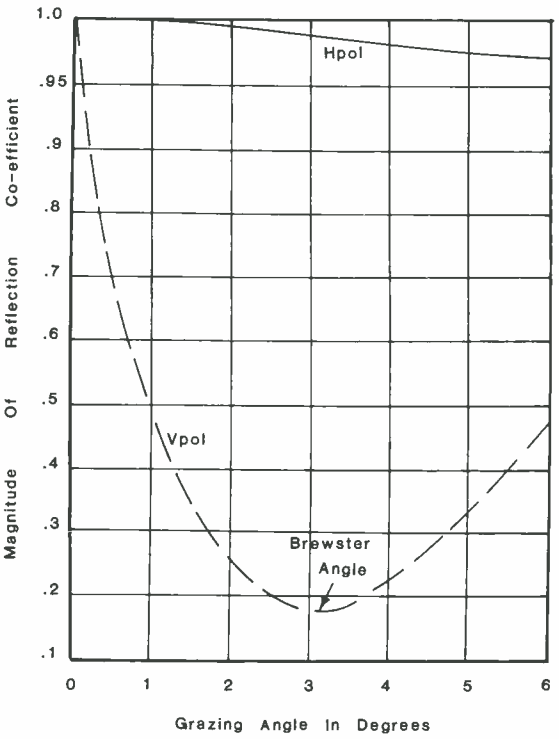


Fig. 3. Magnitude of reflection co-efficients showing differences for Hpol and Vpol, and the Brewster angle.

Fig. 3. The phase of the Vpol changes substantially with angle, while Hpol remains nearly the same. At these useful low propagation angles, there is considerably less Vpol signal reflected than Hpol, when grazing takes place. Field measurements confirm this fact.[7] For this reason, it is impossible to measure accurately axial ratios in the service area. To be meaningful, the Hpol and Vpol ratios must be measured on a good antenna test range.

Brewster Angle

For polarization with the electric field normal to the plane of incidence, there is no angle that will yield an equality of impedances for earth materials with different dielectric constants but like permeabilities. An incident wave with both polarizations present will have some of the second polarization component but little of the first reflected. The reflected wave at this angle is thus plane polarized with the electric field normal to the plane of incidence and the angle is the polarizing angle.

Notice that in Fig. 3 the minimum reflection co-efficient occurs at a grazing angle of about

[7]Moeller, Adolph: "Effect of Ground Reflections On Antenna Test Range Measurements" Microwave Journal, pp 47-54 March, 1966.

2°. Below this angle, the reflection co-efficient rapidly increases to unity. The angle at which the minimum reflection co-efficient occurs is called the Brewster or polarizing angle, after the Englishman who first discovered this phenomenon.

For ground reflections occurring near the Brewster angle, the reflection co-efficient is much smaller for Vpol than the Hpol. Therefore the Vpol signal components of Cpol are attenuated considerably. The greatest attenuation for Vpol from ground reflection occurs at this angle.

Field measurement of Vpol signals will usually show a greater ratio of Hpol to Vpol due to this Brewster angle loss. It must be borne in mind that the Brewster angle is a function of soil conductivity and may change from place to place, as well as from season to season.[8]

It is important, then, that the antenna height above the service area results in grazing angles which are less than the Brewster angle. Otherwise the Vpol will be reduced and the radiation will be much more elliptical than circular in polarization.

Fresnel Zone Clearance

A much neglected consideration in FM transmitting antenna location and height is Fresnel zone radius clearance in the path to the service area. Microwave engineers always make certain that their signal paths have this important clearance.

The effect of clearance above ground or other obstacles was studied by Auguste Jean Fresnel, a French scientist who first discovered this phenomenon in optics. Fresnel zones are circular areas surrounding the direct line-of-sight path of a radius such that the path length to the zone perimeter is a multiple of one half-wavelength longer than the direct path. This is illustrated in Fig. 4. The zone diameter varies with frequency and path length. The greater the path length, the larger the required mid-path clearance required for full signal.

Fresnel also discovered that the entire first zone radius is not required for full signal strength. Six-tenths of the first zone would suffice, which is fortunate since the radius is quite large at the FM frequencies. The equation for determining the first Fresnel zone radius for 4/3rd earth curvature is:

$$R = 1140 \sqrt{d/f}$$

where d is the path length in miles, F is in MHz and R is in feet for the first radius.

[8]Reed, Russel: "Ultra High Frequency Propagation" 2nd Edition, Boston Technical Publishers pp 223-238 1964.

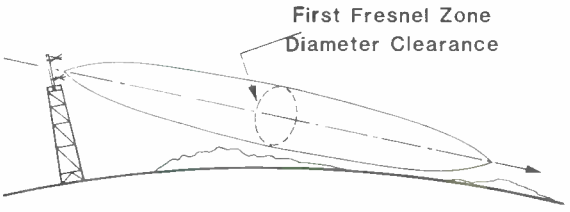


Fig. 4. First Fresnel zone clearance occurs as shown above, but only six-tenths is required for full free space signal level. Not to any scale.

In Table 1 the required 0.6 first Fresnel zone radii clearances at the middle of the path are shown for 98 MHz and service areas up to 52 miles (92 km) from the transmitter. The idea is to raise the height of the transmitting antenna so that the mid-path height is as high as or higher than shown in the Table. Due to the geometry of the Fresnel zone, if the terrain is relatively flat, the mid-path radius will control and be larger than that required elsewhere along the path. If the mid-path clearance is less than the values shown, the FM signal will be attenuated in accordance with the curve shown in Fig. 5.

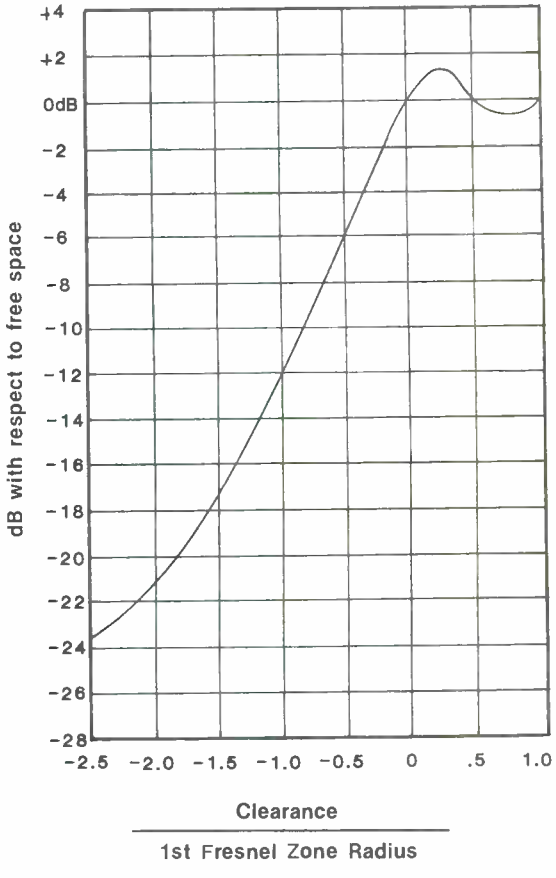


Fig. 5. Attenuation of FM propagation when the path between transmitter and receiver lacks Fresnel zone clearance in the ratios shown.

TABLE 1. Recommended Minimum Antenna Heights (for flat terrain and 98 MHz).

Service Area Radius Required		Fresnel Zone Six-tenths Clearance		Recommended Min. Antenna Height		Probable FCC 80-90 Class
Miles	Km	Feet	Meters	Feet	Meters	
5	8	155	47	310	95	A
7½	12	189	58	378	115	A
10	16	218	66	426	130	A
15	24	267	81	534	167	A,B,C-2
20	32	309	94	618	188	B-1,C-2
25	40	346	105	700	213	B-1
30	48	378	115	756	230	B
35	56	409	125	818	250	B
40	64	437	133	875	267	C-1
45	72	463	141	925	282	C-1
50	80	488	149	975	297	C-1
57	92	522	159	1,043	318	C,C-1

The center-of-radiation heights of the antennas in Table 1 are actual and not height above average terrain (HAAT). Some of these recommended heights will reduce the allowable effective radiated power (ERP) in accordance with FCC 73.211 (b), depending on the class of station and the zone. However, it is better to have the Fresnel clearance than the maximum low height ERP values, as the higher heights will produce stronger signals.

It is a well known propagation axiom that greater heights are more useful in producing higher signal strengths than ERP levels, everything else being equal.

Without the first Fresnel clearance of 60 percent the signal level at the distant point suffers. This reduction will follow the curve shown in Fig. 5 for different values of clearance.

In order for the FCC prediction curves to be valid, the recommended minimum antenna heights should be achieved. These heights not only provide line-of-sight conditions to the service limits but also proper Fresnel clearances. Both conditions are required for the FCC F(50,50) curves to be valid.

The values in Table 1 are for relatively flat terrain but take into consideration the FCC suggested roughness factor of up to ±150 feet (50 m). Where the tower height is limited by HAAT values or other limitations, the signal strength will suffer due to those factors.

Soil Conductivity

The conductivity and permittivity of the soil, together with the vegetation on it, play a part in the attenuation of FM signal strength. Average soil has a dielectric constant of about 15 millisiemens per meter at 100 Mhz.[9]

[9]Skolnik, Merril: "Radar Handbook" McGraw Hill Book Co. New York pp 39-8 to 39-9 1970.

By raising the receiving antenna above the immediate effects of the soil, the signal level will be increased. Actual field measurements have proven a 9 dB increase in signal when the dipole was raised from 3.28 feet (1 m) to a level of 30 feet (9.1 m).

FCC Service Contours

From the FCC coverage prediction charts, it is possible to draw contours of the various grades of service for a given ERP and antenna height above average terrain. These predictions, at 50 percent of the locations, 50 percent of the time, constitute the basis for the service contours. The city grade contour being 70 dBu (3.16 millivolts per meter) and primary service contour which is 60 dBu (1.0 millivolts per meter).

The FCC Section 73.333 charts for these predictions now have a built-in terrain roughness factor, to more accurately predict the distances, as explained above.

CIRCULAR POLARIZATION

Radio waves are composed of electric and magnetic fields at right angles to each other and to the direction of propagation. When the electric component *E* is horizontal, the wave is said to be horizontally polarized, as shown in Fig. 6-B/D. Such a wave is radiated from a horizontal dipole. References are with respect with the earth plane. If the desired electric component is vertical as in Fig. 6-A/E, a vertical dipole could be used to produce the vertically polarized wave.

When the two plane waves are equal in magnitude, and if one plane wave lags or leads the other by 90 electrical degrees, the field will rotate as shown in Fig. 6, at the speed of the carrier frequency and will be polarized circularly.

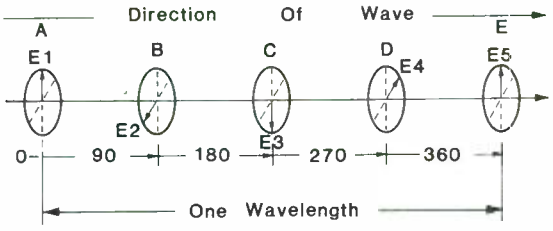


Fig. 6. Circularly polarized wave propagation in one wavelength of travel, showing right hand rotation. Note vector rotation with wave travel.

Only in the special case where the horizontal and vertical components are equal in strength with a 90 degree phase difference is the radiation said to be Cpol.

The direction of rotation shown by the vector arrows in Fig. 6 depends on the relative phase of the two components. Thus the polarization of the wave will appear to have either clockwise or counter-clockwise rotation, as shown. The FCC has set clockwise rotation as the technical standard, in order that similar sense of rotation antennas may be used for receiving in the future.

Notice that in Fig. 6 the polarization rotates at any given place during its propagation. Importantly, vertical and horizontal vector polarization does *NOT* occur at the same instant, at the same place of measurement or observation. It is this rotation which gives Cpol its signal penetrating qualities, so useful in FM broadcasting. The rotating polarization of Cpol will find its way into the FM receiving antenna and provide useful signal levels under conditions where Hpol may not.

The axial ratio as shown in Fig. 7 is that between the maximum and minimum voltage component at any orientation of the reference measuring test dipole which is placed perpendicular to the direction of propagation. An axial ratio of 1:1 (0 dB) is perfect. In practice, axial ratios of 2 dB or better are considered to be excellent and commercially available. Axial ratios over 4.9 dB (1.75 to 1 voltage ratio) are considered to be elliptically polarized, a hybrid form and not as good in signal penetrating qualities as Cpol.

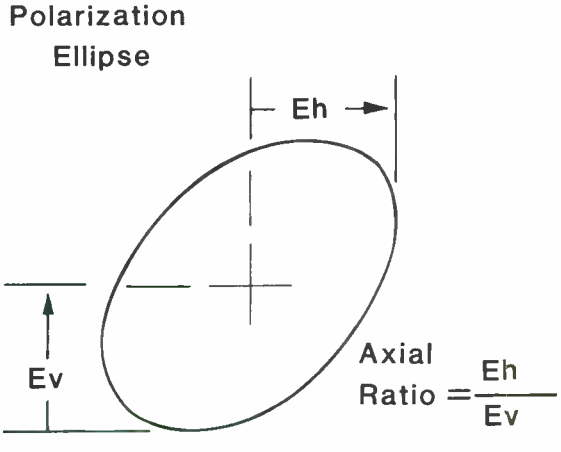


Fig. 7. Axial ratio expressed in dB is the ratio of the larger polarized component divided by the smaller at any reference dipole orientation, where the maximum ratio occurs.

Cpol radiation does not increase the distance to the FCC contours. Interference and allocation contours are not changed when switching from Hpol to Cpol. The service contours are predictions based on the horizontal component of the Cpol radiation only. It must be remembered that the ERP from a Cpol station reaches its maximum Hpol power 90 degrees *after* it reaches its Vpol peak. Hpol and Vpol do not add since they do not occur at the same instance, as shown in Fig. 6.

GENERAL COVERAGE STANDARDS

There are certain height and power levels fixed by the FCC for various classes of stations. The United States has been divided into three different geographical areas based on population density as well as propagation refractive index levels. These ERP and height values have been set to prevent co-channel and adjacent channel interference.

Zone I generally speaking is the northeastern part of the United States. Zone I-A includes Puerto Rico, Virgin Islands and that portion of California lying below the 40th parallel. Zone II includes Alaska, Hawaii and the remainder of the United States not in the above two zones. This is more fully described in FCC Section 73.205.

Under new Rules which resulted from Docket 80-90: "Modification of FM Broadcast Station Rules to Increase the Availability of Commercial FM Broadcast Assignments," in 1983, new ERP levels and additional classes of stations were created. The distance to the 60 dBu (1 mV/m) signal contour is the controlling factor so that the ERP based on the HAAT is adjusted to produce that level and no more at a specific distance for a particular class station.

Table 2 shows for each FM class station, the zone, the maximum ERP, the maximum HAAT and the distance to the 60 dBu contour calculated by using the maximum ERP and HAAT and then rounding to the nearest kilometer and mile. The FCC issued these in that docket and they are currently the standards.

TABLE 2. Docket 80-90 FM station classes, zones, and ERP.

FM CLASS	ZONE	MAX. ERP In kW	MAXIMUM Feet	HAAT Meters	DISTANCE TO Miles	60 dBu km
A	I, I-A	3	328	100	15	24
B	I, I-A	50	492	150	32	52
B-1	I, I-A	25	328	100	24	39
C	II	100	1,969	600	57	92
C-1	II	100	984	300	45	72
C-2	II	50	492	150	32	52

Under these new Rules, Class C stations will be required to have at least 100 kW ERP and an antenna height of more than 984 feet (300 m) above average terrain. Class C-1 stations are now permitted a maximum of 100 kW ERP with an antenna maximum HAAT of 984 feet (300 m), while C-2 stations may go to 50 kW at a maximum HAAT of 492 feet (150 m). Higher HAAT may be used with reduced ERP values, in accordance with equivalent 60 dBu coverage. Class C and C-1 stations may thus share the same community antenna and tower.

Stations may be upgraded using the easiest method which is to increase existing location tower height. Such factors as local zoning laws and aircraft flight patterns may preclude this approach, however.

FM Signal Measurements

The signal strength received at 5 feet (1.5 m) above ground, which is about average for auto whip antennas, is several times lower in level than at the standard FCC measurement height of 30 feet (9.1 m). This fact should be taken into consideration when comparing low height measurements with the FCC Section 73.333 prediction charts, which are made for the higher height. Signals at the higher height are considerably stronger.[10]

Signal levels inside houses, apartments, offices and other structures vary greatly. Levels depend on the type of building construction but in nearly all cases will be lower than those outdoors. Reflections inside the building reduce stereo separation, and cause crosstalk problems with SCA channels. An outside FM receiving antenna is recommended for good reception.

Field strength measurements should not be used to determine the transmitting antenna radiation pattern or efficiency. The propagation factors discussed previously camouflage the true performance. The only technically acceptable way to determine the antenna's characteristics is on an antenna test range.

Elsewhere in the Handbook is an entire chapter dealing with the recommended methods and equipment to make FM and TV field strength measurements. This information may be used to determine the actual quality of service and the areas where useable signal levels in fact exist. Predicted one millivolt-per-meter contours may be considerably different from actual measured values.

Required Signal Strength

What is the minimum satisfactory signal strength? What's the maximum above which it is wasteful? FCC Section 73.315 has indicated some of the following levels:

34 dBu	=	.05 mV/m	For rural areas
60 dBu	=	1.00 mV/m	Suburban areas
70 dBu	=	3.16 mV/m	Principal community
82 dBu	=	12.64 mV/m	Highest useful level

The first three levels were set by the FCC in the early 1950s when tube receivers and Hpol antennas were the vogue. Modern day transistor radios have much greater sensitivity. And Cpol has much greater signal penetrating power than the old Hpol had in the days more than 30 years ago when these levels were first established.

The FCC defines two grades of signal contours on its applications. The first is based on the 70 dBu contour (3.16 mV/m) required to cover the principal community. The second is the 60 dBu contour (1 mV/m) which defines the primary service area.

The FCC also stated that, in rural areas, levels as low as 50 microvolts-per-meter were useful. Indeed current home stereo tuners and FM auto radios operate very well with only 25 microvolts-

[10]Saveski, Peter: "Radio Propagation Handbook" TAB Books Inc. Blue Ridge Summit, PA. pp 148-159 1980.

per-meter. In practice, 50 microvolts-per-meter (0.05 mV/m) is quieting in nearly all automobile and transistor radios receiving a stereo signal from a Cpol station antenna. Therefore 50 microvolts-per-meter should be considered the minimum useful signal level.

If the highest level of 3.16 mV/m is quadrupled, it will be 12.64 mV/m. This is a 12 dB increase, equal to increasing the FCC power level by more than 15 times. It can be safely said that this level of 12.64 mV/m is considerably more signal than necessary by any present day working FM radio. Any signal level higher than this is superfluous and not at all useful.

BLANKETING

Excessive RF signal into a receiver creates a problem of unsatisfactory reception called blanketing. High signal levels overload the front end of receivers and make satisfactory reception impossible. The FCC has defined the 115 dBu (562 mV/m) level as the "blanketing contour" and adopted the inverse distance method to predict how far this contour extends. New or modified FM stations have the responsibility to satisfy all complaints, at no cost to the complainant, of blanketing-related interference inside this contour within one year of commencement of operations.

The distance to the 115 dBu contour is determined using the following equation:

$$D \text{ (in kilometers)} = 0.394 \sqrt{P}$$

$$D \text{ (in miles)} = 0.245 \sqrt{P}$$

Where P is the maximum effective radiated power (ERP), measured in kilowatts of the maximum radiated lobe, irrespective of vertical directivity. For directional antennas, the horizontal directivity shall be used.

ANTENNA GAIN

Antenna gain is expressed in power ratio and may also be stated in dB. For example an antenna with a power gain of 2 is also said to have a gain of 3.0 dB.

The FCC in Section 73.310 (a) of its Rules, defines antenna gain as the square of the ratio of the root-mean-square free space field strength produced at one mile in the horizontal plane, in millivolts per meter for one kW antenna input power to 137.6 mV/m. (In metric units, 1 km and 221.4 mV/m).

Notice that this gain is not in reference to a half wave dipole, nor is it with respect to a Cpol antenna, when the gain is for a Cpol antenna, as is the communications practice parlance.

A two bay Hpol antenna has a power gain of approximately two. But a two bay Cpol antenna in FCC terminology has a gain of about one because the other half of the power is Vpol and is not considered in the gain calculations. Only the horizontal polarization mode is used by the Commission. The vertically polarized energy must not exceed the Hpol however (except for noncommercial, educational FM facilities attempting to minimize interference to TV Channel 6 reception).

The power gain of an antenna is used with the transmitter gain when determining the Effective Radiated Power (ERP). Consider for example a 10 kW transmitter and an antenna power gain of 5. Neglecting transmission line loss, the ERP is 10 kW $\times$ 5 = 50 kW ERP. If the antenna gain were 10 and the transmitter power was 5 kW, we would have the same ERP of 50 kW. (5 kW $\times$ 10 = kW ERP)

EFFECTIVE RADIATED POWER (ERP)

The FCC defines the term Effective Radiated Power to mean the product of the antenna input power (transmitter output power less transmission line loss) times the antenna power gain. Where circular polarization is used, the term ERP is applied separately to the Hpol and Vpol of radiation. For allocation purposes, the ERP is the Hpol component of radiation only.

BEAM TILT

FM broadcasting antennas are normally mounted on towers which are plumb, so the peak power beam in the elevation pattern is perpendicular to the tower axis. A standard FM antenna without any beam tilt radiates more than one half of the ERP above the horizon. All this power is lost.

The higher the antenna is above its average terrain, the larger the coverage area. It also follows that the higher the antenna above terrain, the greater is the elevation angle down to the earth's horizon. This is shown in graph form in Fig. 8. In order to strike the farthest service area from a high HAAT, the beam may need to be tilted down towards the earth.

Consulting engineers who are familiar with this problem can easily work out the required amount of beam tilt, if it is necessary. Practical values are one-half to three-quarters of one degree, depending on the antenna height, distance to the far service area, and the antenna elevation pattern.

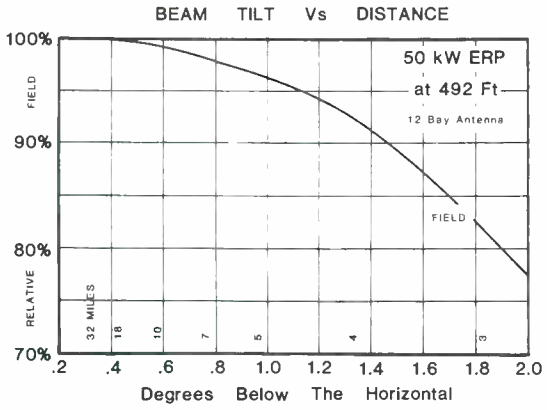


Fig. 8. Twelve bay Cpol antenna with 0.3 degree beam tilt showing ERP distribution with coverage from 492 foot (150 m) tower over flat land. Degrees below the horizon are based on 4/3rd earths curvature. Horizon is — 0.341 degrees at 32 miles (52 km).

Beam tilt is usually accomplished electrically, by delaying the currents to the lower bays, and advancing the phase of the upper bay currents during the design and construction of the antenna at the factory.

NULL FILL

While the beam tilt puts more signal into the far reaches of the service area, it does not solve the problem sometimes caused by high gain antennas within several miles of the transmitter. Elevation angle nulls common to all antennas with two or more bays appear farther and farther away from the antenna as its gain is increased with more bays.

It is a simple matter to determine the existence of elevation pattern nulls from manufacturers literature, to determine where they will fall and the small amount of null fill in power required to produce a useful level of signal strength.

The reader is referred to the TV Antenna chapter for some excellent information on null fill and beam tilt. The matter is essentially the same for FM and TV antenna systems.

TRANSMITTER-ANTENNA COMBINATIONS

Typical Class A Station Coverage

Table 3 shows the FCC predicted signal strengths for a typical Class A facility on a relatively flat plane, with the antenna center 328 feet (100 m) above average terrain (HAAT). The maximum allowable power of 3 kW is used. The first two columns show the distances, with the farthest being the horizon from this height. The third column indicates the true earth angle from the antenna to the distances shown. From the elevation information the ERP from each antenna was determined at each vertical angle. This ERP value was used to find the signal strength from the FCC F(50,50) FM prediction chart, FCC Section 73.333 Fig. 1.

Under signal level in millivolts-per-meter (mV/m) the predicted field strengths are shown in this Table based on the above procedure. From 5 miles (8 km) to the horizon, the signal strengths are identical because the ERP values are very nearly identical. This is due to the shape of the elevation pattern near the maximum.

Departure occurs as the elevation pattern angle becomes larger. At 4 miles (6.4 km) the one bay antenna ERP at 0.92 degrees is 2,982 watts while from the six bay antenna it is 2,912 watts. Anyone who has used the 73.333 charts has found the enlarged versions to be easier to read, but even then a difference of 200 watts between two ERP values is difficult to ascertain, and at best is a calculated guess.

Going towards the transmitter from 4 miles (6.4 km) the field increases in favor of the one bay. This table clearly demonstrates that the high power transmitter-low gain antenna does not improve the signal strength available to the receivers beyond about 4.5 miles (7.25 km) in this example. The signal level starts to increase between 4 and 5 miles (6.4 and 8 km). Any increase above this level is useless because full limiting has certainly taken place in even the poorest FM receiver. (See Required Signal Strength in this chapter)

In Table 3 the signal strengths of 16 mV/m at 5 miles (8 km) are identical coming from either transmitter-antenna combination. This is due to the fact that the ERP power at the vertical angle of -0.74 degrees is about the same from both antennas. The ERP at 0.0 degrees elevation pattern will of course be exactly the same for both combinations. The field does not change measurably until observation is made beyond 1.5 degrees from the peak 100% value in a six bay antenna. This is the nature of things.

The signal strengths in this table were based on relatively flat terrain from an antenna 328 feet (100 m) HAAT. The true earth curvature distance to the horizon is 25.56 miles (41.23 km). Therefore the outer reaches of useful signal drop off very rapidily beyond this point in the typical Class A station.

There are no nulls in the one bay antenna pattern. In the six bay the first null occurs at about -10 degrees, placing it approximately 0.37 miles (0.6 km) from the tower. Antenna arrays are never perfect so the null is never zero power. So assume a minimum radiation of five watts in the

TABLE 3. Transmitter Power Vs Antenna Gain.
Class A 3kW ERP — Zones 1 and 1-A
Maximum HAAT 328 Ft (100 m)

Service	Distance	Vertical	SIGNAL LEVEL IN mV/m	
			7.5kW Transmitter	1kW Transmitter
Miles	Km	Angle	1 Bay Antenna	6 Bay Antenna
1	1.6	3.58	275	210
2	3.2	1.80	88	81
3	4.8	1.21	42	40
4	6.4	.92	24	22
5	8.0	.74	16	16
6	9.6	.63	11	11
7	11.3	.55	8.5	8.5
8	12.9	.49	6.2	6.2
9	14.5	.44	5.0	5.0
10	16.1	.41	3.7	3.7
12	19.3	.36	2.5	2.5
14	22.5	.33	1.8	1.8
16	25.7	.31	1.4	1.4
18	28.9	.29	1.1	1.1
20	32.2	.28	.85	.85
22	35.4	.28	.70	.70
24	38.6	.27	.55	.55
26	41.8	.27	.40	.40

first null. The predicted signal would be 31 mV/m and the second null with the same five watts ERP would be even stronger in this example. So in practice there would be no need to fill in the nulls of the six bay antenna.

Another consideration is that the nulls fall very close to the tower and the number of people occupying the null areas is small. So any problems resulting from these close in nulls would be very minor.

Typical Class B and C-2 Station Coverage

The same comparisons of transmitter-antenna combinations can be made for Class B and the new Class C-2 stations, operating with a HAAT of 492 feet (150 m) with 50 kW ERP. This is shown in Table 5. With 55 kW transmitters now available, a 2 bay Cpol antenna would provide the 50 kW ERP, with high efficiency coaxial lines. It is compared with a 10 kW transmitter feeding a 10 bay Cpol antenna. The terrain flatness is assumed not to exceed ±150 feet (50 m).

Table 5 indicates that the signal levels are the same from 4.6 miles (7.4 km) out to 35 miles (56 km) under similar columns as for the Class A station comparisons. The FCC uses a receiving height of 30 feet (10 m) so the horizon is a bit further away, at 31.3 miles (50.5 km).

From the transmitter out to about 2 miles (3.2 km) the signal rises much more rapidly in the two bay antenna than in the 10 bay, the latter being somewhat similar to a cosecant curve. There is surplus signal close in and more than is needed or can be tolerated.

Therein lies one of several problems with low gain antennas as seen in Table 5. With the two bay antenna there is 900 mV/m at one mile (1.6 km) and 562 mV/m as far out as 1.55 miles (2.5 km). This is above, or at, the blanketing level of 562 mV/m. (See Blanketing in this chapter) The high gain antenna does not cause this type problem under identical conditions.

The signals from both combinations are much more than necessary for present day FM receivers out to about 10 miles (16 km). There is no practical difference technically in USEABLE signal strengths presented to receivers in the entire market area, from either antenna. There is, however, a great deal of savings in capital costs as well as operating expenses between the two combinations.

One antenna factor is not clearly indicated in Table 5. The two antennas have elevation pattern nulls. The two bay antenna null at -30° falls 852 feet (260 m) from the foot of the tower and can be disregarded. The ten bay antenna nulls can be filled to as little as 2½% field, which will not affect its gain. This would represent a minimum ERP at the nulls of 31 watts. Although seemingly very small, it is very effective as can be seen in Table 4.

It is obvious that the 10 bay antenna nulls can easily be filled to produce signal levels in excess of those required. If the transmitter is located in a populated area, these high levels prevent the loss of stereo separation and noise in the SCA, if there are reflections from high level lobes in the built up areas. This problem is common to

TABLE 4. 2½% Null fill in — 10 bay antenna.

Null	Angle	ERP	Distance	Field
First	−5.75°	31 w	4,800 Ft	31 mV/m
Second	−11.50°	31 w	2,240 Ft	70 mV/m
Third	−17.25°	31 w	1,512 Ft	109 mV/m

TV transmitters which produce ghosts from high signal level lobe areas reflecting into null areas. This problem is greatly and satisfactorily reduced with null fill in as shown in Table 4.

ANTENNA SITE SELECTION

The transmitter location must be carefully chosen. Site economics should be secondary to the technical advantages of a particular site. Fresnel zone clearances, and other factors outlined in this chapter should be considered. A site with an operating FM or VHF TV station makes an excellent source of signals to check propagation for a new station. If the existing station is FM, make certain that its antenna pattern has been optimized to provide as much circularity as possible.

A good field strength meter should be used to probe the actual signal from the existing station. Relative readings are important, not the absolute. Check for reflections as well as level changes within a short walking area of about 100 feet (30 m) which would indicate reflections. Check for stereo separation. Using this information, the operation of a new station near the one being checked can be compared and verified before moving or submitting the FCC application. The consulting engineer will want to use this information to insure the suitability of the new site.

TV CHANNEL 6/FM ANTENNA PROBLEM

Television Channel 6 occupies the band from 82 to 88 MHz. The FM broadcast band extends from 88 to 108 MHz. Non-commercial educational FM stations are assigned from 88 to 92 MHz. Interference clearly exists between the two, with the TV station viewers suffering the most. The FM receiver is relatively selective with a response of about 200 kHz, but the TV receiver has a bandwidth of at least 6 MHz. However, more than TV receiver selectivity is involved in this interference problem, which the FCC has been trying to address since 1972. See FCC Section 73.525

Three principal techniques exist to minimize channel 6 interference from FM stations: (1) collocation, (2) where collocation is not feasible, location of the FM station in an area of low population density, and (3) antenna cross polarization.

Collocation

The purpose of collocation is to achieve the same propagation path for both TV and FM stations, thus making possible the maintenance of a nearly constant desired-to-undesired signal ratio in the service area. If possible, both antennas should be mounted on the same tower. If not, a maximum separation of 400 meters between the two has been adopted.

TABLE 5. Transmitter power Vs antenna gain.

Class B, C-2 50 kW ERP
Zone 1, 1-A & C-2

Service Miles	Distance Km	Vertical Angle	SIGNAL LEVEL IN mV/m 55kW Transmitter 2 Bay Antenna	10kW Transmitter 10 Bay Antenna
1	1.6	4.97°	900	140
1.55	2.5	3.25°	562	165
2	3.2	2.49°	310	230
3	4.8	1.67°	153	135
4	6.4	1.26°	92	88
4.6	7.4	1.15°	71	71
5	8.0	1.02°	57	57
7.5	12.	.70°	22	22
10	16	.55°	13	13
15	24	.41°	6.5	6.5
20	32	.36°	3.1	3.1
25	40	.33°	1.9	1.9
30	48	.328°	1.1	1.1
35	56	.332°	.7	.7

The horizontal and vertical plane radiation patterns of both antennas should be similiar because the objective is to maintain a near constant desired to undesired signal ratio. The HAAT should also be similar, thus the desirability of collocating on the same tower. The maximum ERP of the FM stations operating on this basis is in Section 73.525(b) of the FCC Rules.

Alternate Locations

The FM station may not be intended to serve the same community as the TV station, or collation may not be possilbe. In this event the FM broadcasters should locate in an area of relatively low population density by imposing a limit on the population which may be included within that area where a particular undesired-to-desired protection ratio is exceeded.

Two ratios were proposed by a committee which studied this problem in 1983.[11] Their recommendation varied according to the educational station frequency separation from the Channel 6 aural frequency of 87.75 MHz. In any event, the interference area should not have more than 3,000 people living in it.

Alternate Polarization

Several organizations have made discrimination tests in the United States and in Europe with cross polarized antennas. It has thus been well established that discrimination of 16 dB is to be expected in rural areas and 10 dB in urban areas between two stations one using the Vpol and the other using Hpol, and the receiving antenna being similarly polarized. This is sufficient in most cases to resolve the problem.

While technically cross polarization will help solve the problem, the Commissions Rules will not require it. This is left as an option for the FM applicant to use. Most TV channel 6 receiving antennas will remain Hpol while automobile FM antennas will stay Vpol. So if the TV station remains Hpol, this interference problem may be cleared up if the FM station will switch to Vpol.

Rejection Filters

The FCC believes that rejection filters installed at the TV receiver would be helpful, while others think this is not a satisfactory solution. Unfortunately, many viewers do not sufficiently understand this problem and are thus not motivated to have the necessary filter installation made.

It is further complicated by the fact that the majority of the existing TV receivers still have balanced antenna inputs (300 ohms) and filters designed for them do not usually provide the necessary amount of rejection. As more TV receivers with coaxial inputs are purchased by the TV viewing public, this situation could change dramatically. Unbalanced coaxial (75 ohm) filters are excellent, and 20 dB of attenuation of the FM signal is readily available.

VSWR BANDWIDTH

According to theory, the bandwidth of an FM signal is actually infinite if all the sidebands are taken into account. It is also interesting to note that at certain modulation indices, the carrier amplitude goes to zero and all the transmitted power is on frequencies other than the carrier frequency. Practical considerations in the transmitter and receiver circuitry make it necessary to restrict the RF bandwidth to less than infinity of course.

Prior to 1984 the maximum deviation for FM stations was 75 kHz, representing 100% modulation. In that year the FCC changed the maximum deviation to 82.5 kHz (110%) for those stations with 10% injection of subcarrier channels. This additional deviation requires greater antenna system bandwidth than previously needed.

System bandwidth is measured at the point in the antenna system where the transmitter is connected. This usually includes the harmonic filter, all the main coaxial transmission line, and, of course, the antenna itself.

The significant sidebands are usually considered to be those whose amplitude exceeds one percent of the unmodulated carrier. With 110% modulation (82.5 kHz deviation) these side bands require a bandwidth of 260 kHz.[12,13]

The bandwidth is considered to be the VSWR points in the system under consideration having a reflection coefficient of less than five percent which corresponds to a VSWR ratio of 1.1:1

Intermod and AM Distortion

Intermodulation distortion and synchronous AM noise are caused by narrow VSWR bandwidth in the antenna system, as well as from final amplifier circuitry all the way to and including the antenna.[14]

[11]Cohen, Jules: "Proposed Solutions, Channel 6-Educational FM Broadcast Interference Problem" Preceedings 38th Annual Broadcast Engineering Conference, NAB, Washington, D.C. 20036.

[12]Gray, Lawrence: "Radio Transmitters" McGraw Hill Book Co. New York pp 181-186 1961.

[13]Mendenhall, Geof: "Study of RF Intermodulation Between FM Broadcast Transmitters Sharing Diplexed Antenna Systems:" Technical monogram. Broadcast Electronics Inc. Quincy, IL 62301 1983.

[14]Mendenhall, Geof: "The Composite Signal - Key to Quality FM Broadcasts" Technical monogram. Broadcast Electronics Inc. Quincy, IL 62301 1984.

Synchronous AM is AM modulation of the carrier caused by frequency modulation of the carrier frequency in the VSWR notch. At the notch the reflected energy is the lowest. As the deviation takes place, the greater the frequency swing, the greater will be the reflections, due to the VSWR notch. With a flat VSWR curve, this AM does not take place. If the VSWR curve is skewed, synchronous AM will also take place, intermod and stereo crosstalk will also increase.

Checking System VSWR

From time to time, the VSWR of the narrow band antenna system should be checked and adjusted, if necessary, to ascertain VSWR compliance. If the exciter has thumb wheel exciter frequency adjustability in 10 or 50 kHz steps, it may be used to change the frequency to check VSWR on different frequencies, with the transmitter operating at low power during the FM test period. The reflectometer may be used as the indicator.

Alternately one of several methods of checking VSWR in coaxial line systems using test equipment may be used. These include a signal generator with a high directivity directional coupler, sweep generator test setup, or an impedance test set.

The VSWR should be plotted to insure that the reflection response is balanced to 130 kHz on each side of the carrier frequency. With transmission lines longer than 300 feet (100 m) it is suggested that the 260 kHz VSWR bandwidth be under 1.08:1 all the way out to ±130 kHz. The additional delay due to increasing line length becomes more of a problem, so the amplitude of the reflection must be reduced, for best operational results.

Low VSWR Importance

The VSWR shown by the transmitter reflectometer does not increase or decrease the range of the signal. It has nothing to do with coverage. But VSWR values above 1.1:1 may decrease the final amplifier efficiency. Other definite negative effects of VSWR are increased intermodulation products and AM synchronous noise. Stereo separation is also degraded with increased VSWR.[15]

COMMERCIALLY AVAILABLE ANTENNAS

There are several basic classes of antennas available for use from 88 to 108 MHz. These and variations of them are made by several American manufacturers in different models, gains, and input power ratings. They may be broken down into the following general classes:

1. Ring stub and twisted ring
2. Shunt and series fed slanted dipole
3. Multi arm short helix
4. Panel with crossed dipoles

These antennas have many things in common. For example, all the non-symmetrical antennas are designed for side mounting to a steel tower or pole. Radiating elements are shunted across a common rigid coax line. This has eliminated the problems associated with the older corporate feed system using semi-flexible solid dielectric low power cables.

Shunting elements every one wavelength across a transmission line makes impedance matching simple. Bandwidth is limited by the VSWR of the individual elements and the use of an internal transformer.

With more than about seven bays, the first three of the above antennas have a more difficult task in being matched and there is undesirable beam squint, since the elevation beam angle changes with frequency deviation by the transmitter. Antennas with more than seven bays are fed from or near the center, thus dividing the phase change in one-half and effectively eliminating the beam squint. Center feeding also simplifies the VSWR matching.

A means for tuning out reactances after the antennas have been installed on the tower is also common with all the antennas. Located at the input to the antenna, the VSWR tuner consists of adjustable location dielectric or metal slugs on the inner conductor of the main coax line. Several fixed position variable capacitors spaced one eight wavelength along the main feeder near the antenna input are also used on some side mounted antennas, to adjust the VSWR to very small values.

Another variety has curved radiating elements, around a circumference whose diameter is determined by the number of element arms. Each radiator consists of two, three or four such circular arms, depending on the model. Each element is fed thru a shunt arrangement, and then shunted across the vertical rigid feed coaxial line.

Wideband panel antennas are becoming popular where high buildings, favorable mountain sites or high towers are available. Several firms make wide band panel antennas. Some have very wide band VSWR features in each radiators. Others with not so broad VSWR, use phase impedance compensation similiar to the European scheme, which uses 90 degree phase quadrature impedance compensation.

[15]Onnigian, Peter: "Stereo Degradation as a Function of Antenna System VSWR" Audio Engineering Society Annual Meeting, AES, New York City, NY. 10017 1976.

Phase quadrature compensation makes it possible to cover the entire 88 to 108 MHz band with a VSWR under 1.1:1 while maintaining excellent elevation, and azimuth patterns, together with very good axial ratios. Power ratings up to several hundred kW are offered so that many FM stations can be diplexed into one such antenna.

Only the wideband community FM antenna design now uses a corporate feed system, while the others are shunt fed from a common rigid coax line. This corporate feed system, using air dielectric semi-flexible line at the lower power levels, is very successful. It splits the input power to many different dipoles at the correct amplitude and phase.

These four basic antenna classes are described in greater detail on the following pages.

SLANTED DIPOLE FM ANTENNAS

Shunt Fed Antennas

The slanted dipole antenna in its present configuration was developed and patented in 1970.[16] It consists of two half wave dipoles bent in 90 degrees, slanted and fed in phase.

Fig. 9. Three bay Cetec model JSCP-3 non-symmetrical FM antenna mounted on the tower leg. The guy cables are insulated fiber glass rods near the tower legs. (Photo courtesy Cetec Antennas)

The slant angle is critical as it is this factor which determines the ratio of vertically and horizontally polarized radiated power. The phase point center is at the feed insulator on the dipole support arm as seen in Fig. 9. When fed thru a vertical support pole on which the antenna sat during initial development tests, the axial ratio was excellent varying less than 1 dB.

The commercial adaption uses a horizontal boom containing a step transformer. This boom supports two half wave dipoles, in which the included angle is 90 degrees. The two sets of dipoles are rotated 22.5° from their normal plane. Two opposite arms of the dipoles are delta matched to provide a 50 ohm impedance at the radiator input flange. All four dipole arm lengths may be adjusted to resonance by mechanical adjustment of the end fittings. Shunt feeding when properly adjusted provides equal currents in all four arms resulting in excellent azimuth circularity.

Series Fed Antennas

A similiar arrangement of arms supported by a T arrangement may be series fed. That is, part of the outer end is insulated from the rest of the dipole and fed across the insulated break. To allow for adequate power handling capacity and to increase the VSWR bandwidth, 3 inch (75mm) diameter tubing is used.

Both antennas have VSWR bandwidths of about 1 percent, so they make excellent single channel FM antennas. They are usually mounted on the side of a supporting tower or pole, and stacked vertically to achieve required power gain. This antenna has much greater wind loading due to its larger element diameters necessary to achieve useable VSWR bandwidth. It presents considerable torque on its mounting structure and requires large amounts of AC power for electrical de-icing. Plastic radomes also present additional wind loading.

Short Helix — Multi-Arm

The number of arms may be increased to four instead of the two in the slanted dipole variety. To provide Cpol, the arms are curved to form a one wavelength circumference. These short multi-arm helices are also stacked in the conventional manner, like the others in this series for power gains as desired.

The azimuth pattern of all these non-symetrical antennas is affected by the supporting steel structure. With pattern optimization, the pattern can be made quite omni-directional. See Pattern Optimization in this chapter.

---

[16]Onnigian, Peter: Circularly Polarized Antenna, US Patent 3,541,570.

RING STUB AND TWISTED RING ANTENNAS

There are several antennas that are simple adaptations of radiators that were designed and manufactured in the 50s and 60s for horizontal polarization. By adding vertical stubs to the ends of the radiator or twisting the ring, elliptical polarization of sorts is achieved.

Both the ring and the ring stub suffer from temperature variations which tend to change the spacing between the ring openings and thus the electrical capacitance and resonant frequency. The ring stub and the twisted ring are not really circularly polarized because the axial ratio varies considerably with azimuth. At best they may be said to be elliptically polarized.

The radiation patterns are strongly affected by the tower mounting environment. Being of relatively high Q design, they are more susceptible to detuning because of icing. Radomes and electrical deicers are available to overcome this problem. While the icing problems may be overcome, pattern optimization is not offered for these antennas.

The Ring Stub Antenna

The Hpol radiation from these antennas comes from the ring portion whose plane is parallel with earth. There is a minor lobe from each radiator, which is strengthened with vertical stacking for additional power gain. This nadir-zenith lobe is the result of 360° degree stacking on the rigid coax feed line. It reduces the gain and presents a lobe at the tower base which may be detrimental if low level audio equipment is located in a building at the foot of the tower.

In order to keep the cost down, like the twisted ring antenna, the ring-stub is manufactured in several radiator to radiator spacings across the FM band. This results in some minor beam tilt up or down depending on the frequency. The higher priced slanted dipole and helix antennas are spaced exactly 360° and are usually tested to assure this spacing during production.

The Twisted Ring Antenna

This type consists of one or more rings, which have been partially twisted so that the open ends of the ring are about 10 inches (25 cm) apart. One semi-circular arm of the ring is fed with a small loop or by a direct tap on that arm. A number of these rings are fed in the same manner as the ring stubs, and have the same zenith-nadir lobe problem.

The mechanical twist is not the same when viewed in all the azimuth directions. Therefore the current is not the same, with the end result that in some directions there is much more elliptical radiation than in others.

These antennas are very simple and relatively inexpensive for single frequency use, but have some serious operational limitations for Cpol operation. They do not have the same signal penetrating affect as the slant dipole, short helix or the community antenna type of Cpol antennas.

Short Helix

A relatively recent asymetrical radiator is the four arm shunt fed helix. By using four dipoles, curved so that their circumference is about one wavelength, a Cpol antenna can be had.[17] Each dipole is about one half wavelength and is shunt fed. These are supported on a four arm structure, one end of which is tied to the supporting structure. The dipoles overlap so that the current flow around the circumference is circular. The four feed arms are connected in shunt and the feed impedance is quite low, but may be brought up to useful values with an internal step transformer.

The Cpol quality of the four arm side fire short helix is good. Three and two arm models are also available, but their axial ratio is not as good as the four arm. Pattern circularity is ± 1dB for the four arm, together with an axial ratio of about 3 dB.

These radiators are stacked about one wavelength apart on a rigid coax feed line, to obtain the necessary power gain. Like other asymetrical FM antennas its patterns are strongly affected by the supporting structure. See Pattern Optimization in this chapter for the need and methods to circularize the azimuth pattern.

Electrical deicers using the stainless steel dipole arms as one half of the heating circuit are available. Heat is created by passing a large current at low voltage thru each arm from voltage dropping transformers placed at each bay level. Plastic radomes are also available to keep snow and ice off the sensitive VSWR parts of the antenna.

PANEL ANTENNAS

Panel antennas for Cpol FM broadcasting are relatively new in the Western Hemisphere, although Hpol and Vpol have been used in Europe since the mid 1950s. This antenna was developed there to provide a wide band unit for several government stations without the need to change antennas when a new channel was added or the

[17] DuHamel, Ray: "TV and FM Transmitting Antennas" Antenna Engineering Handbook, Johnson and Jasik, 2nd Edition. McGraw Hill Book Co. New York, NY Chapter 28, pp 8-9 1984.

operating channels were changed from time to time.

Panels are from 7 to 8 feet (2100mm to 2450mm) square in the flat configuration. In the cavity style they are about 8 feet (2450mm) in diameter and about 3 feet (1000mm) deep.

A heavy metal frame is often used over which large diameter wire mesh has been welded. The wire mesh screen openings vary from 4 to 12 inches (100mm to 300mm). Electrically they are considered nearly solid metal. For wind calculations these openings produce relatively low wind loads. The entire flat frame or cavity is strong enough to support a man on its mesh openings. Some manufacturers hot dip galvanize their steel after fabrication; others use stainless steel construction.

For FM use, two crossed dipoles are used as the illuminating source for each panel or cavity. Each dipole is fed in phase quadrature, that is one dipole receives its peak current 90 degrees after the other, to produce Cpol. A typical set of electrical and mechanical specifications for a Cpol eight bay cavity community antenna is shown in Table 6.

Flat Panel Antennas

By pulling the dipole back on its feed support arms, the "arrowhead" shaped dipoles control both Vpol and Hpol azimuth patterns. Rotating the dipoles 45 degrees with the earth-ground reference improves the polarization ratios even further.

Round dipoles made of tubing as large as 6-1/8 inches (155 mm) in diameter are used along with a single line quadrature feed. This combined arrangement makes an excellent wideband Cpol panel to cover the entire FM band. Power splitters, dividers and cables along with a number of these panels completes the antenna.

Cavity Panel Antennas

The cavity antenna also uses the reflective properties of the flat screen panel. In the cavity however, the illuminating dipoles are flat instead of round and all four arms are parallel to the plane of the cavity. Like the flat panel with its round dipole supporting balun, the cavity also holds its flat dipoles with a double dipole coaxial balun.

The dipoles in the cavity get their wide VSWR bandwidth thru the sleeve dipole principle.[18] Capacity is provided by a metallic ring close to all four dipole arms placed between them and the back of the cavity. This antenna has the advantage over some other designs of greater VSWR bandwidth. It is considered closer to state of the art due to better elevation and azimuth pattern control of both planes of polarizations by the shape of the cavity.

Crossed Dipole Theory

Common to the flat panel and the cavity is the operation of the dipoles which generate Cpol. The dipoles are fed currents in phase quadrature, thru a coaxially balanced balun, which provides equal currents to all four arms of the two dipoles. They excite the entire cavity or flat panel with a rotating RF field in a plane parallel to the dipoles. The RF field is thus Cpol and may be ideally represented by a rotating vector of constant magnitude revolving one revolution per wavelength of propagation distance. It is right hand polarized as the field rotation is clockwise as viewed from behind the screen, looking toward the direction of propagation, if the phasing between the two crossed dipoles is properly made.

[18] Bock, E.: "Sleeve Antennas" VHF Techniques, Vol. 1, McGraw Hill Book Co. New York, NY Chapter 5, pp 119-137 1947.

TABLE 6. Typical measured community antenna performance.

Operational frequency range	88 to 108 MHz
Safe RMS input power rating	200 kW
Power gain ratio, each polarization	4.4 (6.43 dB)
Maximum VSWR any frequency between 88-108 MHz	1.1:1
Elevation pattern beam tilt	−0.5°
Polarization	Right hand circular
Axial ratio	Better than 2 dB
Azimuth circularity Vpol or Hpol	Better than ±2 dB
Antenna dead weight, less than	7,000 Lbs (3,183 kgs)
Active wind load, RS-222-C 50/33 PSF	8,000 Lbs (3,636 kgs)
Antenna input flanges, two, size	6-1/8 inch
Number of bays (stacks)	Eight
Radiator type	Circularly Polarized Cavity

Radiation patterns, associated beamwidth and directivity are determined to a large extent by the size of the cavity or flat panel. The geometry of the dipole has less effect than the reflector size. The size and shape of the dipole controls the antenna impedance and the VSWR. The screen panel, be it flat or a cavity fulfills the following five important electrical functions:

a) Isolates the radiating elements from the tower or the mounting structure, and reduces mutual coupling.

b) Provides sharper beamwidth and more gain than achievable with the dipoles alone

c) Furnishes pattern control so that the beam width is nearly equal for both horizontal and vertical plane polarization.

d) With an effective balun feed system, the crossed dipole radiated pattern phase is very uniform as the amplitude changes normally with azimuth.

e) Computer aided designs are easily achieved in production for various width towers because the pattern is simply pure electrical geometry.

WIDE-BAND ANTENNA FULFILLMENT

In order for an antenna to be useful throughout the 20 MHz FM band, its operation must be the same on any frequency. The VSWR on 89 MHz for example, must be just as good as on 108 MHz. The Cpol azimuth pattern should remain the same on one end of the band as the other, as must the axial ratio. This is a much more rigorous requirement than placed on the single channel slanted dipole or the ring stub. In the wideband antennas, several factors go together in order to meet these severe requirements:

a) Basic wideband dipole radiators

b) Screen-panel pattern control

c) Quadrature phase distribution

By using these three principle parameters in a wide-band antenna the radiation pattern, VSWR, and the gain can be nearly the same on any channel within the FM band.

Several methods are used to make the VSWR of the crossed dipoles as good as possible. The dipoles are usually fed with a folded balun or the

Fig. 10-A. Series fed element of Harris model FMXH non-symmetrical antenna. Typical pole mounting with rigid inter-bay coaxial feed line. (Photo courtesy Harris Corp.)

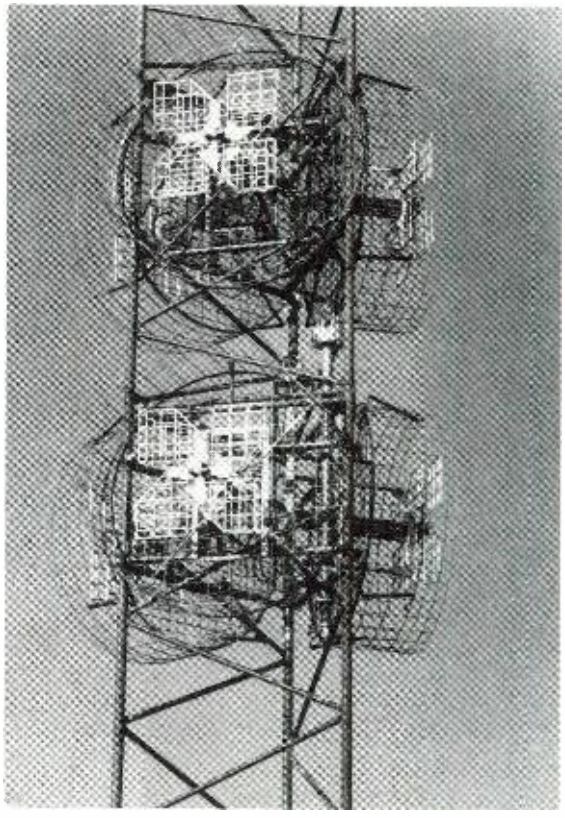


Fig. 10-B. Two bay cavity backed crossed dipole community antenna. Dipoles as well as cavity are made of heavy gauge steel mesh. Typical VSWR is under 1.1:1 across entire FM band. (Photo courtesy Cetec Antennas)

split tube type balun.[19] This improves the impedance match, phase as well as amplitude linearity of the resulting azimuth pattern.

The length to diameter (or width) ratio is usually about three. This not only reduces the Q but also increases the safe power handling capacity by increasing the voltage flash over levels. The low Q also increases the band-width by decreasing the rate of reactance change with frequency.

A natural factor aiding the VSWR problem is the fact that in order to fulfill Cpol from two crossed dipoles, there must be a phase quadrature of the two currents feeding the crossed dipole. The two reflections, as a result of VSWR, return back to the phasing device 180 degrees out of phase with each other. Being the same amplitude, they cancel.

All of the above factors, plus two or three more levels of quadrature reflection cancellations, bring the overall system input at the antenna to under 1.08:1 across the band. This cancellation technique eliminates the need for electrical deicers or plastic radomes, as the VSWR is not affected by moderate ice coatings. However radomes may be necessary with flat panels, to physically protect some radiators from falling ice.

These and other factors all contribute to make the panel-cavity antenna the best possible for either single channel or community antenna use.

Community Antenna Economics

The community antenna fits best in multiple station service. This allows sharing costs so all parties benefit from a superior antenna that each independently could not economically justify.[20]

FCC Docket 80-90 enacted May, 1983, became law in 1984. It requires Class B and Class C stations with less than maximum facilities to upgrade to a minimum facility or face being downgraded. This FCC requirement has widespread impact on existing FM broadcast stations. If a Class C station does not upgrade to the minimum required antenna height of 984 feet (300 m) HAAT within three years of the effective date of those Rules, it will be down graded to a lower classification.

Granted, it is expensive for one station to install its own 1,000 foot (305 m) tower and antenna. But its advantages may be worthwhile depending on the markets served, if it is located on relatively flat terrain with less than required HAAT. The cost is reduced when several stations get together and use one community antenna facility.

Class B and C-2 stations may want to consider putting up their own wide-band antenna at the 492 foot (150 m) level on this same tower. Class A and B-1 stations can settle at the 328 foot (100 m) level, resulting in even greater savings to all tall tower users.

If enough planning is done in advance, it is possible to install all the FM stations of one community on one tower, at considerable savings to all users. Some preclusions are lack of adequate mileage separations, the existence of excellent present facilities, and FAA tower height limitations.

The break-even point appears to be with four stations. When five stations are involved, there is a 20% reduction in cost to each of them, over putting up their own individual single channel antenna and tower at the same height. See Table 7 for a break out of costs for a wide-band community antenna system.

The costs used in Table 7 include the supply of an eight bay Cpol omni-directional community antenna with a gain of 4.40 mounted at the tower top. It also includes a dual run of 6-1/8 inch (155 mm) coaxial transmission line, for upper-lower half feed system. The 1,020 foot (310 m) tower height puts the antenna center at approximately 984 feet (300 m) maximum HAAT level on flat terrain.

The guyed, lighted and painted tower is EIA-RS-222-C spec rated for 85 mph (137 km) ground wind areas. The number of diplexers are equal to the number of stations so there there is always one thru wide-band port left for emergency use if one station loses its diplexer. The dual coax line permits using one half of the antenna in the event of an emergency in one line or one-half of the antenna.

The single channel comparison antenna system also has the same 984 foot (300 m) tower, but with one run of 3-1/8 inch (79 mm) line. Diplexers are not used of course. An eight bay single channel slanted dipole antenna with a power gain of 4.30 is side mounted and has electrical deicers. Its pattern is optimized for a smooth circular azimuth pattern. The VSWR is field adjusted to be under 1.1:1 for ±250 kHz at the station carrier frequency.

TABLE 7. Wide-band panel antenna costs (1985).

Number of Stations	Total Cost of System	% of Single System Cost
4	$1,410,000	Break Even
5	1,460,000	−20%
6	1,510,000	−31%
7	1,560,000	−39%
8	1,640,000	−44%
9	1,690,000	−49%
10	1,740,000	−52%

[19]Rudge, A.: "Handbook of Antenna Design" Vol. 2, Peter Peregrinus Ltd. London, England. pp 917-922 1983.

[20]Onnigian, Peter: "Multi-Station FM Antennas" paper presented at 23rd Broadcast Symposium, IEEE Group on Broadcasting, Washington, D.C. 1973.

All outdoor installation work was included in the costs shown. Both sets of costs have one antenna field technician for VSWR and checking-adjusting the diplexers in the community example. Tower foundations and buildings are not included as this is a variable cost item, and may be done by the owners.

Community Antenna Technical Advantages

Besides the financial advantages cited under the economics heading there may be the competitive advantage of protecting the channel classification under Docket 80-90 and using the same height antenna as the competitor. Other advantages include its emergency upper-lower half feature for transmission line or antenna half backup. The flat VSWR curve is highly useful for SCA and stereo operation. Stations sharing this type antenna will all experience less intermodulation interference than if they had separate antennas, but closely placed.

DIRECTIONAL ANTENNAS

The FCC sometimes requires that the azimuth radiation pattern be directionalized to reduce normally allocated ERP towards a given short spaced station, or for other reasons. See Sections 73.213 and 316 (c) and (d). To conform to these specifications, most broadcasters order antennas which are pattern adjusted, measured, and certified to the Commission's requirements. Directional antennas are licensed for peak ERP values resulting from the azimuth pattern. The Vpol RMS gain may not exceed the Hpol gain in a Cpol directional array, nor may Vpol exceed the Hpol in the protection direction (except in the case of FM protection to TV Channel 6, previously mentioned). The amplitude away from the null cannot climb more than 2 dB per 10° of azimuth.

Directional antennas are usually on poles although some have been tower mounted. Since the support affects the pattern, they are sold with the pole or tower on which they are tested. One firm supplies a choice of four standard patterns, while others will make the antenna meet the specific pattern requirements. There have been some instances of protection to two stations, making the pattern attainment quite difficult.

Directionalizing is a combination of the natural pattern resulting from side mounting and the use of parasitic elements. Using the two factors, any directional pattern specification may be met with sufficient work.

High Transmitter Power ERP Myth

Some people have thought that a high power transmitter with a low gain antenna to yield the required ERP somehow would put a stronger signal into the service area, than a low power transmitter with a high gain antenna. Nothing could be further from the truth.

The ERP is the product of the antenna power gain and the antenna input power. Many different combinations of power gain and input power will yield the same ERP. The azimuth pattern will be quite similiar for many different antenna power gains.

The only difference in various combinations is the elevation pattern. As discussed under Typical Class A and Class B coverage section in this chapter, there is no momentous or important difference in serving listeners from very different transmitter/antenna ratios.

The signal strength at any given location is a direct function of the ERP from the antenna elevation pattern angle to that location, the height of the antenna, and the propagation path. The ERP at the pertinent angle is the product of the elevation pattern amplitude at that angle squared, times the maximum ERP. In practice there is no significant difference between a 3 kW ERP Class A station using a 7.5 kW transmitter and a one bay Cpol antenna, or, one using a 1 kW transmitter and a six bay Cpol antenna, all other factors being equal.

ANTENNA GAIN AND TRANSMITTER POWER

Several available combinations of antenna gain and transmitter power will provide the necessary ERP. But which combination is the best? The choice is further complicated by the nature of the terrain in the service area. Is it all flat, some rolling hills, mountainous or a large valley? What are the regulatory limitations on the antenna supporting tower height?

Important considerations when choosing the transmitter power and the antenna gain combination to produce a given ERP can be listed as follows:

Transmitter	Feed System
Antenna	Transmitter Tubes
Tower	AC power consumption

The transmitter, antenna, tower, and coaxial feed line are one time capital costs for the station equipment. Tube costs and commercial power use, however, are a continuing hour-by-hour cost factor. From the above it is apparent that a low power transmitter is much more economical than a high power transmitter. But is there a difference in signal strength?

It must be remembered that normally all the ERP above the antenna elevation pattern to the horizon is wasted. It is the radiated power below

the angle to the horizon that strikes the earth with all its FM receivers. Therefore only the radiated power towards the earth should be considered useful.

The ideal antenna system would put the same signal level from the base of the tower all the way out to the horizon. This requires an antenna whose elevation pattern is a cosecant curve, the normalized reciprocal of sine. It would be the perfect antenna elevation pattern. Although this curve is impossible to achieve, it is approached as the antenna gain becomes greater.

High Gain Antenna Contradictions

The many advantages of high gain-low power transmitter combinations to produce the ERP have been shown. Their superiority in relatively flat land applications cannot be disputed.

There is however the matter of unusual height over terrain to be considered. If the transmitter is located at Mt. Wilson, California for example, or on a very tall building in Chicago, or New York, the elevation pattern problem becomes serious. This is especially serious, when there are listeners near these sites as is the case for all three locations cited.

Mt. Wilson serving the greater Los Angeles metropolitan area is more than one mile (1.6 km) above most of its listeners. In fact coverage is required from 11 miles (17.75 km) out to the horizon which is −0.57 degrees at 105 miles (168 km). Pasadena the city nearest is −13 degrees below the horizon. A high gain antenna tilted down −0.5 degree would serve the far reaches well, but would not lay down a moderate signal at −13 degrees.

Docket 80-90 limits the ERP for overheight antennas such as those on Mt. Wilson which average 2900 feet (884 m) HAAT. New stations using that height must reduce ERP in accordance with the equivalence calculation, so that the predicted signal at the 1 mV/m contour does not extend beyond 32 miles (52 km) for Class B stations.

In these situations a moderate gain antenna should be considered. From Mt. Wilson several existing four and five bay antennas now provide excellent service.

STATION DIPLEXING

Diplexers are used to combine the power of two or more stations and feed the combined power to a common transmission line and/or a common transmitting antenna. This system of utilizing one well-sited high quality antenna has become popular, convenient and economical.

Wide band panel antennas, although expensive for use by one station, are very cost effective for two or more stations. These antennas maintain their omnidirectional horizontal plane patterns and VSWR thru out the FM broadcasting band from 88 to 108 MHz. Thus, they make the ideal antenna for multi-station diplexing.

Diplexers

A diplexer is a passive device used to combine two or more stations into a single master antenna. New channels at any power level may be added in any order by connecting another diplexer in tandem to the previous unit. The first channel may be fed into a wide band antenna without a diplexer, of course. When two stations are to be combined, the first diplexer is put into service. When the third station is added to the system, a second diplexer is required and so forth. Figure 11 shows this arrangement.

Each diplexer contains a thru broadband input port and an injected frequency port. Nearly

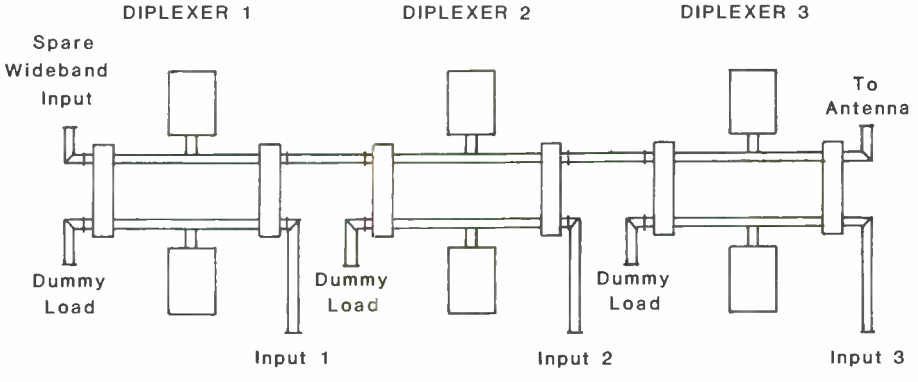


Fig. 11. Three diplexers connected to provide combining facilities for three different stations for one community antenna. Note spare emergency wide band input port.

TABLE 8. Typical measured diplexer performance.
(Three Channels Into One Antenna)

Channel frequency	93.5 MHz	99.3 MHz	100.5 MHz
Input VSWR, plus minus 250 kHz	1.1:1	1.04:1	1.04:1
Isolation: From 93.5	—	-80 dB	-80 dB
From 99.3	-59 dB	—	-50 dB
From 100.5	-80 dB	-50 dB	—
From broad band port	-56 dB	-44 dB	-39 dB
Amplitude Response:			
Carrier plus minus 250 kHz	0.15 dB	0.25 dB	0.35 dB
Group Delay, in nanoseconds:			
Carrier plus minus 250 kHz	25	27	38
Insertion Loss, carrier	0.23 dB	0.24 dB	0.23 dB

all uncombined diplexer power and other undesired products are absorbed by a dummy load connected to the fourth port. The third port goes to the antenna or to the next diplexer's broad input port.

The combining of two different channels must be done without degradation to either of them. The important factors are amplitude, phase delay, VSWR bandwidth, isolation and insertion loss. Insertion loss is a continuing expense item as it consumes RF power that is generated by the transmitter at considerable expense.

Diplexer specifications can be tailored to the specific requirements of the transmitters being used. See Table 8 for a typical three diplexer measured performance. The end user can rest assured in advance of construction that the system will perform to specifications without fear of over or under design of the components within the system.[21]

Constant Impedance Type Diplexers

The constant impedance type takes its name from an operating characteristic of one of its components, namely the constant impedance of the broadband 3 dB hybrid. All of this type use two hybrids and cavities. Because of the use of hybrids the type is sometimes called a hybrid combiner.

An efficient diplexer is not a complicated device, as it consists of two basic components, the two hybrids and two cavities. A terminating absorption load soaks up any rejected power. Coax is used to interconnect these components. Hybrids and cavities either have coaxial flange connections or are directly coupled. Some units are pressurized to keep moisture from tarnishing the cavities which may be silver plated or polished copper, in order to attain high Q.

A terminating load, rated at one half the highest transmitter power being diplexed in that unit is connected to the reject port. In the event of failure of one or both cavities, half of the power will appear in this load, before thermal and other sensors normally turn the affected transmitter off.

The hybrid, sometimes called a 3 dB coupler, is a four port device. When power is fed into one port, it appears split 50/50 percent in two other ports, thus the name 3 dB coupler. Another very useful feature is that the two split powers are 90° apart in their phase relationship. The fourth port is isolated from the input port typically by 26 to 40 dB. If two of these hybrids are connected back to back, nearly all the power entering the first input port will appear in one of the output ports, and a second port will be isolated.

In TV use, a single hybrid is quite useful in feeding a turnstile batwing antenna, which requires split input power with a phase quadrature displacement. The old square quarter wave TV hybrid diplexers are similar in operation, but they are relatively narrow band devices and not suitable for wide-band use in FM community antenna diplexing.

These FM diplexer hybrids are capable of extremely high power as they are usually made of large coaxial components with quarter wavelength coupling bars. Their large physical size and low Q greatly reduces power loss which rarely exceeds 0.05 dB (1.1%).

Many constant impedance diplexers use only reject cavities. Each diplexer contains a thru broadband input port and an injected frequency port. Nearly all uncombined diplexer power and other undesired products are absorbed by a dummy load connected to the fourth port. The third port goes to the antenna or next diplexer's broad input port.

In this approach, such as the band reject diplexers shown in Fig. 13, the signal from TX_1 splits equally in hybrid H_1. It passes by the cavities which are tuned to TX_2 frequency. The two signals of TX_1 combine in the antenna output port of hybrid H_2 since the two inputs to H_2 are equal in amplitude but 90° out of phase, due to the action of hybrid H_1.

[21]Smith, S. and Weirather, R.: "Design Criteria For Multi-Station Combining Systems" NAB Engineering Conference, NAB, Washington, D.C. 20036 pp 125-144 1983.

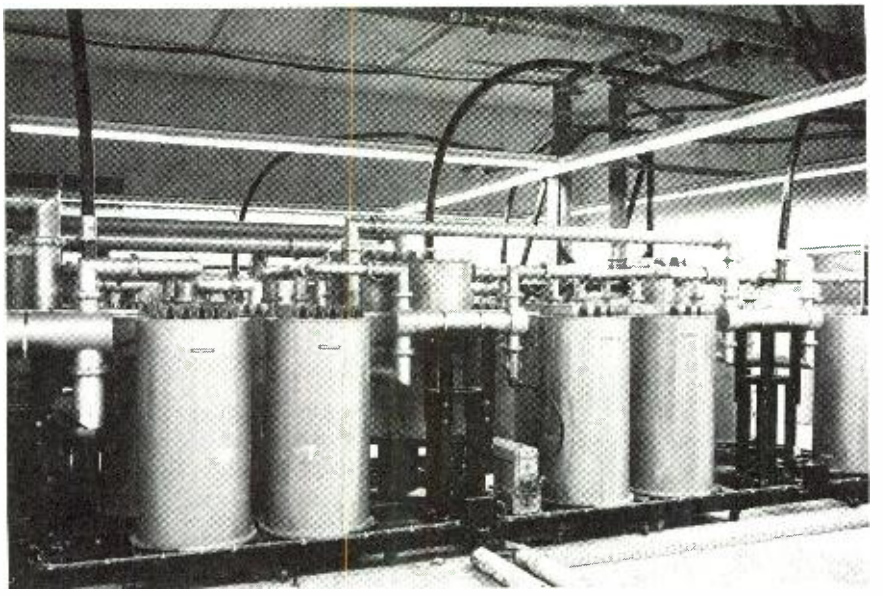


Fig. 12. This Senior Road, Houston, Texas ten port diplexing system, combines nine FM stations into one community antenna. It is capable of 350 kW total input power. (Photo courtesy Harris Corp.)

The signal from TX_2 splits equally in hybrid H_2 and are 90° out of phase with each other. Cavities C_1 and C_2 are tuned to the TX_2 frequency and present a short circuit to it. So the signal is nearly 100 per cent reflected back to the inputs to H_2. These signals are 90° out of phase so they combine only in the antenna port of H_2 and go up to the antenna.

TX_1 frequency is not critical and can be any frequency within the FM band, as long as it is removed from the cavity frequencies by at least 1.0 MHz. However, it will work with some makes of reject diplexers when the separation is a minimum of 800 kHz.

The cavities tuned to TX_2 are not critical in their spacing from hybrid H_2. Because of the nature of the two hybrids, the VSWR remains low and is not affected by temperature variations. The isolation also remains high under these conditions.

Another advantage of the constant impedance notch diplexer is that any beat frequency or intermod product generated in the transmitter TX_2 will be absorbed in the dummy load since only TX_2 will be reflected. This is due to the frequency selectivity of C_1 and C_2.

When more than two transmitters are to be combined, the additional diplexers are merely added in series as shown in Fig. 11. Additional diplexers do not affect the performance of the rest of the system, and can be added at a later time if the need arises. Because of the simplicity of the constant impedance diplexers, they are virtually maintenance free.

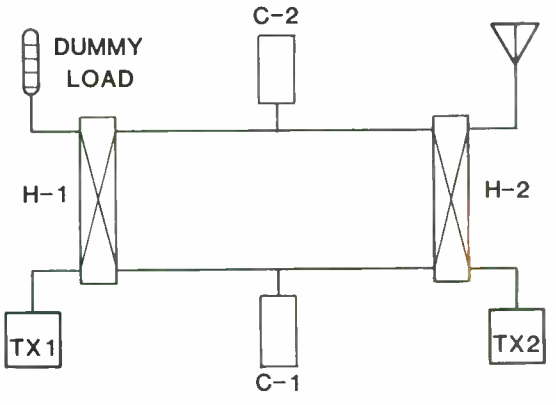


Fig. 13. Basic constant impedance diplexer. See text for explanation of component functions.

Branched Starpoint Diplexers

This type does not use hybrids. Each transmitter feeds into a set of branching filters. In each set there is a bandpass cavity tuned to pass the operating frequency and at least one reject cavity tuned to the frequency of the adjacent channel to sharpen the skirt selectivity. If more than two frequencies are being combined, the middle frequencies have reject filters for both their adjacent frequencies.

All the filter sections connect to one common junction or starpoint which is the combiner's output. Coaxial cable lengths between each diplexer and the starpoint must be a defined electrical length for proper filtering action and low VSWR. This type of diplexer does not use an absorption load, as the small amount of rejected power is consumed by the rejected frequency transmitter and the antenna.

There is no broadband input, so adding channels requires that balanced modules be added on the output. If there is a failure of one branch, it will usually not take the others out of operation. Since there is no broadband port, the affected frequency cannot be switched as would be done with a hybrid diplexer system. However, the transmitter from the failed branch may be operated into one half of the antenna, while the output of the combiner, containing the unaffected channels feeds the other half, for an ERP reduction of 3 dB.

The principal advantages of a branched system are in space and price. There are fewer components, i.e. no dummy loads, no hybrids, and fewer cavities. They are frequently fan cooled, thus permitting the use of smaller cavities. This is all at the price of flexibility and, in the case of some makes, performance.

Cavity Construction

In order for these diplexers to work, a frequency selective electrical short circuit is required to be placed between the two hybrids. This is provided by high Q cavities.

During World War II, low pass and high pass filters were developed for VHF communications and radar. The need for microwave receivers with greater selectivity led to the development of magnetically coupled quarter wave length long cavities. Improvements since the 40s have made cavities with excellent loaded Qs and extremely low insertion loss.

Temperature stability improvement is the result of invar steel, and the high Q resulting from silver plating and polishing the inside of the cavities. Cavity size for FM use varies due to the resonance mode selected by the design. Round cavities as small as 20 inches (508 mm) in diameter and 30 inches (760 mm) long have been used. Square types as long as 60 inches (1524 mm) using waveguide modes have been used. Generally speaking the larger the cavity, the smaller the RF loss thru the cavity.

A very high loaded Q is necessary for close frequency spacing of 800 kHz being the closest assignment in any specific community. Practical values vary from 1,000 to 12,000.,

The power dissipated in heat will expand critical parts of the cavity, detuning it if the heat is not efficiently removed. Air blowers, cooling fins or simple black paint are used, depending on the amount of heat to be removed.

The cavities contribute most of the loss found in a diplexer, due to the ineffectiveness of the cavities. A diplexer with its two cavities tuned to the first possible channel 800 kHz away could have an efficiency of about 95% (0.25 dB loss). Efficiency goes up as the spacing between the pass and the reject frequency increases so that at 1.6 mHz it could be 96% and at 2.3 mHz, about 97%.

An extremely high Q would be excellent on the operating frequency but would not be useful on the FM sidebands. Using twice as many cavities and stagger tuning them increases costs and does not really solve the efficiency problem.

TYPICAL COMMUNITY ANTENNA SYSTEM

In 1984 a group of Houston, Texas broadcasters formed the Senior Road Tower Group, and installed a 2,049 foot (625 m) tower supporting a 12 bay community FM antenna system, with its HAAT at 2,000 feet (610 m).[22] This height permits the maximum ERP under Docket 80-90.

Two runs of 8-3/16 inch (208 mm) diameter coaxial lines are used to feed the antenna in such a manner that power in both the lines causes right hand Cpol from the antenna for all stations.

The nine stations use one diplexer each, all housed in one 2,400 square foot (223 square meters) room. The 10 port modular diplexer has a total power handling capabilty of 350 kW. The insertion loss for each station is 0.80 dB (17% loss). The coupling between the various transmitters does not produce intermodulation products exceeding the Commissions requirements.

All the diplexers are monitored at a central operating rack which indicates each diplexer's forward, reflected, and rejected power. This permits trouble shooting in an orderly and rapid manner. Electrically operated coaxial switching permits each station to be connected to the dummy load for individual testing. Air conditioning and chilled water are used to remove heat produced during operation.

The tower also holds one UHF TV antenna below the FM antenna, in addition to three levels of two way radio communications antennas at the 800, 1,200 and 1,400 foot (244, 366 and 427 m) levels. In addition there are individual single-bay Cpol antennas for each station, fed with a 3-1/8 inch (79 mm) line.

The income projected from the use of the 2 way radio antenna facilities can defray the operating costs of the entire plant including the electrical power bills.

This community FM antenna project is important because it clearly demonstrates the technical feasibility of a large system with nine FM users. It demonstrates that the full intent of FCC Docket

[22]Fisk, Ronald: "Design and Application of a Multiplexed Nine Station FM Antenna, Senior Road Tower Group" Technical Monogram, Harris Corp. Quincy, IL 62305 1983.

80-90 can be met to the broadcasters satisfaction, as well as its wider range of listeners.

The technology is now available to combine multiple Fm stations efficiently and without problems. The only hindrance is the chemistry required to bring broadcasting managements together to start, talk, fund, and complete such a large undertaking.

FM ANTENNA INSTALLATION ON AM TOWERS

The current trend is to locate FM transmitters in places where the best service may be rendered to the most listeners. This usually permits the maximum possible height to be used. Sometimes however, it may be economical and convenient to install the Fm antenna on a tower used for AM broadcasting. If the steel AM tower is not base insulated but is grounded and shunt fed, the FM coaxial line may be connected to the tower, without any further problems.

However if the AM tower is insulated at the base in the conventional manner, an isolation transformer may be used. This is designed to couple the FM power across the base insulator of a transmitting tower used jointly as an AM and FM radiator without introducing objectionable mismatch into the FM antenna feed line. An isolation transformer is especially desirable for feeding high impedance AM radiators or AM radiators which are part of an AM directional antenna system which might be adversely affected by a bazooka type (quarter wave) isolation system.

These transformers have two tightly coupled RF coils which are resonant at the FM operating frequency. An adequate air gap is provided for the AM power thru the two resonant loops. The capacity is quite low resulting in a very high capacitive reactance placed across the tower base insulator.

Fig. 14 shows the internal basic construction of a typical isolation transformer. The insulation for AM under the top of the box may be high density polyethelyne, teflon, or fiberglass. The metal top provides a rain shield as well as protection from dust, mud or snow.

The use of these isolation transformers permits the AM tower to operate undisturbed by the presence of the FM antenna. It also allows the FM coaxial line to be connected in the usual manner, except for the placement of the isolation transformer. These have internal gas blocks and permit the passage of dry air pressure thru the transformer via a plastic tube.

In addition to lower cost, the isolation transformer method has another advantage in directional AM tower use. It does not cause undesired

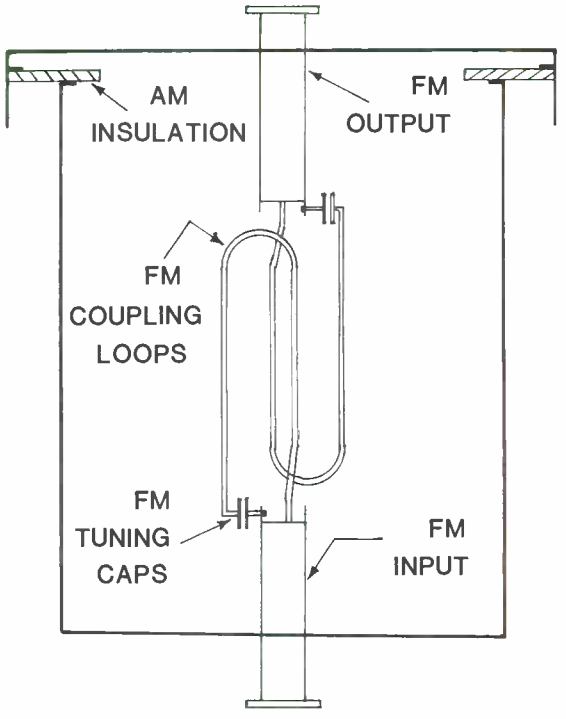


Fig. 14. Typical AM-FM tower isolation transformer, used to decouple FM transmission line on a series fed AM tower.

AM radiation which may change the protection null values.

A less popular and older method is to use the technique of quarter wavelength transmission lines. Simply stated, the opposite end of a shorted quarter wavelength line has high impedance. This high impedance is placed across the AM tower base and may be successfully used to provide the necessary isolation. It is more difficult to physically accomplish this as the tower should be at least one quarter wavelength high, and the FM antenna coax line must be insulated all the way down the tower. In practice the insulated part may be as short as 75 degrees of line, as the line hangers and distributed capacity of the line tend to electrically increase the physically shorter line.

FM TOWER GUYING

Need For Breakup

The presence of continuous steel guy cables going thru the FM antenna level on a steel supporting tower was studied by Jampro Antenna Company (now Cetec Corp.) in 1968. It was found that guy cables had an effect of less than 0.6 dB in the azimuth pattern of a Hpol antenna. On Vpol the maximum variation was 1.8 dB on the azimuth pattern. The strongest effect is

on Cpol where the azimuth pattern change was as great as 3.4 dB. The elevation pattern was also affected since the first and second nulls were filled as much as 4 dB.

In addition to pattern anomolies the steel cables reradiate near the ground. This may cause RF feedback problems in some high power installations with low level audio equipment located in a building near the base of the tower.

Strong currents may be induced when the steel guys are in the immediate vicinity of the radiators, and pass very close to them. If that guy passes close to the side of the radiator, it will be acted upon by the field on that particular side of the antenna element and currents will be induced on it. The radiator currents become unbalanced and the impedance of the element is disturbed, changing its VSWR and radiation pattern.

Because of these effects, it is now common practice either to break up the guys using insulators, fiberglass rods, or plastic guy cable, within 10 feet (3m) of the antenna radiators. When a Cpol antenna is side-mounted on a guyed tower, the vertically polarized field will have an appreciable component parallel to the guy wire in its aperture and will induce currents in the wire. If the guys are continuous, a progressive wave traveling toward the ground will result, and will radiate most of its energy before reaching the ground. The energy will be radiated in cones concentric with the wire. A small amount of the Vpol power will thus be bled off.

Porcelain Insulators

If the FM antenna is side-mounted on an AM tower, which usually will have metal guys and porcelain break-up insulators, those insulators will probably be spaced several FM wavelengths. The induced currents will form standing waves on the sections between insulators and radiate multilobed patterns into space at many angles from the wire axis. If the sections between insulators happen to be of a resonant FM wavelength however, currents in the guy wires and their radiated fields will be considerable.[22]

Some broadcasters have thought they should be spaced 3/8 wavelength. It has been pointed out that a single isolated piece of guy wire with its ends insulated can only resonate in multiples of one half wavelength, and so this spacing of insulators must be avoided. In fact, with the capacitive end loading of the insulators, the resonant length of wire will be somewhat less than one half-wave, and so 3/8 wavelengths should also be avoided. A quarter wavelength is much better, but this would be quite expensive as it requires insulators every 30 inches (762 mm).

Because of this all the guys thru the FM antenna aperture on the tower should be replaced with plastic cable, which is transparent to RF energy.[23]

Plastic Guys

To keep up with the state of the art, any guy cable going thru the antenna level should be of non-conducting material. Plastic fibreglass (GRP) insulating rods as well as flexible plastic rope covered with a PVC plastic jacket are often used. The black jacket prevents deterioration due to ultra violet sunlight radiation, which may be injurious to the plastic strands of the rope. This plastic rope has been successfully used for more than 25 years.

The idea is to remove metallic RF conducting steel guy cables from within the antenna aperture. The rest of the guy may be of steel construction. The length of the steel guy from its attachment point near the antenna is simply replaced with an equal length of fibreglass rods, or plastic rope.

The plastic rope is available in continuous lengths of up to 1,000 feet (304 m) and kits are available for installing the end fittings. The cable is quite flexible as the Fig. 15 shows a 225 foot (69 m) length coiled up with its end fittings installed at the factory.

The cable may be purchased in strengths exceeding similar diameter steel guy cable. These strengths are shown in Table 9 for corresponding size of commonly used EHS (extra high strength) steel guy wire. Sizes smaller and larger than shown in the table are available.

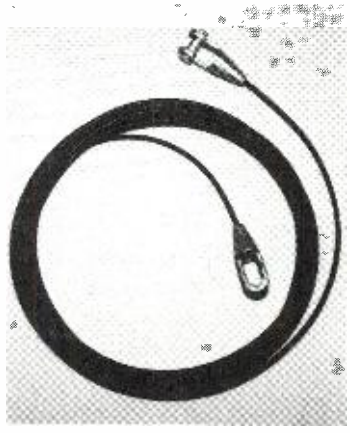


Fig. 15. A roll of plastic guy cable with eye and jaw end connectors in place. Diameter strength is equal to EHS steel stranded guying cable. (Photo courtesy Phillystand—Philadelphia Resins Corp.)

[23]Gregorac, L.: "Electrical and Mechanical Analysis of Plastic Guys of Broadcast Towers" Technical monogram. Radio-Television Ljubljana, Yugoslavia. 12 pp 1973.

TABLE 9. Phillystran type HPTG plastic guys.

Outside Diameter		Break Strength		Jacketed Weight		EHS
Inches	mm	Pounds	Kgs	1,000 Ft	300 m	Equivalent
0.20	5.1	4,000	1,815	18	8.2	3/16
0.29	7.4	6,700	3,039	31	14.1	1/4
0.42	10.7	11,200	5,080	55	24.9	5/16
0.46	11.7	15,400	6,975	69	31.3	3/8
0.53	13.5	20,800	9,435	93	42.2	7/16
0.58	14.7	27,000	12,247	115	52.2	1/2
0.63	16.0	35,000	15,876	142	64.4	9/16
0.68	17.3	42,400	19,235	167	75.8	5/8
0.73	18.5	58,300	26,445	195	88.5	3/4

PATTERN OPTIMIZATION

Single station FM antennas are usually side mounted on a pole or tower. This is economical and it frees the tower top for other possible uses. Unfortunately the pole or tower tends to distort the radiation pattern, seriously affecting station coverage in some directions.[24]

This problem arises from the fact that FM antennas have nearly always been randomly attached to a support tower. FM antenna makers do not manufacture and sell towers. A few have made supporting poles on which the FM antenna has been affixed, adjusted, and pattern tested. TV antenna makers, on the other hand, always make the antenna as a complete self-supporting structure to be mounted on top of a support. They are not usually faced with this side mounting problem.

Due to the early uneconomic days of FM broadcasting this practice of arbitrarily mounting the single channel antenna continues. The logical but more expensive solution would be to make the FM antenna a self supporting structure just like TV antennas.

Best guess and gut feelings used to pick a particular mounting or orientation on the tower leg or face have proven futile and in some cases disastrous. Measured patterns have indicated many times that the maximum radiation can be in the opposite direction from the best guess direction.[25]

Why Optimize?

Why gamble with the FM stations antenna coverage? Nulls may be toward important service areas. Nulls as low as one percent of the RMS power have been measured with towers varying in width from 18 to 120 inches (0.5 to 3 m).

Another problem is that with nulls come lobes. Lobes as great as 9.8 dB over RMS have been found. When used without pattern optimization, this lobe would produce an ERP in a given direction nearly ten times the FCC licensed value.

Translating this to a 50 kW ERP station there would be radiation in some directions of only 0.5 kW and others with 477 kW. This is a maximum to minimum ratio of 29.8 dB and clearly not acceptable to the broadcaster.

With Cpol came additional problems as the Hpol and the Vpol ratios are not always the same and vary moderately in any given azimuth. This ratio can be as great as 15 dB and must also be addressed in order to resolve the horizontal plane circularity problem. The axial ratio should be improved, as the Vpol radiation in certain directions can be much stronger than the Hpol. This violates the Commission's requirement that with Cpol, the Vpol must not be stronger than the Hpol component.

Section 73.316 of the Rules covers FM antennas but does not specifically address this problem of azimuth circularity. In fact the FCC assumes that FM non-directional broadcast antennas have perfectly circular horizontal radiation patterns.[26] In practice they do not.

In order to produce a horizontal plane pattern which even approaches a circle requires considerable work by the firm making the antenna. Since it is nearly impossible to do so with a non-symetrical side mounted antenna, the term optimum—to do the best possible—is in common usage now.

Theory of Optimization

Fig. 16 indicates how energy from the horizontal loop representing Hpol is intercepted by a pole and re-radiated. Similarly, in Fig. 17 energy from the vertical "dipole" is intercepted and re-ra-

[24]Knight, Peter: "Re-radiation From Masts at Radio Frequencies" Proceedings of IEEE, Vol. 114, pp 30-42, January, 1967

[25]Jampro Antenna Co., division of Cetec Corporation. Internal technical communication. Cetec Corp. 6939 Power Inn Road, Sacramento, CA 95828

[26]FCC Public Notice "Criteria For Licensing of FM Broadcast Antenna Systems" Notice 84-437 35004, September 14, 1984 Federal Communications Commission, 1919 M Street, N.W. Washington, D.C. 20554

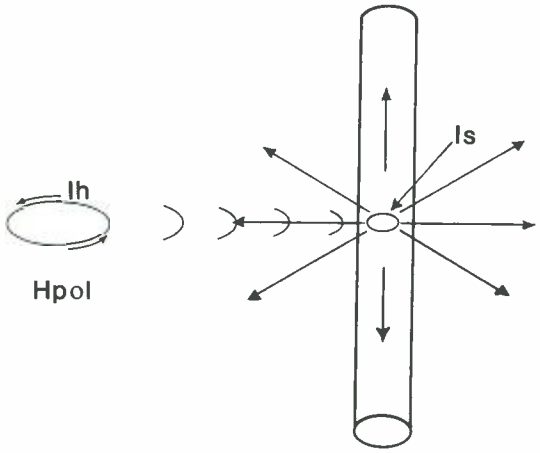


Fig. 16. The effects of supporting steel towers or poles on one side of a non-symmetrical antenna are shown as horizontally polarized currents Ih flow on supporting members as Is and re-radiate in all directions.

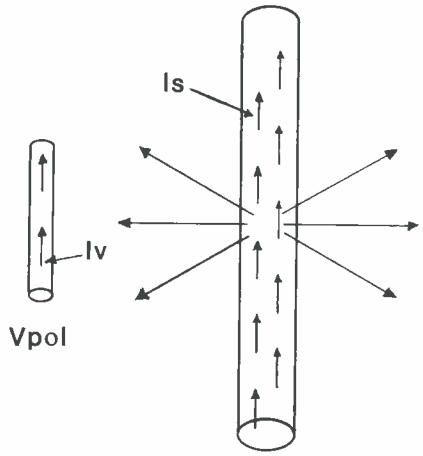


Fig. 17. Vertically polarized current Iv flow over the supporting structure members as Is and re-radiate in all directions.

diated as Vpol. In the first case, the pole diameter is small in wavelengths in the direction of the electric field, thus, scattering is minimal and not much in the Hpol radiation pattern can be expected. However when the Vpol dipole excites the pole, a large amount of energy is intercepted (Is) and re-radiated because the large dimension of the pole (length) parallels a great part of the electric field. A similar effect is produced by the vertical transmission line which is common to the antenna itself, Iv in Fig. 17. The result is appreciable distortion of the vertically polarized azimuth pattern.

Fig. 18 compares the resulting Hpol and the Vpol patterns. As seen, the pole and/or vertical

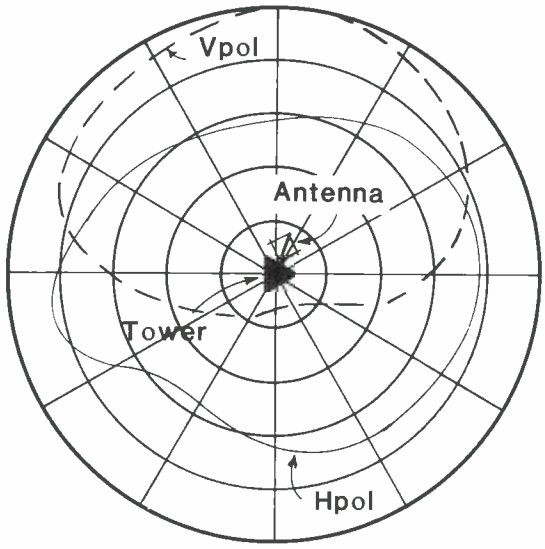


Fig. 18. Combined results of Hpol and Vpol re-radiation distort both patterns, producing more than 17 dB variation. This poor Cpol pattern should be pattern optimized to smooth out the azimuth pattern.

coaxial line have transformed the Vpol pattern from circular to a cardioid, while the Hpol pattern remains essentially omnidirectional. The null of the cardioid is generally more than 7 dB down from the RMS value. This phenomenon is well known, and as a compromise, broadcasters generally install the antenna on the side of the tower support structure facing the main service area. There are many exceptions to this, as some measured patterns on triangular towers of standard construction have shown.

In Fig. 18 the Vpol is much stronger than the Hpol in the favored direction. In the opposite direction, there is little Vpol. The power ratio of Hpol to Vpol is 16 times. This makes for a very poor Cpol antenna.

Towers and poles under about two feet (0.6m) in cross section will exhibit the same effects on the antenna patterns, as in Fig. 18. Towers greater than this size obviously will increase the complexity of scattering effects. Three or four tower legs, the horizontal and diagonal cross members, transmission lines, ladders, if any, tower lighting and deicer conduits, all will be excited by the vertical and horizontal currents from the radiators. All these surfaces will re-radiate and affect the horizontal plane patterns.

In contrast to the unique simplicity of the antenna on the side of a pole, the tower supported antenna may be mounted on the face, or on a corner, at or between horizontal cross members, or tilted at various angles compared to the tower—all multiplying the complex factors affecting the patterns.

Optimization Methods

The most popular technique to achieve the desired pattern is thru the use of Yagi antenna principles wherein parasitic elements are placed in the field of the radiator to modify its radiation pattern. As known, a shortened dipole (director) placed in close proximity to a radiator re-inforces radiation in the forward direction, and suppresses the signal in the opposite direction. If the parasitic element is longer than the radiator (reflector), the effect is reversed. The signal is suppressed on the side of the parasitic element and reinforced in the direction of the radiator.

Similarly, parasitic elements can be used with FM antennas mounted on the sides of towers or poles, to produce pattern changes. As discussed here, both directors and reflectors may be used. Both are frequency sensitive. The effects of the supporting structure are also frequency sensitive.

Therefore, an arrangement of parasitic elements for a given FM frequency will not necessarily be the same for another, nor will the pattern be the same for a given arrangement, if it is moved up or down the tower by as much as one and one half feet. (0.5m)

The resulting patterns cannot be predicted. There are many factors which affect the horizontal plane pattern. Only by actual antenna pattern range testing can the patterns be adjusted and properly measured. Therefore the cost for doing this is high, since it is time consuming, and requires qualified antenna technicians and the use of a complete range. In addition the final parasitic arrangement must be fabricated, and hot dip galvanized. However the results are well worth it.

Pattern Service

There are two basic types of pattern service furnished by several antenna manufacturers in the United States. FM antennas may be adjusted for the best omnidirectional pattern possible or they may be adjusted to provide minimum ERP values in particular azimuth directions. One California firm takes the minimum required values plotted on a polar chart by the broadcasters, with the tower orientation. Using the customers make and model tower, two or more bays of the antenna are fabricated, installed on the tower, and put on the test range. Adjustments are made such as leg chosen, distance from the leg and the orientation of the antenna with respect to that leg. After this has been optimized, parasitic elements are used to further improve and shape the pattern, so that the minimum ERP values will be achieved in the customers service area as given with the order on the polar plot.

For example, the customer of a Class A station may wish that a minimum of 3 kW be radiated in a pie from say 90° to 120° and the remainder of the azimuth be no less than 1.5 kW. This would then require the technicians to achieve a pattern without any field voltages less than 70% and that the vectors between 90 and 120 degrees to be 100%. This sort of work has been done since 1964 by Jampro/Cetec, and later by ERI, Shively and Dielectric Products/RCA. See Fig. 19 for a typical optimized pattern.

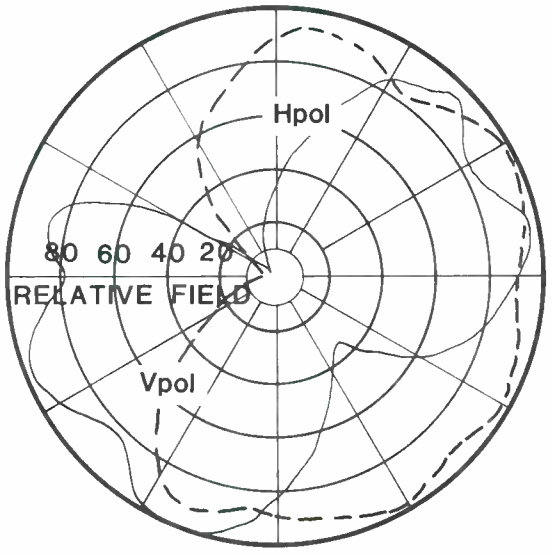


Fig. 19-A. Measured non-symmetrical Cpol pattern of tower side mounted antenna. Vpol variation is ±15 dB, while Hpol is ±12 dB. The axial ratio was 24 dB. Antenna patterns are very poor.

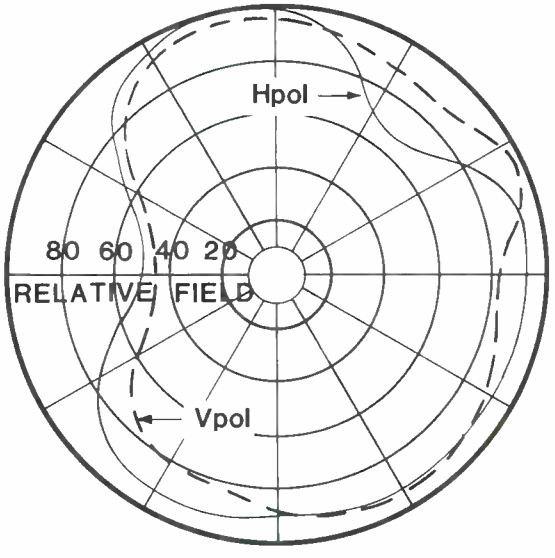


Fig. 19-B. Same antenna as 19-A but much improved after pattern optimization. Hpol variation is ±3 dB and Vpol is ±3.4 dB. Axial ratio is quite acceptable at 2.9 dB.

Various methods have been used to optimize FM antenna azimuth patterns. Some firms use models at twice the operating frequency. Others use theoretical methods, backed up by experimental proof. The best method, assuring greatest accuracy is to use the actual tower section(s) from the customer, and to build the new FM antenna right on that portion of the tower. The final optimized antenna is match marked on the tower sections so that it will be assembled exactly as it was made and tested at the fabricators plant, and tested on its antenna range.

A complete set of installation prints must be provided so that the antenna is assembled exactly as tested, with all the correct locations, and angles of all the parasitic elements.

INSTALLATION PROCEDURES

If the installation is not properly planned and carried out, there may be unwarranted delay and cost associated with putting the FM antenna on its support tower. It is suggested that the following be carried out so as to avoid unnecessary delays and expenditures.

Receiving And Unpacking

The boxes are usually numbered and the total number is indicated on each box; contact the shipper if not all boxes are delivered, or if equipment is received damaged. Do not store the material outdoors, boxed or otherwise.

As soon as the antenna is received, open and examine for shipping damages so that any necessary claims may be filed with the shipping company immediately as well as the material checked against the parts list and installation drawing.

The box with the installation drawing and instructions are usually so marked; open it first, so that the balance of the items may be easily identified and counted. Contact the factory immediately if any material appears to be missing or is damaged during transportation.

Do not call the riggers until all antenna and coaxial line is completely on hand at the site. To do otherwise will result in unnecessary delays and costs.

Planning The Installation

Because of the extremely high cost of rigging services, it is essential to carefully plan the installation, making sure that all parts are on hand.

The installation of the antenna should be planned by a technically qualified person who must supply accurate tower construction information to the antenna manufacturer. If this information contains errors, these will be carried thru the design and fabrication of mounting hardware, and finally show up in the field to plague the installing crew, wasting time and money at every stage of the process.

The station should consider hiring a tower rigging firm that is financially qualified and mechanically well equipped to do the work. A written contract should exist between the station and rigging firm, with a fixed price. The rigging contractor should be licensed as a contractor in your state, and should post a completion bond. He should also supply an insurance policy to hold the station harmless, and making the station and its personnel co-insured. Only in this manner will the broadcaster be protected in the event of death or property damage.

The tower man, should be knowledgable regarding antennas and coax line, should inspect the tower and check out the mounting design of the brackets before the full rigging crew arrives.

If any factors are discovered which appear to negate the installation design, contact the factory immediately. Particular attention should be paid to the following:

a) Fit of mounting brackets to tower members

b) Freedom from interference of the mounts with gussets, leg flanges, guys, and their attachment points, tower face members, obstruction lights, etc.

c) Compatibility of transmission line and antenna input coax terminals.

d) Location of transmission line run relative to antenna input terminal

e) Use of fiberglass guys on the tower in the region occupied by the FM antenna; refer to the paragraphs on guying in this chapter

f) Availability of proper voltage, current and tower cable size for deicers if required.

g) Adequacy of tower to carry the windload placed upon it by the antenna, particularly where radomes are used. This radome/antenna load should be checked by a competent structural engineer, as all antenna installations should be checked. This is usually required by the insurance company carrying insurance on the tower.

Installation Procedures

This information by the writer is based upon nearly 15 years of experience as a chief engineer, plus 25 years as a broadcast antenna manufacturer faced with field installation problems nearly every week. These instructions should be closely followed by the rigger. The suppliers furnish detailed installation procedures with their products. Those together with these will insure a perfect installation saving time and money.

The following items are specifically called to the attention of the broadcasters engineer, in addition to all those stated before, to permit proper installation and good performance for many years.

1. Follow manufacturer's instruction. See that the riggers also read these instructions.
2. Do not leave antenna parts where rain or moisture can enter. Store indoors or keep units capped as received.
3. Do not allow dirt or other foreign matter to enter any coaxial part.
4. Protect all antenna parts from physical damage and abuse.
5. Hoist antenna members carefully, with a tag line to prevent damage by striking against the tower.
6. Install on the tower as indicated by the manufacturer's instructions, remembering that bay number 1 is the uppermost top unit.
7. Riggers should lubricate "O" rings with a small amount of silicone grease before mating flanges.
8. The full complement of flange bolts must be used and they should be as tight as possible.
9. Tuners or individual element devices, if used, should be adjusted only after the entire antenna and tower installation has been completed.
10. Rigid transmission lines should be properly installed with two hangers per 20 feet (6m) length, and with the inner conductor retaining pin on the top of each section.
11. If semi-flexible cable such as Heliax or Wellflex is used, it should be firmly tied down at least every 5 feet (1.5m) for 3 inch (76 mm) line, and every 3 feet (1 m) for 1-5/8 inch (43 mm) coax line.
12. After physical installation has been completed in accordance with the manufacturer's recommendations, the main transmission line should be pressurized with dry air thru a dehydrator, air pump, or by using dry nitrogen gas. See elsewhere in the chapter for complete information.
13. Dry air or gas pressure should be maintained at all times. Most antenna warranties are not valid unless this is done. It is the riggers responsibility to make certain that the entire coax and antenna holds air pressure.
14. The antenna system should be checked by a qualified rigger every time the obstruction lights are replaced, or if lights are not used, at least once a year. The rigger should look for vibration and storm damage, loose or broken coax hangers, and signs of arcing across exposed insulators. A dry rag soaked in 91% isopropyl or other solvent alcohol or equal should be used to wipe clean all exposed insulators in each antenna element. (DO NOT USE CARBON TETRACHLORIDE!)

STRUCTURAL CONSIDERATIONS

Most FM antennas in the western hemisphere are installed on the sides of a steel tower, between 18 and 60 inches (45 to 152cm) wide. The antenna and its transmission line together with all mounting bracketry introduce wind loading, in addition to their dead weight. The live wind loading is a result of the amount of physical surface presented to the wind. It is sometimes called the wind catch area. This consists of either flat or round antenna members, coaxial lines and mounting brackets, hardware, all represented as surfaces which are exposed to the wind.

The dead weight of the antenna system is fixed and is always present on the tower. The live load is a variable, depending on the wind velocity, and is added to the dead load for the total amount present.

The standard wind load starts at an assumed wind velocity of 87 mph (139km), which will produce a push of 35 pounds per square foot. (170.8 kgs/sq.m) With lesser wind speeds the wind push is less and more with higher velocities. Various building codes determine the rated winds to be considered in the design of the tower system. While most of the United States has a 35 pound per square foot minimum rating, some parts of the country have higher requirements due to higher wind velocities. Some insurance companies may require even higher safe wind ratings.

ANTENNA POLE MOUNTING

Non-symetrical antennas may also be installed on a round pole, made of various diameters of steel pipe. Several antenna manufacturers supply these as a complete system and will optimize the horizontal plane pattern. The advantage of pole mounting on top of a tower or building is that the pattern may be more easily contoured. This provides more signal in the service area since the antenna orientation is not limited by a fixed triangle formed by a guyed tower.

TRANSMISSION LINE SYSTEMS

Two types of coaxial transmission lines may be used to feed FM antennas. One uses rigid coax-

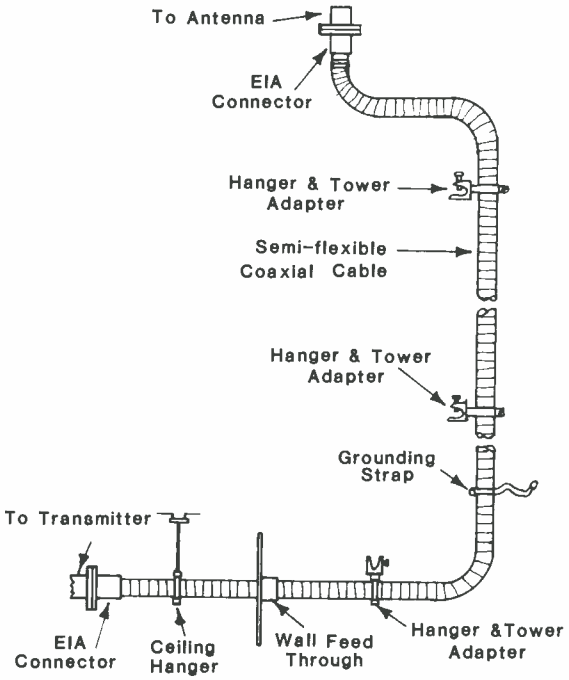


Fig. 20. Typical semi-flexiable coaxial cable installation on a tower. Number of various pieces of hardware depend on length and the diameter of the cable.

ial line sections, each 20 feet (6.09 m) long and requires elbows, flanges, spring hangers and other devices.

The other has a semi-flexible coaxial line which is available in either air or foam dielectric, with fixed hangers. Semi-flexible cable is available on a spool whose diameter depends on the line size. EIA end flanges mate to the antenna flanges as well as other RF equipment. A typical semi-flexible coaxial transmission line layout is shown in Fig. 20.

A supply of dry air should be used with all air dielectric transmission line. Its purpose is to keep out moisture, which may find its way into the line. Dry air not only keeps the mosture from covering the internal plastic insulation and thus arcing is greatly reduced. It also keeps the internal copper from corroding. Copper which has been exposed to moisture will turn dark brown and oxidize after due time. Rigid as well as semi-flexible line in the 3 and 3-1/8 EIA size which had not been pressurized have been measured with increased attenuation of nearly 4 dB per 100 feet (30.4 m) at 100 MHz. This is a power loss of 60 percent. See the section on Air Pressurization on how this may be accomplished.

Popular types and sizes of coaxial cable transmission line are shown in Table 10. The most popular are the semi-flexible air cables marketed by some manufacturers. Also made is the foam dielectric type of line. Rigid coax in 20 foot lengths (6.09 m) is available from several manufacturers.

The safe power ratings shown in Table 10 are for a perfect VSWR of 1.0:1 It is considered good engineering practice to derate this by dividing the power in kilowatts by the expected VSWR. For example three inch Heliax rated at 36.8 kW at 100 MHz and divided by 1.1 derates it to 33.45 kW. Other increases and decreases of coaxial cable ratings may be found in the catalogs of most manufacturers of transmission lines.

Ratings are for a VSWR of 1.0:1; ambient temperature of 75 °F (24 °C) with one atmosphere of dry air pressure. Rigid line at 122 °F (50 °C). LDF and HJ series are manufactured by Andrew Corp. of Chicago, IL while the rigid line is by Shively Labs., of Howell Labs. Inc. Bridgton, ME.

AIR PRESSURIZATION

If the antenna is operated without positive pressure of dry air or nitrogen, the manufacturer will not assume any responsibility for failure under power. Moisture or even the accumulation of water within the coaxial transmission line is a very serious matter. Its presence causes the VSWR to rise, and when a sufficient amount of moisture is present, arcing will take place, burning the line or antenna radiating elements. High humidity or moisture will cause the inside of the coaxial transmission line to corrode over time, thereby increasing the line loss. For this and other reasons, the entire antenna system must be dry air pressurized.

After the antenna is installed and the transmission line connected, the system is purged with dry gas or dry air to remove entrapped moisture, before RF power is applied. A manually opened or pressure actuated purge valve is installed in nearly all FM antennas made by American firms. When the gas pressure is raised to 10 psig (0.68 atmospheres), the automatic pressure relief valve (if the antenna has one) will open up letting moist air out, until the dry air from the building reaches it. The complete system purge requires a considerable volume of dry gas.

Before expending this amount, it is good practice to perform a quick check for major leaks. The system pressure is raised to a point below the relief valve setting, such as 8 psig (0.48 atmospheres) the source of supply shut off, and a pressure gauge left on the antenna side of the shut-off valve. The pressure, when corrected for temperature, should not fall to less than half its initial value in a 24 hour period.

If more than this, it should be gone over with a leak detector, or soap suds, to locate the leak. A pinched or missing O ring is the most common cause for large leaks.

TABLE 10. Coaxial transmission line.
(Characteristics At 100 MHz)

Line Type & Number	Nominal EIA Size	Attenuation In dB	100 Ft Eff. %	Safe FM Power-kW
-Foam-				
LDF5-50	7/8	.385	91.5	5.2
LDF7-50	1-5/8	.231	94.8	13.1
-Air-				
HJ5-50	7/8	.373	91.7	6.4
HJ7-50A	1-5/8	.205	95.4	14.2
HJ8-50B	3	.142	96.7	36.8
HJ11-50	4	.115	97.4	56.1
HJ9-50	5	.078	98.2	73.9
-Rigid-				
1213-1	1-5/8	.191	95.7	10.0
1313-1	3-1/8	.096	97.8	40.0
1413-1	4-3/8	.070	98.4	81.0
1613-1	6-1/8	.050	98.8	161.0

Once the system is known to hold pressure, it should be purged with dry air or gas. Either must be dry enough to have a dew-point well below the coldest temperature expected to be encountered. When using nitrogen, it should be of the "oil dried" type, to remove nearly all the moisture from the gas.

Five to eight psig (0.34 to 0.48 atmospheres) should be maintained in the system at all times to ensure that no mositure will be able to enter. Very small leaks, will pull in moisture, if the pressure is lower than suggested above, if the transmitter is turned off nightly. This is due to the pumping action due to expanded dry air/gas pressure, cooling down, and contracting below the outside air pressure, during cold ambient temperatures.

PROTECTION FROM ICING

High Q antennas are subject to increased VSWR ratios as well as pattern distortion, with light to moderate coatings of ice. Low Q antennas such as the panel type are usually not affected in this manner. Where climatic conditions cause sufficient ice or in some cases snow to affect the antenna's performance, there are two remedies. The radiating element may be covered with a plastic cover, or, it may electrically be heated to melt or prevent the formation of ice on its sensitive surfaces.

Electrical Heaters

By far the more popular method is to order electrical heaters at the time the antenna is ordered. Electrical deicing equipment is supplied as an option and is factory installed. Kits are furnished for interbay connections but the broadcaster must supply power from the building to the center of large arrays, or the bottom element on smaller antennas. Local electrical codes of course must be followed.

While a thermostat may be used with small total deicer wattages, a power relay operated by such a device is required, and furnished with most electrical deicer kits by the antenna supplier. Due to the higher power costs a sophisticated deicer control which operates when both temperature and humidity conditions produce sleet or icing is often required.

Most deicers use a resistance heating element which is inserted inside the antenna radiator arms. One maker however uses a different method, dropping the 230/240 volts to a few volts with a transformer located at each bay level. The low voltage is passed thru the ice sensitive arms of the radiator and connected to the far ends, by a heavy teflon coated wire. The current return is by the stainless steel antenna element, whose ohmic resistance is sufficient to produce enough power heat loss to melt or keep the ice off. This method is becoming obsolete as the transformers are expensive and heating costs are rising, as hourly electrical rates go up. The voltage dropping transformers as not as efficient as direct heaters.

A word of caution when selecting a FM antenna with electrical heaters. Some deicers use 1 kW of power for each bay as described above and increase the wind loading by 225%. Others have a switchable power option feature using 125/500 watts per element, with only a 15% increase in windloading, when compared to an antenna without electrical deicers. The continuing cost of electrical deicers is a consideration of the operational cost of the station and should not be overlooked.

Fig. 21. Rigger finishing electrical tie in box for deicers. Looped stainless steel heaters were factory installed in the four arms, plus one in the feed support boom. (Photo courtesy Cetec Antennas)

In the most basic system the heaters are switched on and off by means of a thermostat which will turn the heater on when the temperature gets below a pre-set level. Recommended automatic deicers are those with a thermostat for mounting near the antenna for accurate temperature sensing of the actual ambient temperature. The temperature zone of +20° F to +35° F (−7° C to +2° C) is generally the most likely icing range, depending on humidity conditions. Deicers should be turned on at +35 °F, prior to ice formation, because it is better to prevent icing than to remove it once it is formed. Power should be turned off when the temperature goes below +20° F since ice does not usually form below this temperature. Fig. 21 shows electrical deicers being wired.

Radomes

The primary purpose of using radomes on FM antennas is to prevent the VSWR from rising with the formation of ice, if the site and height causes icing to occur during the winter months. Ice formation detunes high Q radiators, increases the VSWR, and causes vertical plane pattern changes. See Fig. 22 for a typical radome enclosing a radiator.

Ice may form on the radome but does not particularly affect the operation of the radiator if that ice is kept at least 0.05 wavelengths from the sensitive portions of the antenna element.

Radomes are particularly desirable in heavy icing environments where deicers are not adequate even with very high heat density. They are also useful in protecting antenna elements from falling ice when they are so exposed.

They are cost effective with single channel high Q antennas where electrical deicer heating power costs are expensive. The deicer power cost is a continuing one, while radomes are a one time capital investment, which may be depreciated over time.

A radome is a protective dielectric housing for an antenna radiating element. Its function is to protect the antenna not only from ice, but snow and physical damage due to ice dropping from above. Radomes also protect the radiating element from environmental corrosive atmospheres.

Radomes are generally composed of low loss dielectrics with low values of dielectric constants and loss tangents. Laminated fiberglass, using glass cloth re-inforcements, has a constant of about 4.1 and a loss tangent of about 0.15. Water absorption by the radome increases its dielectric constant and loss tangent. Materials which do not easily absorb water or those treated with a protective gel coat are often used to shed water and prevent the adhesion of ice.

Good radome designs take into consideration operating temperature, a relative humidity of 100 per cent, safe wind pressures, ice, hail, and snow loads, rain adhesion, wind and supporting tower vibration, fire retardant plastic, and the ability to safely withstand air contaminants over the useful life of the antenna. All these factors increase the cost, but are necessary for long useful life. Radome shapes are dictated by the form of the radiating element in most instances.

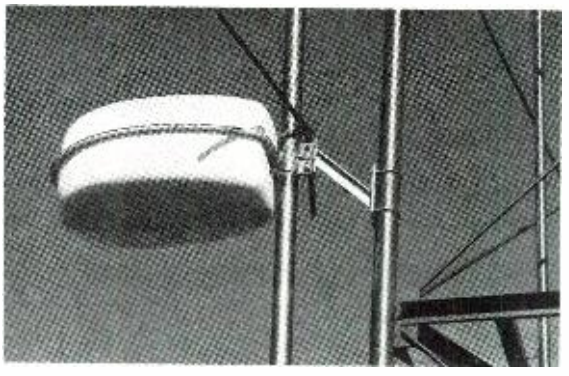


Fig. 22. Radome over radiating element. Transparent to RF, it keeps ice from detuning high Q radiator. (Photo courtesy Cetec Antennas)

In all cases radomes are supplied by the antenna manufacturer, and usually supplied in two pieces which are bolted together with stainless steel fasteners.

LIGHTNING

Lightning is a natural phenonmenon that has always fascinated man. It performs the function of maintaining a balance in the global electrical system. But apart from this, lightning is an extremely destructive force—annually killing an estimated six thousand people and inflicting a billion dollars in propery losses—including FM antennas.

Because FM towers are usually located on high ground, hilltops, or high buildings, they require lightning protection since they are likely recipients of lightning strikes. The type of damage that can be caused by lightning to a FM tower is varied. Smaller coaxial lines will usually melt; larger coax (1-5/8, 3-1/8) will also melt in some cases, and others will conduct the heavy current into the transmitter building to do damage there.

The FM antenna itself may heat, arc, melt, and otherwise be damaged. Holes in the outer conductor, burns and melting at flanges are common. Teflon or polyethlene insulation will burn, depositing a film of carbon, causing further damage if RF from the transmitter continues after the strike.

Protection of the FM antenna system may be provided to some degree, by taking several pre-cautions. The top of the tower should have a lightning rod, about one foot (0.3m) higher than the uppermost obstruction light part. The FM antenna itself should be firmly grounded to the tower. If the coaxial cable is buried between the tower and the transmitter building, it must be at least six feet away from any tower base grounding system copper wire or strip.[27]

A ground system should be located immediately around the base of the tower. This should have a direct current loss of less than 10 ohms to earth ground. This low resistance may be obtained by using ground wires buried in the soil. Six radials spaced 60° degrees if possible, buried as deep in the soil as possible and running out up to 150 feet (46 m) each, should provide a suitable ground of less than 10 ohms, even if the soil is shallow or rocky.[27]

Guyed tower anchors should also be grounded. This is covered in the chapter Design, Erection and Maintenance of Antenna Structures. It is important to install the proper number of ground rods and/or copper wire radials in order to obtain a connection to earth ground of less than ten ohms. In any event these ground rods or radial wires must be tied together with number AWG 4 or larger copper wire, or copper strap two inches (5cm) minimum width. This is to provide for thousands of amperes of current flow for less than one second in the event of a direct lightning hit.

If the FM antenna is located on an AM insulated base tower, then the spark gap should be set at the lowest point providing protection for the highest AM modulation peak voltage.

Another way to protect the FM transmission line isolator (if one is used), as well as the tower and FM antenna, is to use a RF choke across the insulated tower base. This tends to reduce the static build up voltages due to passing thunderstorm clouds, snow, hail, or dust storms. Arcovers due to these sources usually do not cause damage, but may trip the FM transmitter reflectometer since they will create a current flow through the reflectometer circuitry.

If the base insulated tower supporting the FM antenna is located in an area of regular thunderstorms, another way to protect both antennas from lightning is to ground the AM tower at the base, and shunt feed it. Several excellent methods exist. The folded unipole method not only grounds the tower for lightning purposes, but improves the VSWR bandwidth, so necessary for AM stereo. See the chapter for AM Antennas for several suggested methods.

FM SCA MULTIPLEXING

With a 92 kHz sub-carrier, 110% modulation could result in a peak deviation of 110 kHz. Intermodulation products may be created due to mixing of the various sub-carriers with their own harmonics within non-linear devices. One such nonlinear device can be the antenna system.

Antenna linearity is determined by its VSWR response curve versus frequency. Phase delay in the antenna system is also important. In the past with 67 kHz being the highest SCA frequency, the ±100 kHz bandwidth was considered sufficient. Now with a 92 kHz sub-carrier and 110% deviation (82.5 kHz) the minimum bandwidth is ±130 kHz under 1.1:1 VSWR.[28] See VSWR BANDWIDTH in this chapter for more specific requirements and recommendations.

Tests have shown that 92 kHz is the frequency of choice for a new aural SCA service after 67

[27]Marshall, J.L.: "Lightning Protection" Canadian Broadcasting System, John Wiley & Son, New York, NY pp 53-54 1973.

[28]Kean, John: "Distortion of FM Signals Caused by Mismatched and limited Bandwidth Transmitting Antennas" National Public Radio, Washington, DC 20036 pp 37-42 1984.

kHz.[29] This produces lower intermodulation product levels and less interference to the main channel stereo service than 67 kHz.[30] It may be successfully operated in addition to stereo and existing SCA services.

Other non-linearities in the exciter, transmitter, plus multi-path reception, receiver misalignment and user mis-tuning are contributions to the received intermodulation distortion of the baseband signals. In addition these products can cause small levels of audible swishing beat notes in some types of FM receivers.

SPURIOUS FREQUENCIES

Interferences to other stations within the FM broadcast band as well as to other services outside the band can be caused by RF intermodulation product energy developed between two or more FM broadcast transmitters. It may be due to coupling thru a diplexer or coupling between two antennas. This phenomenon has been well documented.[13]

Detailed information on the susceptibility of various types of transmitters to interference from other collocated transmitters has not been thoroughly investigated. A method has been devised by which the mixing loss between two transmitters can be accurately characterized.

When two or more transmitters are coupled to each other, new spectral components are produced by mixing the fundamental and the 2nd harmonic of each of them. The dominant intermod product generated by each transmitter is at twice the transmitter's frequency minus the interfering transmitter frequency. For example, 101.1 and 102.7 transmitters would produce two intermod signals appearing on 99.5 and 104.3 MHz.

Second harmonic traps or low pass harmonic filters in the transmission line of either transmitter prior to the diplexer have little effect on the generation of intermod products. This is because the harmonic content of the interfering signal entering the transmitter output circuit has much less effect on intermod generation than the harmonic content within the non-linear device itself. The resulting intermod falls within the passband of the low pass filters and outside the reject band of the second harmonic traps, so these devices offer no attenuation to intermod products.

Even the perfect diplexer by its very nature will reflect some of the undesired energy back to each transmitter, generating intermod products. The key to this problem is to keep that undesired power level as low as possible using proper transmitter output circuitry and tight diplexer specifications.

HARMONIC FILTERS

The FCC specifications Sec. 73.317(a)(10) calls for the harmonics of FM transmitters to be up to 80 dB or more below the transmitter output. This requirement is usually met by using a low pass filter which passes the station carrier frequency power but attenuates its harmonics.

The transmitter provides some harmonic attenuation of course, and is usually 25 to 38 dB for single ended amplifiers. The worst case harmonic is the third. Harmonic filters by several firms provide a minimum of 50 dB for harmonics from the second through the tenth. Adding the transmitter attenuation to that of the filter normally provides more than the required level.

The high level of rejection is made possible by using high impedance (inductance) and low impedance (capacity) coaxial sections for m-derived three to five section filters, with half-pi end sections. Harmonic filters are commonly made in three production schedules while one firm actually adjusts them to the customers operating frequency, so that there are no attenuation gaps in the higher harmonics. They are not tunable outside the factory as the insertion loss and attenuation along with pass band VSWR are closely related. It requires sophisticated knowledge and equipment to properly adjust.

The insertion loss in the pass band varies from .05 to .08 dB while the rejection from the second through the tenth harmonic is from 50 to 60 dB, depending on the number of internal filter mid-sections. The VSWR in the pass band varies from 1.05 to 1.1:1 Harmonic rejection is due to the very high VSWR on the harmonic frequencies which may be as high as 15 to 1. This rejected power is passed back to the transmitter amplifier.

Harmonic filters are available in straight rigid coaxial line sections and may sometimes be pressurized. Power capacity varies from 10 kW for 1-5/8 EIA line size to 50 kW for the 6-1/8.

ACCESSORY ANTENNA SYSTEM EQUIPMENT

Several other devices are associated with the antenna system. The dry air pressurization of coaxial transmission line was discussed under that heading in this chapter.

[29] McMartin, Ray B.: "Super Eight" Preceedings of the 38th Annual Broadcast Engineering Conference, NAB, Washington, D.C. 20036 pp 160-166 1984.

[30] Denny, Robert: "Report on SCA Operation" Preceedings of the 37th Annual Broadcast Engineering Conference, NAB, Washington, D.C. 20036, pp 187-196 1983.

Reflectometers

The reflectometer is a device for detecting the ratio of power flow from the transmitter to the antenna (forward) and the rejected power back from the antenna (reverse). A short coaxial line section about 12 inches (305 mm) contains diode detectors, coupling loops and terminations to produce D.C. current, which drives a suitable. VSWR meter.

Reflectometers are wide band devices and therefore must be placed AFTER the harmonic filter. Putting them between the transmitter and the filter causes them to read the rejected harmonic power along with the reflected, thus giving an erroneous reading.

Dummy Loads

A very useful test device in an antenna system is the terminating load. This is extremely useful when two amplifiers are combined and fed to the antenna, or when a number of diplexers are used in a community antenna arrangement. Dummy loads are available in several power levels up to 50 kW and are cooled by air. Water cooling types are also available.

RF Switches

Sometimes used with a dummy load, coaxial line switches are available to provide electrical or manual switching of transmitter power to diplexers, antennas, standby transmitters, etc. They are not pressurized.

2.6

Antennas For Television Broadcast

Thomas J. Vaughan
Micro Communications, Inc.
Manchester, N.H.

This chapter begins with a review of the demands placed on broadcast radiating systems, including radiating patterns, power handling capacities, and gain. This is followed by a review of antenna theory as it relates to these demands, as well as a review of specific applications. The chapter concludes with a summary of tests, installation and maintenance procedures.

To facilitate using the material here, a brief chapter outline is provided.

—INDEX—

Requirements

Definition

Specifications—General

- Azimuth Pattern (Horizontal Plane)
- Vertical Pattern (Elevation Plane)
- Gain
- Gain Requirements
- Input Impedance
- Non-Ionized Radiation

Specifications—Technical

- Radiating Characteristics
- ERP
- Circular Polarization
- Beam Tilt
- Power Capability
- Non-Ionized Radiation
- Patterns
- Antenna Input Impedance
- Deflection and Wind Load

Design and Theory

- Elemental Radiators
- Antenna Patterns
- Multiple Antenna
- System Planning

Types of Antennas

- Low Band VHF—Horiztontal Polarization
- VHF—Circular Polarization
- UHF—Horizontal Polarization
- UHF—Circular Polarization

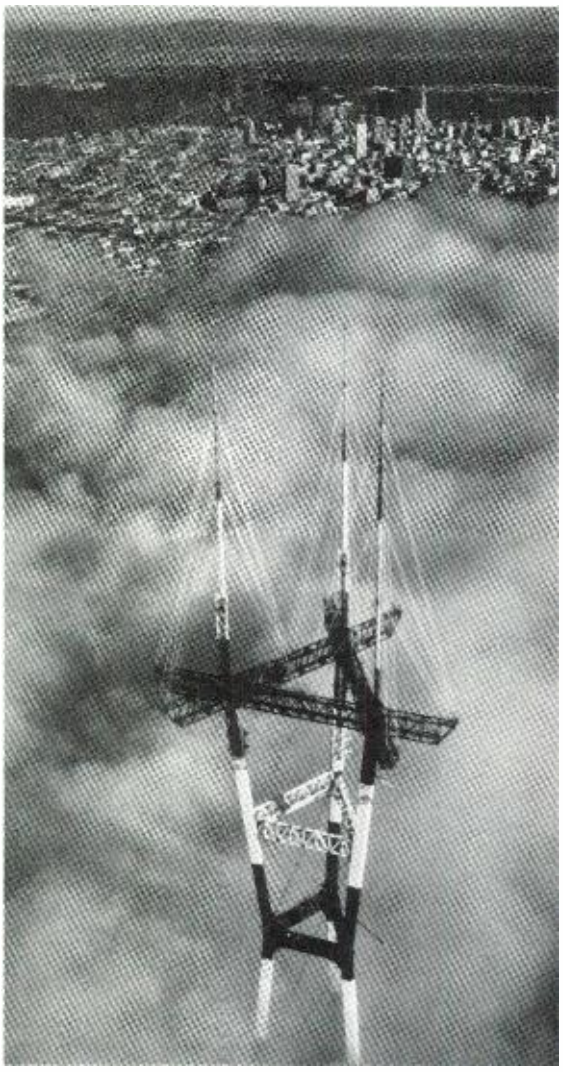
Antenna Tests

- Before Shipment
- After Shipment
- After Erection

Installation

Maintenance

NOTE: This chapter incorporates some material from Chapter 14 of the previous, 6th, edition of the *Handbook* prepared by H.E. Gihring, RCA Corporation.



The Mt. Sutro installation serves the San Francisco area with eight active and 5 standby broadcast television antennas. (Photo courtesy of RCA)

REQUIREMENTS

Television broadcast antennas currently operate at the following frequencies:

Channels 2 to 6—54 to 88 MHz
Channels 7 to 13—174 to 216 MHz
Channels 14 to 69—470 to 806 MHz

Definition

An antenna is defined as a structure associated with the transition between a guided wave such as may exist in a transmission line and a free-space wave. Such a structure usually consists of radiating elements and means for distributing the energy to these elements.

The antenna terminal is defined as an accessible point where the entire antenna including the distribution system terminates into one feed line at the design characteristic impedance.

The azimuth pattern shall be circular or omni-directional unless a directional pattern is authorized. A directional pattern can be used to improve the service area, but the null shall be less than 10 db (CH 2-13), 15 db (CH 14-69). The radiation pattern in the vertical plane can be shaped by electrical means so the maximum radiation occurs at an angle below the horizontal plane.

The gain is the increased in signal relative to the same power fed to the standard dipole.

Antenna power gain is the square of the ratio of the root-mean-square free space field intensity produced at one mile in the horizontal plane, in millivolts per meter for one kilowatt antenna input power to 137.6 mV/m. This ratio should be expressed in decibels (dB). (If specified for a particular direction, antenna power gain is based on the field strength in that direction only.)

The product at the antenna input power and the antenna power gain is the Effective Radiated Power (ERP).

The polarization (the orientation of the electric field) can be linear horizontal, or circular. If circular is used, the term ERP applies to horizontal and vertical components separately.

SPECIFICATIONS: GENERAL

Azimuth Pattern (Horizontal Plane)

Definition. An azimuthal pattern is a plot of the free-space radiated field intensity versus azimuth angle at a specified vertical angle with respect to a horizontal plane (relative to smooth earth) passing through the center of the antenna.

A horizontal pattern is an azimuthal pattern when the specified vertical angle is zero.

For many higher gain antennas where beam tilt is employed, the azimuthal pattern at the specified beam tilt is significant. In general it has been customary to determine television broadcast antenna radiation by an azimuthal pattern at the specified beam tilt and a sufficient number of vertical plane patterns taken at various frequencies in the channel.

An omni-directional antenna is defined as one that is designed to radiate the same signal in all directions. Antennas with variations up to ± 3 dB have rendered satisfactory service and are considered to be omni-directional.

A directional antenna is one which is designed to radiate more signal in one direction.

Vertical Pattern (Elevation Plane)

Definition. A vertical pattern is a plot of free space radiated field intensity measured in the Fraunhofer region versus vertical angle in any specified azimuth plane which contains the center of the antenna and the center of the earth.

The Fraunhofer region, or "far field," as usually defined extends beyond a point where the distance between the transmitting and receiving point is a $2a^2/\lambda$, where a is the length of the radiating portion of the antenna and λ is the wavelength.

Requirement for broadcast service. A free-space radiated field should not be influenced by the proximity of the earth in such a way as to set up a nonuniform field over the antenna aperture, and proper precautions must be taken to accomplish this.

Gain

Definition. Gain is the ratio of the maximum power flow per unit solid angle from the subject antenna to the maximum power flow from a thin, lossless, half-wave, horizontally polarized dipole[1] having the same power input, when the measurements are made in the Fraunhofer region.

As can be seen from the above, gain depends on several factors.

1. The amount of power concentrated in the maximum direction
2. Losses in the antenna, which include ohmic and other losses such as energy radiated at polarizations other than the desired one.

The amount of power concentrated in the maximum direction can be determined by a comparison with a reference antenna[2] or by integrating the total power flow through a sphere, which is done by taking a sufficient number of vertical patterns and an azimuthal pattern. Both methods are capable of giving accurate results when the proper precautions are taken. Ohmic losses are taken into account in the comparison method or can be calculated when using the power integration method. Cross-polarized radiated energy can be measured. The measurement of gain must be carefully done with a full knowledge of all the problems that are involved. The measurement of gain used in the calculation of ERP for a circular polarized antenna must be made relative to a horizontal dipole. The gain of a circular polarized transmitting antenna relative to a "like" circular polarized receiving antenna will be 3 db higher than that of the horizontal dipole.

Gain Requirements

Gain requirements for a television broadcast antenna depend on transmitter power, economics, and field-strength requirements as determined by the terrain and population distribution.

Transmitter Power. The maximum effective radiated powers currently permitted by FCC are:

Channels 2 to 6—100 kW
Channels 7 to 13—316 kW
Channels 14 to 69—5,000 kW

For the most popular transmitter sizes in each range, the following gains are needed allowing 75 per cent transmission-line efficiency:

Channels 2 to 6—4 to 6
Channels 7 to 13—12 to 18
Channels 14 to 69—25 to 60

Economics. Economics is a factor in antenna choice. As a general rule for a required ERP the combined costs of transmitters and antennas are less when a higher gain antenna is used. This is true until unsupported antenna heights are of the order of 200 ft., where structural considerations cause antenna costs to go up rapidly.

Input Impedance

Input impedane is the complex impedance looking into the antenna terminals throughout the television channel.

Most antennas are designed for the same input impedance as the standard transmission line at the antenna terminal. Impedance matching requirements for television antennas are generally more severe than for other types to avoid reflected energy which would cause an echo or ghost in the picture when the antenna does not terminate the line properly.

Non-Ionized Radiation

A recent concern is the biological effect due to non-ionized radiation (the TV signal) and its influence in the selection of a TV broadcast antenna.

Lacking a federal standard, many states and localities have established their own. The levels of exposure vary.

	ANSI 95.1	Massachusetts and Oregon
LoV	1 mW/cm²	0.2 mW/cm²
HiV	1 mW/cm²	0.2 mW/cm²

[1] The directivity of a ½ wavelength dipole antenna over an isotopic antenna is 1.64.

[2] "IRE Standards," Antennas, Methods of Testing. C.C. Cutler, A.P. King, and W.E. Kock, Microwave Antenna Measurements, Proc. IRE, vol. 35, pp. 1462-1471, December, 1947.

	ANSI 95.1	Massachusetts and Oregon
UHF-CH14	1.3 mW/cm²	0.26 mW/cm²
CH 70	2.6 mW/cm²	0.53 mW/cm²
Exposed Time	0.1 hr.	0.5 hr.

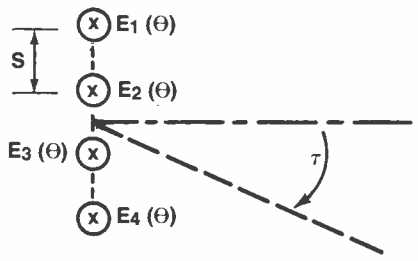
SPECIFICATIONS—TECHNICAL

Radiating Characteristics (Element Theory—Array Theory)

The TV antenna should have an omni-directional pattern in the azimuth plane and a narrow beam in the elevation plane. For the omni antennas the gain is approximately one per wavelength[3] per like polarization. Most broadcast antennas are spaced one wavelength, therefore, the gain of a linear polarized antenna is approximately equal to the number of elements.

Elevation Pattern

The elevation pattern is the product of the element pattern times the array pattern.



$$F(\theta) = E_n(\tau) \sum_{n=1}^{N} A_n e^{j[(2\pi n s)\sin\tau + \delta_n]}$$

Where: $E_n(\tau)$ = element elevation pattern
$\approx \cos^m(\theta)$
s = element spacing
τ = elevation angle
δ_n = phase of nth element
A_n = amplitude of nth element

The element spacing is normally one wavelength. For a $\cos^1(\theta)$ element pattern the gain vs spacing is shown below:

[3] It can be shown that the maximum theoretical gain is 1.2 per wavelength. Ohmic loss side lobes, cross polarization, and aperture illumination contribute to a reduction in overall gain.

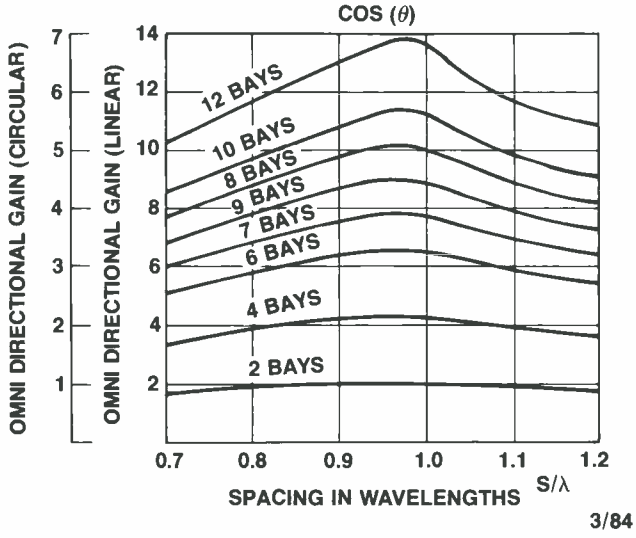


Fig. 1. Power gain vs. element spacing.

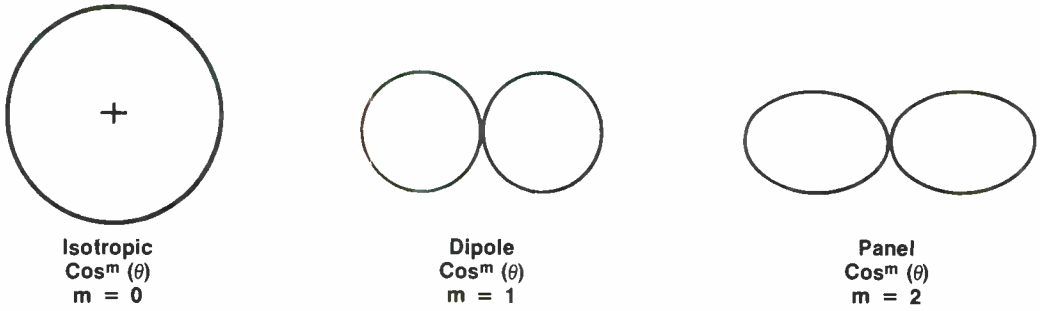


Fig. 2. Element patterns for different values of M.

The reason that most antennas are spaced approximately one wavelength is that the gain peaks at this spacing and fewer elements are needed reducing the number of feed points, wind load, and costs.

The element pattern can vary from value of m = 0 to m = 2.

The variation in gain for other than cos^{1}(θ) element patterns is shown below. As can be seen there is no significant difference until one wavelength spacing is approached. The reason the gain falls off rapidly as one wavelength is approached for the isotropic pattern is that the element pattern does not drive the array pattern downward lobe to zero at ±90°.

Azimuth Patterns

The ripple content of the azimuth pattern is dependent on the element pattern and ρ the distance to the phase center.

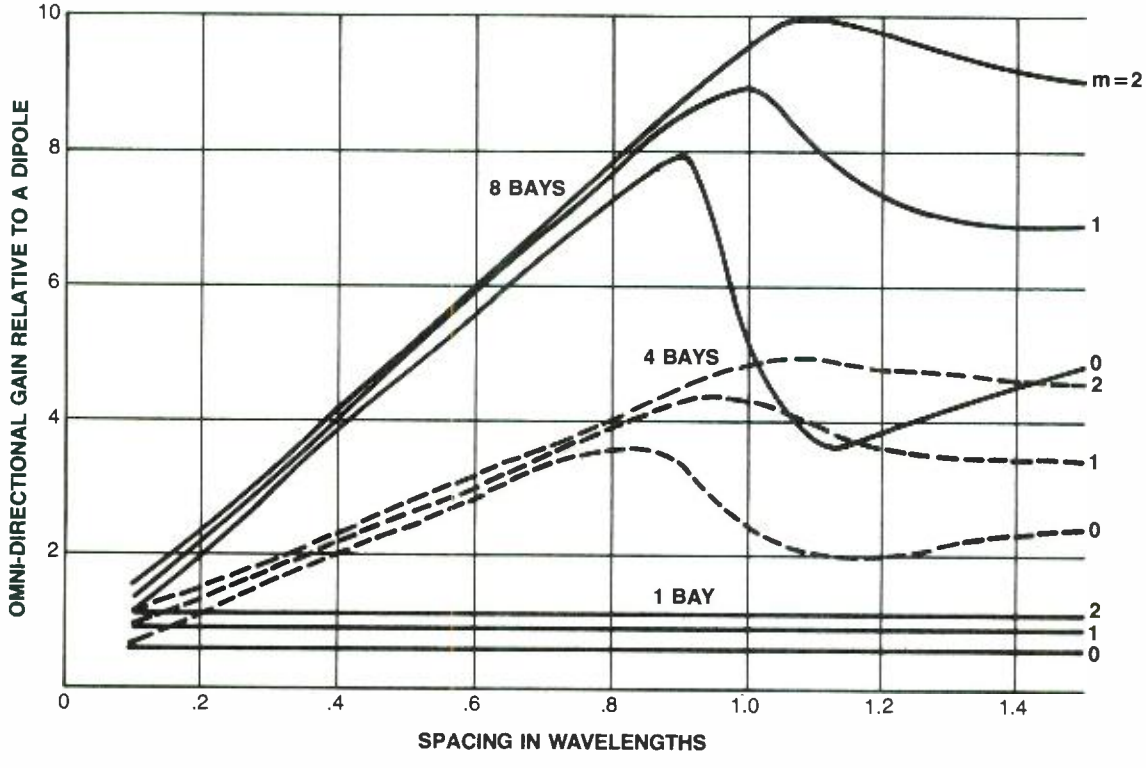


Fig. 3. Power gain vs. element spacing for 1, 4, 8 bay array and m=0, 1, 2.

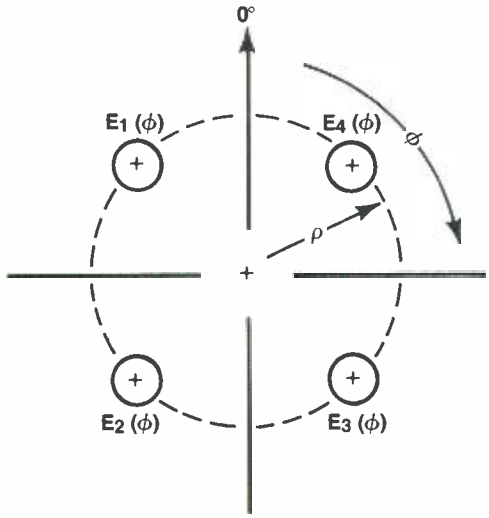


Fig. 4. Azimuth pattern calculation.

$$F(\phi) = \sum_{n=1}^{N} E_n(\phi) A_n e^{j[(2\pi)\cos(\phi-\phi_n)+\delta_n]}$$

Where: $E(\theta)$ = element pattern
ϕ = azimuth angle
δ_n = phase of nth element
A_n = amplitude of nth element
ρ = distance to phase center (in wavelengths

Some antennas such as cross dipoles (turnstile/batwing) have $\rho = 0$. Others such as panels have value of $\rho = .25$ to 1.0.

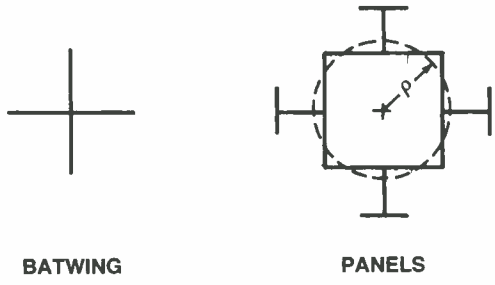
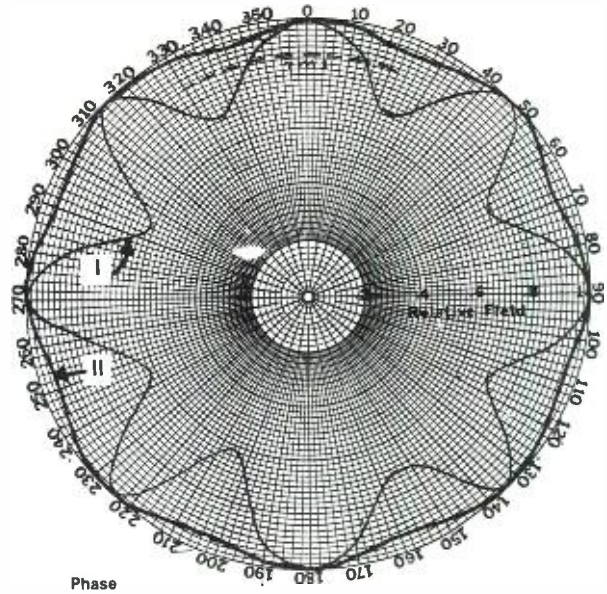


Fig. 5. Arrangements of cross dipoles for turnstile and batwing antennas.

The ripple content in the azimuth plane is dependent on ρ and the element pattern. The ideal element pattern for a three-sided tower is $\cos(\phi)$, four-sided $\cos^2(\phi)$. Below is the ripple of four panels having $\cos^2(\phi)$ with $\rho = 0.5\lambda$, 1.5λ.



	Phase Center Diameter	Gain	Ripple
I	1.49λ	.762P	±1.5dB
II	.485λ	.949P	±0.3dB

Fig. 6. Ripple content for four panels having COS².

ERP

In achieving the given effective radiated power (ERP) required to serve the area under consideration, there is a choice between using a low power transmitter and a high gain antenna or vice versa.

For VHF antennas, the transmitter power to antenna gain ratios are fairly well established. For Channels 2-6, antennas usually use gain values from about 4 to 6 depending upon the length of the transmission line run. For the Channels 7-13 band gain values vary from 12 to 18, depending upon the transmitter power and the length of the transmission line run. For UHF antennas, it is economically not feasible to use low gain antennas such as are used for VHF, for several reasons:

1. The ERP values permitted are higher in order to compete with VHF performance.
2. Transmitters must generate higher powers and are therefore more costly.[4]
3. The antenna gain must also be increased since otherwise the cost of the transmitter would be excessive. Hence, vertical gains of the order of 25 to 60 are used. It is feasible to do this since the mechanical structures are of a reasonable height because of the shorter wavelength.

However, the higher gain requires some special considerations since the higher gain results from narrowing the main beam. For a given transmitter input, the high gain antenna may

[4] At 0.07¢ per kW/hr. it costs $1500/yr. to generate 1 kW of RF.

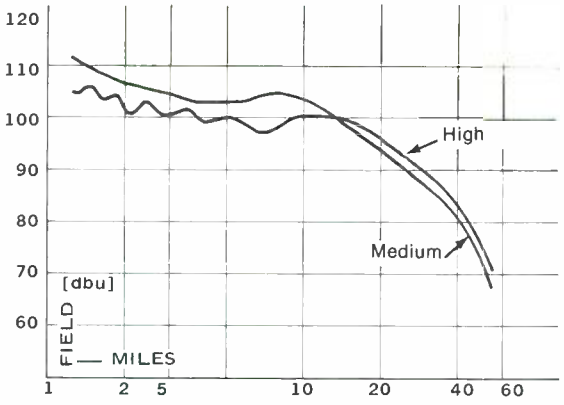


Fig. 7. Comparison of high and medium gain antenna performance with the same power input. Note the reduction in local coverage with an increase in gain.

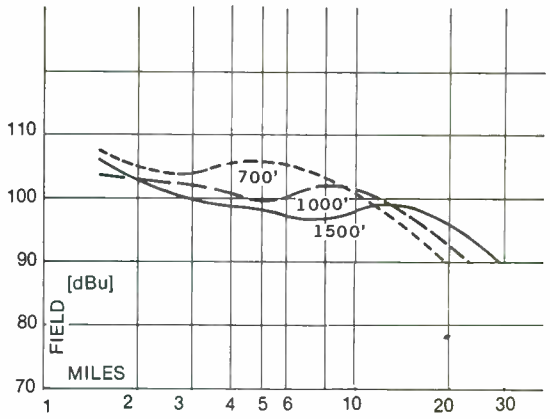


Fig. 8. Comparison of the same antenna, and the same ERP at a height of 700, 1000, and 1500 feet. Note the reduction of local coverage with an increase in height.

sacrifice local coverage for more distant coverage, see Fig. 7.

Hence, if a higher gain antenna is contemplated, local field strengths should be calculated, using the FCC (50,50) propagation curves. It is generally advisable to maintain a 100-dBu level over the important local area to be covered. Most UHF vertical patterns are designed to accomplish this with an ERP of the order of 1 megawatt at 1,000 ft. In hilly terrain it may be desirable to increase this figure by 10 dB or more and in heavily populated cities with large structures by 6 dB or more.

If fields of this order cannot be achieved with a high gain antenna, the transmitter power should be increased.

An increase in height over terrain has the same general effect as increasing the gain of an antenna. For distant areas within line of sight covered by the main beam of the antenna the field strength is millivolts per meter for a given ERP increases approximately as the height over smooth terrain. However, the nearby areas generally receive less field strength since the vertical angle looking up towards the antenna is steeper to a point where the vertical pattern usually radiates less energy (See Fig. 8 comparing a 46 gain antenna at three heights). Hence, an increase in height should be studied in the same manner as an increase in gain.

Circular Polarization

FCC regulations covering FM circular polarization (CP) broadcasting do not specify the 'sense of rotation', i.e., whether it is left-handed or right-handed, either of which characteristic may be built into a true CP signal; nor is there any limit as to how elliptical the signal may be. In fact, slant linear polarization of 45 degrees is permitted (Fig. 9.)

In the case of television, however, since several of the anticipated advantages of CP broadcasting rely on the use of rotation-sensitive CP-receiving antennas, the sense of rotation is specified as right-handed.

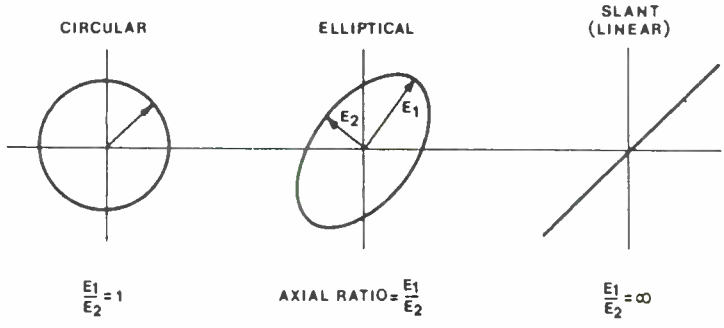


Fig. 9. The ideal circular pattern (left) of a CP signal produces an axial ratio of 1, and in practice is never achieved. The lowest quality CP signal is the slant linear field (right).

The advantages that may accrue from the use of circular polarization are:*

1. Less critical antenna azimuth orientation, permitting good reception on all types of indoor antennas including rabbit ears, whips and rings.
2. Improvement in service and penetration because of the two orthogonal fields—one horizontal, the other vertical—each with the same power as the original horizontal signal.

When circularly polarized receiving antennas are used, these further advantages are foreseen:

1. Reduction of reflection problems due to ghosting. This important benefit is realized because reflected CP signals tend to undergo a change in the sense of rotation, and are rejected by the right-hand CP receiving antenna (Fig. 3).
2. Improvement in coverage at the fringe area due to twice the power. Through use of CP receiving antennas, improvement on the order of 3 dB, amounting to 5 to 8 kilometers in calculated coverage, can be expected.

Many of the stations that have gone to CP have at the same time moved their complete transmitting plants and changed the heights of their antennas, making a direct measured signal comparison between HP and CP impossible. Experiences reported by stations using CP indicate:

1. Receiving antenna orientation is less critical, specifically for rabbit ear and whip antennas.
2. People in close proximity to portable receiving antennas have less effect on reception.
3. Signal penetration has improved.
4. Fringe area coverage has improved.
5. No ill effects have taken place.
6. In some areas where CP receiving antennas have been used, reductions of approximately 14 dB have been observed.
7. No change in adjacent or co-channel interference has been reported.

*Matti Siukola, "Evaluation of Circular Polarized TV Antenna Systems." IEEE, BC-24, March 1978.

Beam Tilt

Beam tilt should be used to bring the main vertical beam tangential to the earth (radio horizon), which is curving away from it. The distance to the radio horizon can be determined from Fig. 11.

It should be noted that height over the service area may not necessarily be the height over average terrain especially in a mountainous area. Also, if a body of water limits the service area, as in the case of Los Angeles, with the transmitter on Mt. Wilson, it may be desirable to aim the main beam to a point somewhat below the radio horizon.

In some cases, a little higher beam tilt may be desirable to improve local coverage. Beam tilt does reduce the vertical power gain in the horizontal direction, especially for a higher gain antenna. However, the loss in local coverage is generally a more important consideration than vertical power gain in the horizontal direction.

Power Capability

Power in TV systems is usually in terms of "Peak TV Power," which is the instantaneous power developed in the peak of the synchronizing pulse of the visual transmitter. Since the black level signal is 0.75% of the total voltage value of the pulse, the black level power (for a totally black picture) is 0.75^2 or 0.5625. The duty cycle of the synchronizing pulses, both horizontal and vertical, adds about 4 percent to this power so that black level power is 60% of the peak TV power. Since the aural FM transmitter is usually 10% of the peak TV power, the total heating or

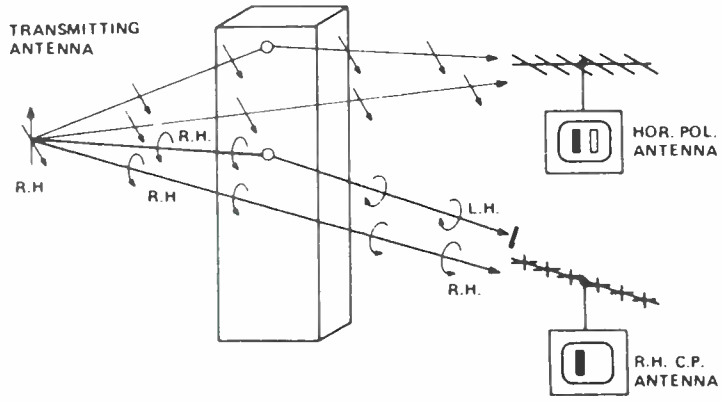


Fig. 10. Right-hand CP signals after striking an object are converted to left-hand signals which are rejected by the right-hand CP antenna, eliminating them as ghosts.

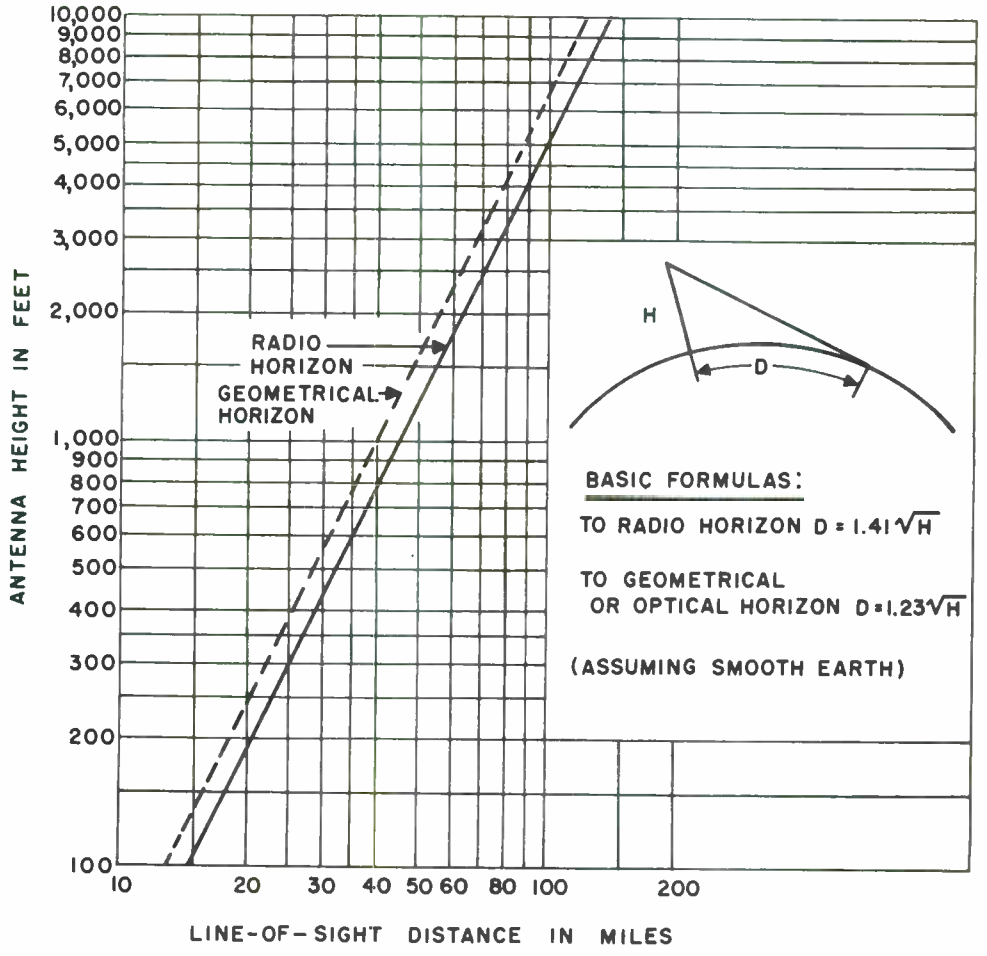


Fig. 11. Distance to radio horizon vs height of transmitting antenna.

CW power of the TV signal is 70% of the peak TV power.

The average power level (APL) of the video signal with typical program has recently measured* over a long period of time and shown to be 4.32dB (37%) below the peak TV power. The total CW power during programming would be 47% of the peak TV power.

The design of all TV antennas should allow for a sufficient safety margin to handle the peak to peak sync level, imperfections in the transmission line, VSWR, changes in pressure, and the aural power. Long transmission lines feeding the antenna will usually attenuate this figure by 10% to 20%.

Non-Ionizing Radiation— Design Consideration

As mentioned in the above Section 11 the antenna pattern is the product of the array pattern times the element pattern. The array pattern for one wavelength spacing has a downward and upward lobe as large as the desired side lobe. If the element pattern is not a $\cos^1(\theta)$ the element pattern will not drive the array downward lobe to zero, hence we could have a very large signal in the vicinity of the tower. See below.

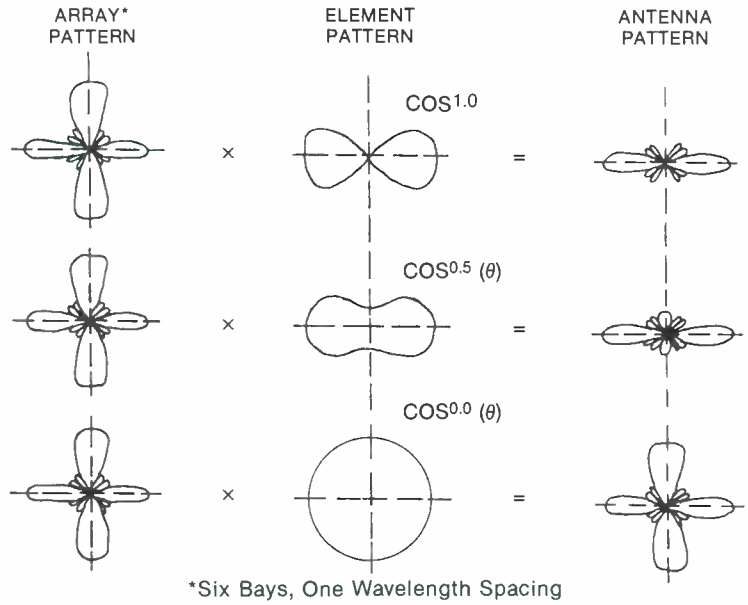
Care should be exercised in making sure the element pattern has a distribution in the elevation plane of cos (θ) or $\cos^2(\theta)$.

A well designed antenna system should not create a non-ionizing radiation problem. The tower for maximum signal coverage should be high enough and therefore free from directional radiation into habitable areas.

Some older antenna installations may be economically locked into existing sites, and because of Co- and adjacent channel considerations, moving may not be possible.

The distance along the main beam to the 10,1,0.2 mW/cm^2 contour for maximum power installations is listed in the enclosed table.

*J. Giardina, T. Vaughan, J. Neuhaus, "True APC Levels" Broadcast Symposium, 1984.



Distance in Feet Along the Main Beam to Different Power Density Levels

	LoV	HiV	UHF
ERP	**100kW**	**316kW**	**5,000kW**
EIRP	**164kW**	**518kW**	**8,200kW**
Power Density			
10 mW/cm²	80 Ft.	142 Ft.	568 Ft.
1 mW/cm²	251 Ft.	443 Ft.	1,764 Ft.
0.2 mW/cm²	565 Ft.	3,146 Ft.	12,471 Ft.

These calculations are very conservative in that they assume a far field condition and allow for a 2:1 reflection. A more exact "Near Field"* analysis would show the following:

Distance to 1 mW/cm²

	Exact	Approximate
LoV	89 Ft.	251 Ft.
HiV	163 Ft.	443 Ft.
UHF	629 Ft.	1,764 Ft.

The minimum height the antenna should be above ground assuming typical patterns, side lobes, etc., would be as follows:

Distance in Feet Between Array Center Line and 6 Feet Above Ground

	LoV	HiV	UHF
ERP	**100kW**	**316kW**	**5,000kW**
EIRP	**164kW**	**518kW**	**8,200kW**
Power Density			
10 mW/cm²	35 Ft.	64 Ft.	269 Ft.
1 mW/cm²	120 Ft.	203 Ft.	851 Ft.
0.2 mW/cm²	268 Ft.	453 Ft.	1,898 Ft.

**Near Field Analysis of Broadcast Antennas,* by J. Pezgar, T. Vaughan.

Here again a more exact "Near Field" analysis would show the following:

Minimum Height to 1 mW/cm²

	Exact	Approximate
LoV	43.0 Ft.	120 Ft.
HiV	72.6 Ft.	203 Ft.
UHF	304.0 Ft.	851 Ft.

Pattern

Vertical Patterns

The vertical pattern is usually shown as a plot on rectangular coordinate paper of relative voltage versus depression angle below the horizontal.

The angular width of the main beam of the antenna is directly related to the gain although this may vary somewhat with the method of pattern synthesis.

The half power beam width (0.707 voltage point) for an array with a uniform field distribution is

$$\text{B.W.} = \frac{58.3}{L} \approx \frac{58.3}{\text{Gain}}$$

since the gain for a omnidirectional linear polarized antenna is approximately equal to the length in wavelengths.

Hence, the specified gain generally determines the shape of the main beam. The amount of fill at greater depression angles than the main beam can be varied within limits although this will also decrease the gain. The greater the fill, the lower the gain. These relationships can be seen from the patterns Fig. 12 and the table below where

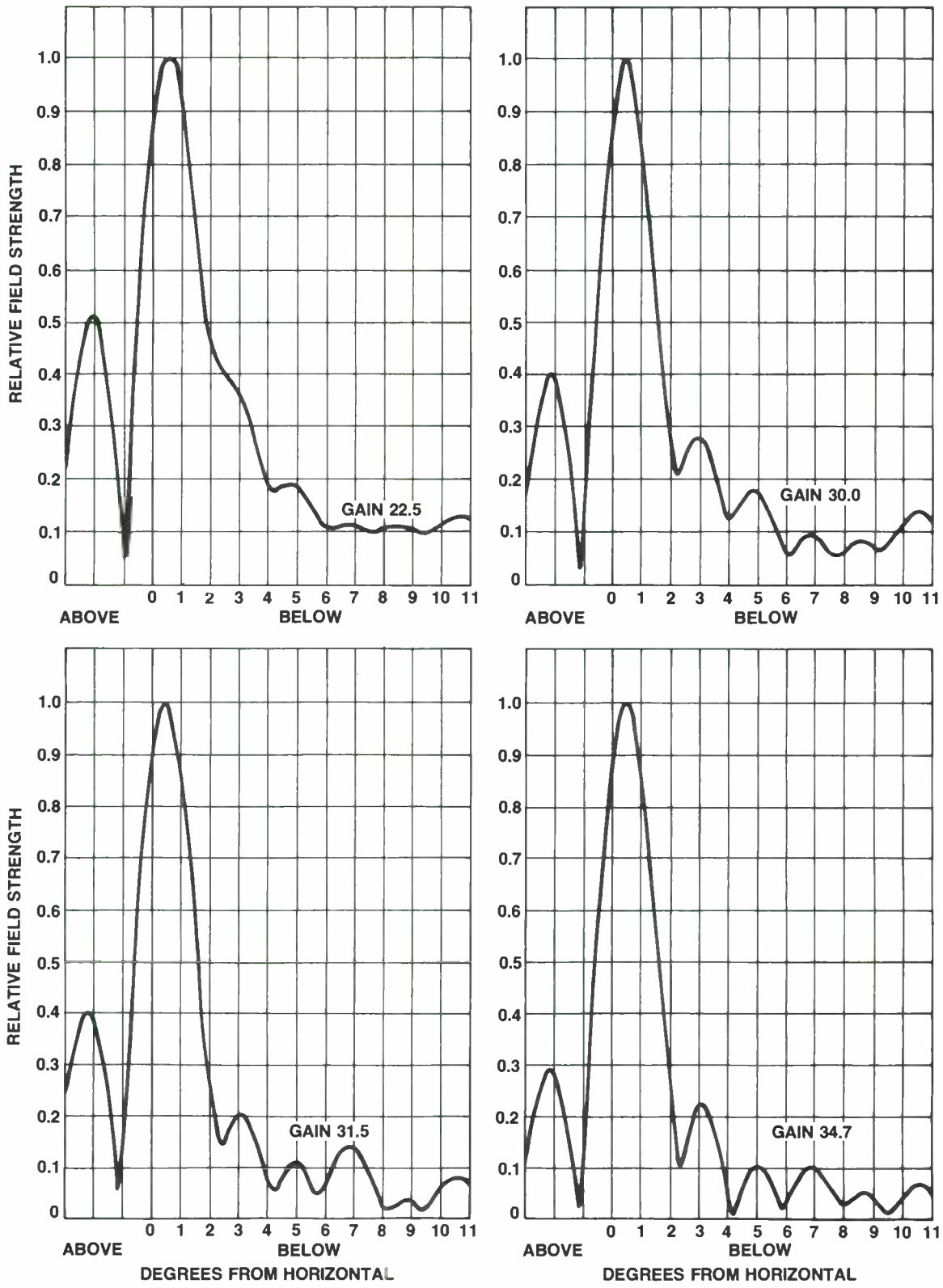


Fig. 12. Four vertical patterns of the same thirty-one layer antenna. Note the decrease in gain as the fill from 2.5° to 11° is increased.

the same number of layers for a given beam tilt will have gains and values of fill as follows:

Null Fill Value in Percentages

	Null No.		
Gain	**1**	**2**	**3**
34.7	11%	1%	2%
31.6	15	6	5
30.0	21	7.5	6
22.5	39	17	10

The amount of null fill and the number of nulls that need to be filled depends upon how close the populated area is to the transmitter site. Allowance should of course be made for population movement towards the site in the fiture. The depression angle below the horizontal, which requires null fill, can be determined from Fig. 13 for the known value of height and distance to the population center.

If the transmitter site is in the center of the population area or right on the edge of it, consideration should be given to a "shaped" pattern of the types shown in Fig. 14 which will provide fill to fairly steep angles.

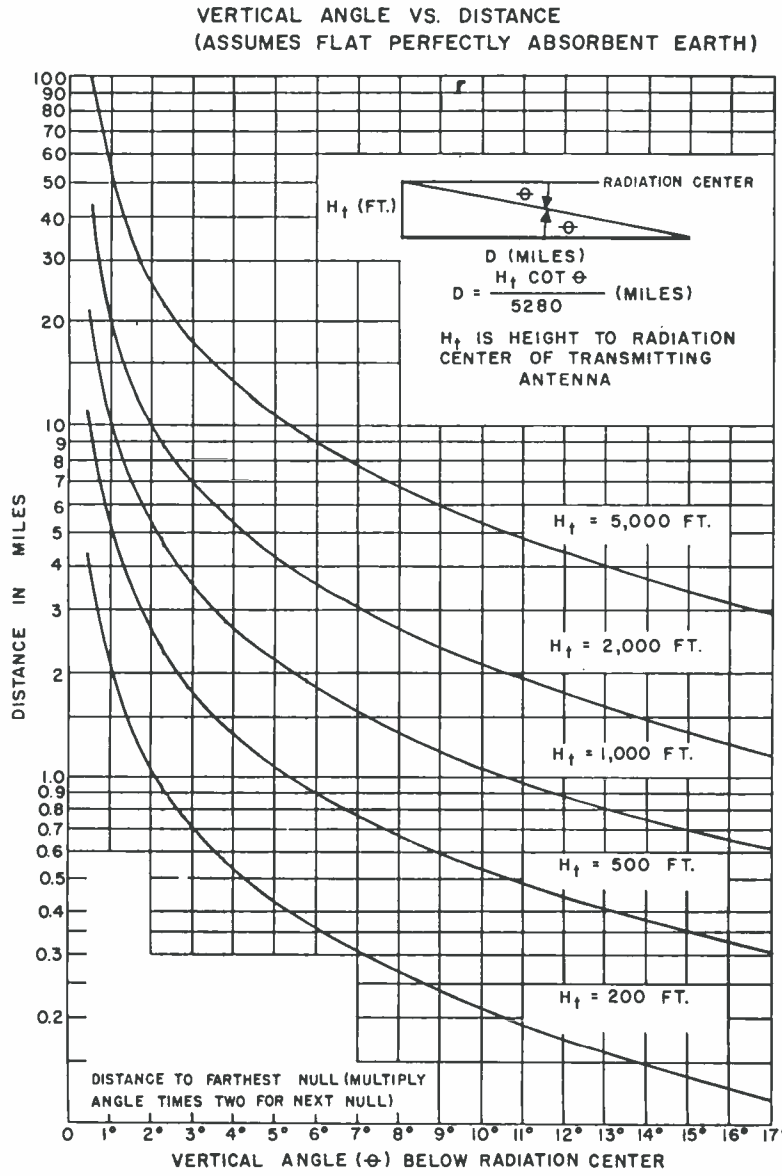


Fig.13. Distance to farthest null as a function of depression angle below horizontal (multiply angle times two for next null).

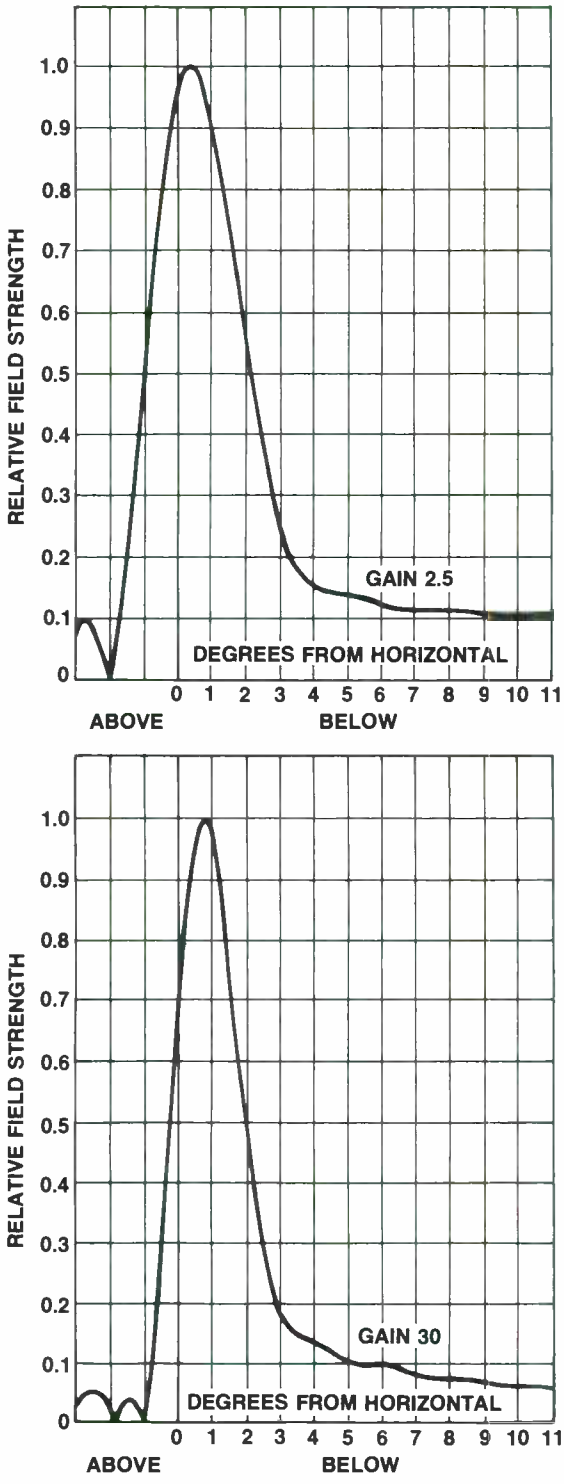


Fig. 14. The "shaped" pattern is generally used in large metropolitan centers where the service area starts very close to the antenna.

Horizontal Pattern

Most omni-directional antennas have a circular pattern with a "circularity" of the order of ±3 dB.

A directional antenna is advisable only for special terrain situations where the antenna is located near a large body of water or where the service areas are at certain separated locations. It must be recognized that the number of square miles over which a given field strength is obtained is always less with a directional antenna. The optimum condtion in this regard is an omnidirectional antenna located in the center of the area to be served. This can be seen from the following considerations:

Some relative approximate relationships can be deduced from propagation formulas which pertain within the radio horizon over plane earth, as follows:

$$r \propto \sqrt[4]{p}$$
$$A \propto \sqrt{p}$$
$$P \propto \sqrt{h^2}$$

Where r is the distance to a given field contour; p is the "effective radiated power" in the main beam;[5] A is the area served within a given field contour; h is the height of the antenna above the service area.

In Fig. 15 the area enclosed by a given field intensity contour for a relative "effective radiated power" of "1" and a relative height of "1" is πr^2. The transmitting site can also be moved to the perimeter of the circle and a directional entenna employed which has a horizontal pattern in the shape of a quarter of a circle as shown in Fig. 15b. The horizontal gain of such an antenna is four, hence, P = 4.

From the relationship above r $\propto \sqrt[4]{p}$, r becomes the $\sqrt{2}$. The area to the same field intensity contour served is then:

$$A = \pi \frac{(\sqrt{2}r)^2}{4} = \frac{\pi r^2}{2}$$

Hence, using the same transmitter power with an optimum directional antenna with a horizontal gain of 4, only one-half of the area is covered as compared to Fig. 15a and, hence, the coverage efficiency is 50 per cent.

It can be stated generally that because of the fourth root relationship between distance and radiated power, the center of the area to be covered is the best location for maximum coverage efficiency.

However, there is another factor: height. From the relationship above, it is noted that if the height is doubled, the "effective radiated power" increases four times. Hence, in Fig. 15b, doubling

[5] The value here used is not only the product of transmitter power and antenna gain, but also the increase in "effective radiated power" due to an increase in height.

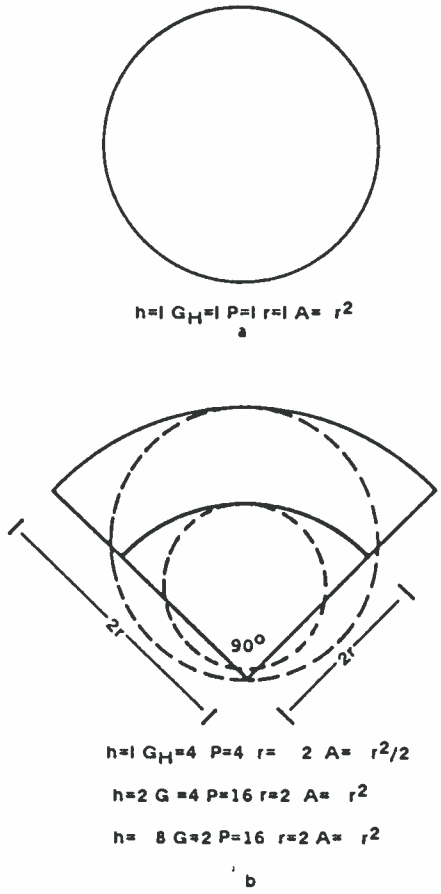


Fig. 15. The most efficient coverage is obtained when the antenna is located centrally in the service area. Only one half of the area is covered with the same input power at the same height from the perimeter using a directional antenna.

the height will provide "effective radiated power" "p" of 16 and "r" becomes 2. The area covered is then:

$$A = \frac{\pi(\sqrt{2}r)^2}{4} = \pi r^2$$

which is the same as for "a".

The antenna postulated in "b", however, is not permitted under the 15 dB rule. A practical antenna may have a horizontal gain of about 2. To obtain an "effective radiated power" of 16 will require a height increase of $\sqrt{8}$ or 2.8 times.

Another general rule is that where a sufficient natural height can be obtained, a directional antenna can be an advantage. To obtain any advantage, however, heights beyond a relative value of 2.8 must be obtained under the conditions postulated above. Hence, it can be seen that the maximum area is covered with a given ERP from the center of the area to be served. If the antenna is located on the perimeter instead of the center of the same area using a directional antenna, the area covered drops to approximately one-half or less. This results from the fact that the service radius varies approximately as the fourth root of the ERP. If a natural low cost height, such as a mountain site, is available at the perimeter which is approximately three times as high as that which would be used in the valley, the full area can be recovered. The economics of each situation should be studied. Because of the fourth root relationship between the service radius and the ERP, a voltage plot of a directional antenna can be misleading. The area to be covered should calculated using propagation formulas to obtain a true evaluation. Often the benefits may be found to be marginal and possibly detrimental.

Antenna Input Impedance

The primary purpose of an input impedance specification is to obtain a good match to the transmission line which carries the power up to the antenna. If the mismatch is too great, the reflected power may be of such magnitude that it travels back to the transmitter where it is generally re-reflected back to the antenna and appears as a secondary image on the television picture. The image is delayed by twice the length of the transmission line.

Subjective experiments have established that the reflection should be no greater than 3 percent of the incident voltage. The method of measuring this is described under "System Specifications."

However, when the antenna is being designed and tested, a complete system is not available so that VSWR (voltage standing wave ratio) across the channel is used as a design guideline.

The relationship between the percentage of reflection and the VSWR of the antenna to achieve it can be related by a computer program. Due to the concentration of energy at picture carrier and ¾ mHz above, the VSWR values should be kept fairly low in this region, say below a VSWR of 1.05 at visual carrier. The values below visual carrier are not as critical since the slope in the receiver cuts off most of the energy in this region as shown in Fig. 16. Hence, the VSWR over the balance of the picture pass band should be as shown in Fig. 17.

However, these values are really only designed guidelines and should not be used as a specification since the real criteria is the 3 percent pulse reflection value, which is the only specification that is really meaningful. It is a temptation to include as many specifications as possible in the hopes of arriving at a good system. However, specifications that are redundant and more stringent than necessary only serve to increase costs without any improvement in performance.

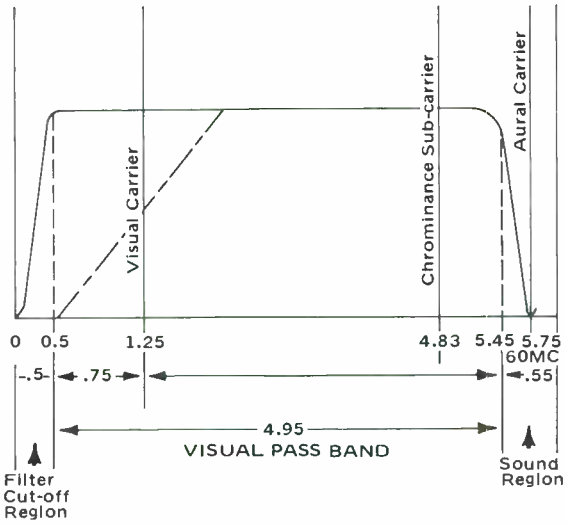


Fig. 16. Note that the visual band is located one half megacycle away from the edges of the channel. Due to the receiver characteristic the VSWR values below visual carrier have a relatively lesser effect on the RF pulse reflection value.

System Tests

The primary purpose of testing the antenna system in threefold is:

1. That the transmission line and components are properly assembled.
2. To determine that the reflection from the antenna and other components at or near the tower top are sufficiently well matched so that no visible ghost occurs.
3. That the impedance presented to the transmitter will result in the maximum transfer of energy.

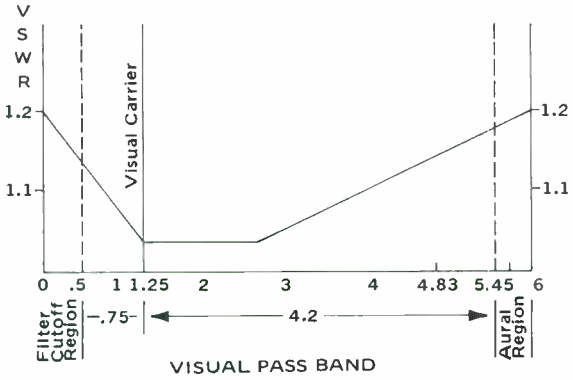


Fig. 17. Based on the visual energy distribution in the channel and the receiver response, the above VSWR versus frequency characteristic will achieve better than a 3 percent pulse reflection value.

Transmission Line and Components

For an extremely broad band device like a coax transmission line which is usually designed to cover the entire, or at least, a large portion of the TV band, the dc pulse is very effective test to determine if the line and components have been properly assembled. This is a short pulse of perhaps 20 nanoseconds at about a 15,000 cycle repetition rate. The wave front is steep enough so that each section of line can be discerned on an oscilloscope. Each joint will manifest itself as a separate vertical line. If one of the pulses is higher than the others, the joint should be investigated for an improper connection or other fault. It is sometimes good practice to assemble the line from the bottom up so that the reflection from each piece can be seen as it is inserted and an immediate correction made. It is also advisable to tap each joint with rubber mallet to locate incipient trouble due to single point contact or improper connection.

Time Domain Reflectometers (TDR) are now generally available for making dc pulse measurements. For UHF installations, a circular or rectangular waveguide is now used. Since a waveguide has no inner conductor, dc pulse measurements cannot be made. Measurement must be made with RF signals.

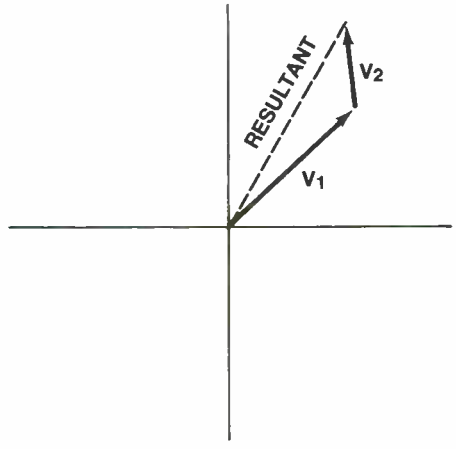
It should be understood that measurements made of the input to the transmission line measure the combined input impedance at that point only, and not the discreet reflections that can cause ghosts.

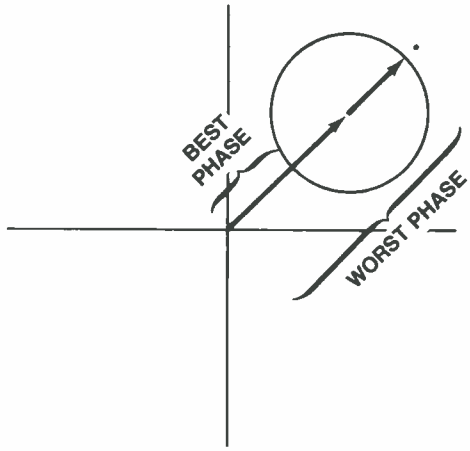
There are usually two sources of reflection assuming the line to be reflectionless:

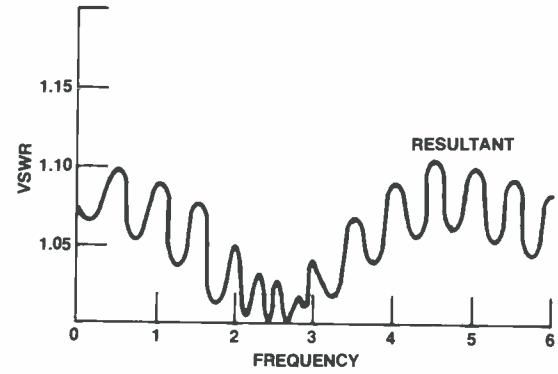
(A) Lower elbow complex—V1
(B) Upper elbow complex and antenna—V2

When measured at the input to the system these can be thought of as two vectors.

Each vector individually will rotate about the preceeding vector at a frequency corresponding to the distance from the point of measurement.







The frequency of rotation can be calculated as follows:

$$\Delta f = \frac{496^*}{L} \quad \text{coax}$$

$$\Delta f = \frac{496^*}{L}\left(\frac{\lambda o}{\lambda g}\right) \quad \text{waveguide}$$

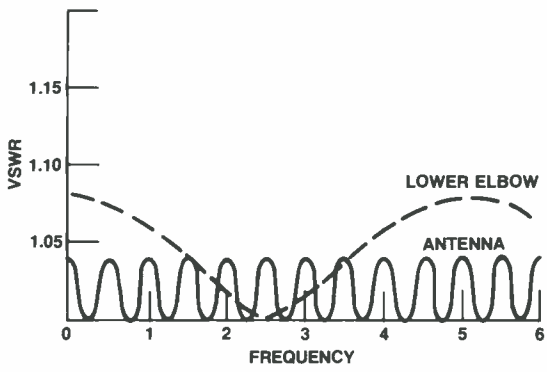
*Half (coax) the velocity of light with L in feet.

The displacement of the corresponding echo (ghost) on a TV screen would be the reciprocal of the frequency Δf (Echo = $1/\Delta f$).

If we use the following example

Reflection Location	Distance	Magnitude VSWR	Γ1	Δf MHz	Displacement Microsec on TV Receiver
Lower elbow complex	100 ft.	1.08	4%	4.96	0.2
Antenna	1000 ft.	1.04	2%	0.496	2.0

The resulting combined reflections (VSWR) would be as shown:



The worst VSWR would be when the vectors are in phase $(1.08) \times (1.04) = 1.12$ and the best $(1.08) / (1.04) = 1.038$ assuming both vectors remain on the same side of the Smith chart.

The half period between 2 and 3 MHz is because the antenna vector is going to the other side of the Smith chart.

The antenna reflection would be more objectional than the lower elbow complex because of its distance and displacement rather than its magnitude. A 5% (VSWR 1.10) echo would not be as objectional at 0.2 μsec as it would be at 2.0 μsec.

The antenna reflection should be kept to less than 3% although the input reflection may read higher due to near and far end reflections.

An example of combined transmission line and antenna VSWR can be seen in Fig. 18.

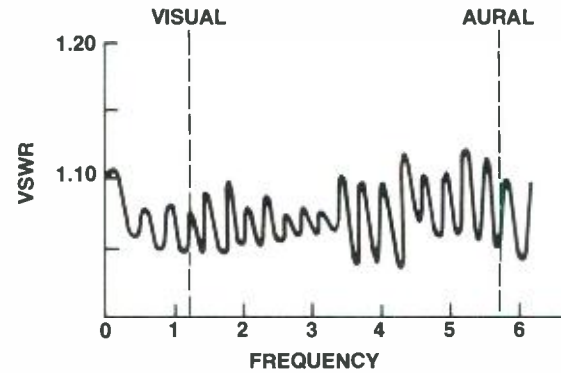


Fig. 18. Example of combined transmission line and antenna VSWR.

Careful examination will show three cycles in this UHF waveguide installation.

SOURCE	PERIOD	DISTANCE TO REFLECTION	
		COAX	WAVE-GUIDE
LOWER ELBOW	8 MHz	62 FT	44 FT
TRANSFORMERS	2 MHz	248 FT	177 FT
ANTENNA	0.27 MHz	1837 FT	1312 FT

The directional coupler used to measure system performance is located in the transmitter. Another source of near in reflections would be the components in the transmitter room.

This would include elbows, switches, combiners, diplexers—etc. The combined transmitter room reflection should be kept very low (less than VSWR 1.08) not because of its echo displacement but because the interaction of this reflection with the antenna reflection can result in varying transmitter readings when line lengths change due to thermal expansion and contraction.

AT UHF frequency where the guide wavelength is 2 or 3 feet, a 50° C temperature change on a 1,000 foot tower can result in electrical length changes of $\lambda/4$ to $\lambda/2$ wavelength.

Deflection and Wind Load

Guy tension in guyed towers is usually adjusted so that the tower deflects as a straight member.

Towers for broadcast service, when so specified, are designed for maximum deflection of 0.5°, which means that the top plate will deflect this amount for the maximum wind velocity. For instance, a 40 lb. tower will thus deflect 0.5° for a 100 mph wind. Since tower deflection varies as the square of the wind velocity, the deflection will be 0.125° for a 50 mph wind.

Structurally a free-standing antenna can be considered as a cantilever beam in which the deflection increases toward the end. Antenna deflection is stated as the angle from the vertical of the chord that connects the base to the top of the antenna.

In order to evaluate the effects of deflection, an example for a high gain UHF antenna will be given.

Figs. 19 and 20 show the pattern variations of a UHF antenna of the slotted cylinder type with a gain of 46 when the antenna is 102.8 ft. in height. The entire antenna is constructed of 18 in. steel tube with a 1.218 wall using six peripheral slots in each layer.

The phase and amplitude of each layer of the antenna were synthesized to obtain a vertical pattern for the curved condition where the antenna was bent toward the service area and away from it.

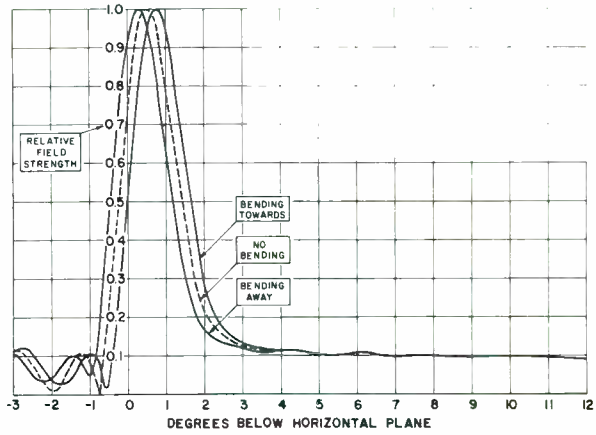


Fig. 19. Calculated vertical patterns of the TFU-46C antenna affected by static load: flat-surface wind load 10-psf, wind velocity 50 mph.

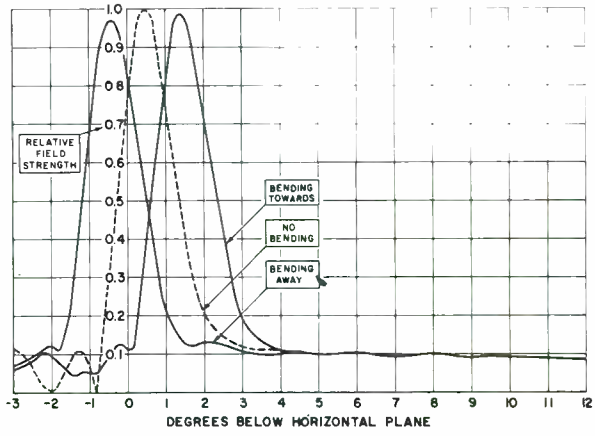


Fig. 20. Calculated vertical patterns of the TFU-46C antenna affected by static wind load: flat surface wind load 40psf, wind velocity 100 mph.

Two conditions are shown for a wind velocity of 50 to 100 mph as summarized in Fig. 21.

The 50 mph wind condition is one that may occur[6] twenty-five times a year at a 1,000 ft. elevation above terrain and about four times a year at a 500 ft. elevation.

The 100 mph wind is a design limit figure which rarely occurs and is one during which there would probably be little television viewing. Most outdoor receiving antennas would probably be severely damaged in such a wind, and power service seriously curtailed.

Hence, the 50 mph figure is one that is generally considered applicable for an evaluation of this type.

[6] Report of TASO Committee on 1.3 on Television Antennas. Final Report of TASO Sub-Committee 1.3.2 on Towers, Sec. 3.6.

Wind Velocity mph	50		100	
Wind load psf	10		40	
Deflection of antenna at top, in.	4.9		19.6	
Deflection, degrees, of chord from bottom to top	0.227		0.914	
Tower deflection degrees	0.125		0.5	
Antenna and tower deflection degrees	0.352		1.414	
Signal Variation for Deflection Extremes, dB	Toward Service Area	Away from Service Area	Toward Service Area	Away from Service Area
At horizon (main beam) antenna only	−0.5	−0.3*	−7.8	−5.8
At horizon for antenna and tower	−0.7	−0.4	−18.8	−13.4
At a location with respect to the vertical pattern where the greatest signal variation occurs for antenna only	+3.6	−2.7	+6	−10.8
At a location with respect to the vertical pattern where the greatest signal variation occurs for antenna and tower	+4.2	−5.3	+12.7	−5.2

*Values are not the same, since in this antenna, radiation above the horizon has been suppressed and the pattern is not symmetrical.

Fig. 21. Signal strength variation as a result of transmitting antenna deflection in high winds.

Most television receivers are designed to have a flat AGC response down to 100 microvolts across the receiver terminals. Hence, no effects due to wind acting on the transmitting antenna will be noticeable except in fringe areas where the signal drops below this value.

In the case cited above, the signal variation in the fringe area would be less than 1 dB and could be considered negligible.

The maximum variation in the case cited above occurs at 1.75° below the horizon or at 6.3 miles for a 1,000 ft. difference in elevation between the transmitting and receiving antenna. At this distance the field strength is usually at a sufficiently high level so that a 2 to 1 variation will not go below the 100 microvolt level at the receiver terminals.

Analyzed on this basis even the 100 mph wind condition is not too serious except in the fringe area. It should be noted that the variations are limited by the fact that the antenna is designed not to have nulls near the main beam.

For lower gain antennas with a wider beam the variation would be even less than those shown.

DESIGN AND THEORY

Elemental Radiators

Television antennas in common use are developments of one or another of a few basic types of radiator. These are the half-wave dipole, the loop (magnetic doublet), the slot, and the helical. Some of the antennas combine characteristics of more than one of these types.

For purposes of mathematical representation or as a reference for comparison of charactristics of antennas, the concepts of "point source"—a fictitious emitter so small as to have no dimensions—and "isotropic radiator"—which radiates energy uniformly in all directions—are sometimes used.

Half-wave Dipole

If the ends of the open-wire transmission line are turned outward, as shown in Fig. 22A, they form what is known as a dipole. The electric (E) fields, at right angles to and connecting the two sides of the transmission line, extend outward, forming circles in all planes passing through the axis of the dipole, as shown in Fig. 22B. The magnetic (H) fields which, in the transmission line encircled the separate wires and tended to cancel each other owing to the opposing directions of the flow of current in the two wires, now appear as circles about the dipole.

If the length of the dipole is made a half-wavelength long at the frequency of an imposed signal, it becomes, in a sense, a resonator, with energy reflected from the ends of the radiator setting up standing waves. The energy is alternately stored in the electric and magnetic fields.

At high frequencies, the fields so formed do not have time to collapse completely before other fields, of opposite polarity, are set up. The result is that outer portions of the field never return but are pushed out of the area close to the antenna known as the "induction-field" region and move away, forming the "radiation field."

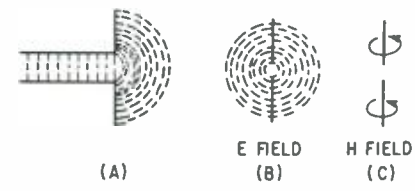


Fig. 22. Electric (E) field, and magnetic (H) field of a dipole.

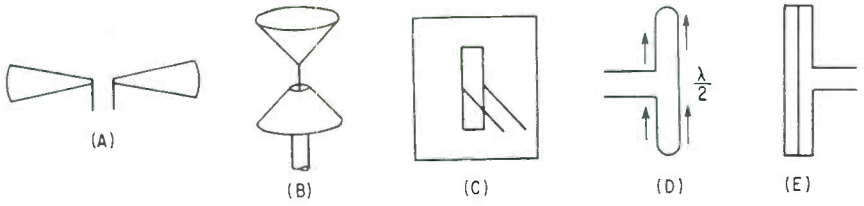


Fig. 23. Examples of radiators having dipole-like charateristics: (A) and (B) biconical antennas, (C) slot-fed sheet, (D) folded dipole, (E) folded dipole with additional element.

Since the power in the field is dissipated power (I^2R) in the same sense that power appearing as heat due to ohmic resistance in the dipole is dissipated power, it is convenient to relate this power to the current which produces it by a fictitious "radiation resistance." This is in addition to the ohmic resistance in the radiator circuit.

The ratio of stored energy to dissipated energy is called the Q of the antenna circuit. As any circuit contains L, C, and R, this is a function of the relationship between the inductive reactance of the circuit and the resistance. In the case of the dipole the inductance decreases with increasing diameter of the dipole arms. Also the amount of energy reflected from the ends, resulting in greater stored energy, is reduced by increasing the size of the arms. This results in greater bandwidth. Application of this fact leads to the biconical radiators in Fig. 23a and 23b and to the slot-fed sheet radiator, Fig. 23c.

Another form of the dipole is the half-wave folded type shown in Fig. 23d. Here, the ends of a simple dipole have been joined by another closely spaced element. Since the voltage distribution is the same in both, the currents are in the same phase and direction. The result is an input impedance of 300 ohms as compared with 73 ohms for a simple half-wave dipole. Addition of rectangles as in Fig. 23e increases the input impedance by a still greater factor.

Because the folded ends act like stubs, they become capacitive at high frequencies. This is opposite to the tendency of the series LCR circuit by which a dipole can be represented. The result is a cancellation to some degree of the reactances and a tendency for the impedance to remain constant, making the antenna more broadband than the half-wave dipole.

The distant radiated field of the folded dipole is the same as that of the simple dipole.

Loop

The folded dipole discussed above may be considered as a special case of a loop antenna as well as a type of dipole. In fact, any closed loop of conductor which does not carry equal and opposite currents very close together, that is, within the "near," or "induction," zone, will fall into this category and will radiate at least some of the power supplied to it.

The loop or ring radiator may be rectangular or circular, as seen in Fig. 16a and b.

Variation in the size of the loop yields radiation patterns of various shapes, in planes at right angles to that of the loop, as could be expected by comparison with the horizontal fields of two AM radiators with various spacing and phase relationship. That is, if sides 1 and 2 of the square loop in Fig. 24a are considered to be the two AM radiators, the combined radiation pattern in a plane at right angles to them will vary with the spacing between them. For loops with diameters less than 0.585λ the maximum field will be in the plane of the loop, and loops much smaller than a wavelength are therefore most commonly used as elements of television antennas. Radiation in a direction normal to the loop is always zero, regardless of the size of the loop.

Slot Antenna

As has been mentioned under Half-wave Dipole, the slot antenna has a great similarity to a dipole.

Figs. 25a and 25b show the two types, oriented so that the (E) fields of both are horizontal. Currents in the slot type spread out over the entire sheet, and radiation takes place from both sides of the sheet.

The resemblance between the two becomes even more pronounced when it is recognized that the field patterns of the two will be equivalent if the physical dimensions of the slot and the cross section of the dipole are the same. For example, the fields of the two radiators in Fig. 25c and 25d

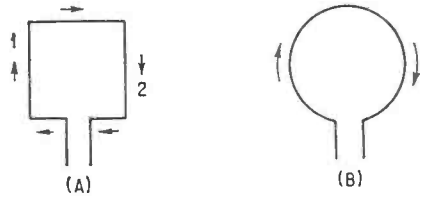


Fig. 24. (A) Square loop and (B) ring radiator.

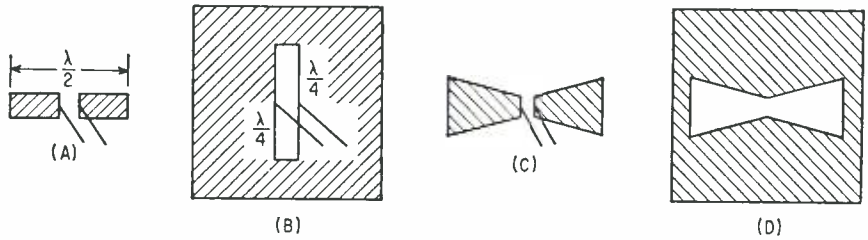


Fig. 25. Dipoles (A) and (C), with complementary slot-fed sheet radiators (B) and (D).

are the same. A very similar situation occurs in optics, where the phenomenon is known as Babnets principle. Using a term from optics, the antennas are said to be complementary where this situation exists.

Furthermore, the impedance of the slot is proportional to the admittance of the dipole of the same dimensions by the relationship

$$Z \text{ slot} = \frac{35{,}476}{Z \text{ dipole}}$$

and the bandwidth characteristics of one are the same as those of the other.

Actually, the above discussion is rigorously accurate only if the sheet is of infinite extent, but it is substantially correct if the edge of the slot is half a wavelength from the slot.

The input resistance to a slotted sheet is of the order of 500 ohms. This can be modified by shifting the position of feed along the slot. A value of 50 ohms can, for example, be obtained with the feed about 0.1 of the slot length from one end.

Radiation can be limited to one side of a very large sheet by boxing in the slot on the othe side. If the depth of the box is such as to present zero susceptance at the feed point, the input impedance will be approximately double that of the same antenna without the box (see Fig. 26).

Bending the sheet into a cylinder results in another form of slot antenna which also takes on characteristics of a stack of coaxial rings (Fig. 27).

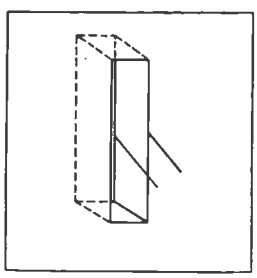
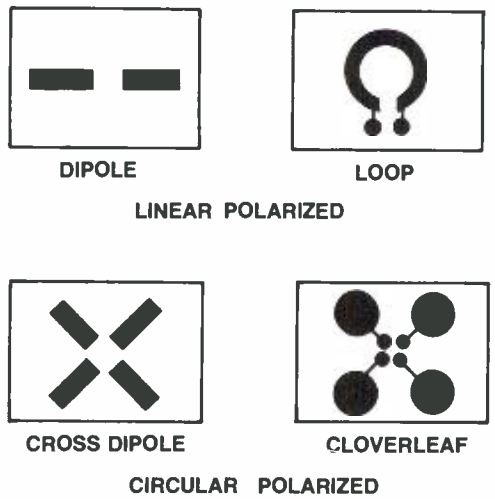


Fig. 26. Slot-fed sheet radiator with slot boxed to limit radiation to one side of sheet.

Panels

Many of the newer antennas are of the panel type that is either dipole or loops mounted $\lambda/4$ in front of a panel. These antennas will have a directional ($\cos \theta$ or $\cos^2 \theta$) pattern in the azimuth and elevation planes.



The pattern is directional since the energy radiated from the element sees its image in the ground plane resulting in a $\lambda/2$ spaced end fire radiator.

The omni-directional pattern ripple of panels mounted around the tower is dependent on the physical size of the tower hence dependent on the channel. As mentioned previously, there is an optimum relationship between the phase center diameter and element pattern for square and triangular towers. A large variety of pattern

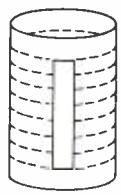


Fig. 27. Slot-fed sheet radiator bent to form a cylinder, showing resemblance to stack of ring radiators.

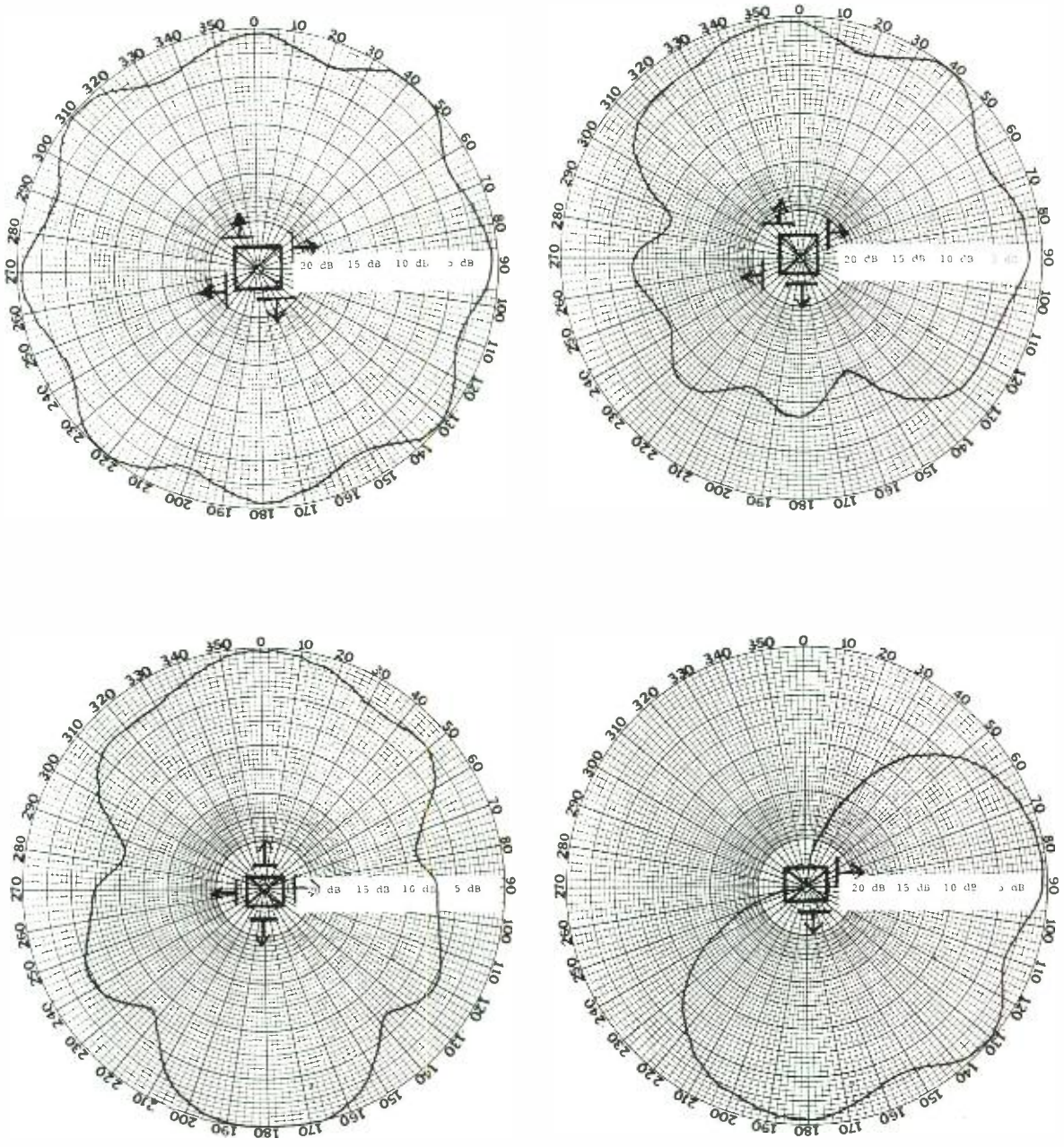
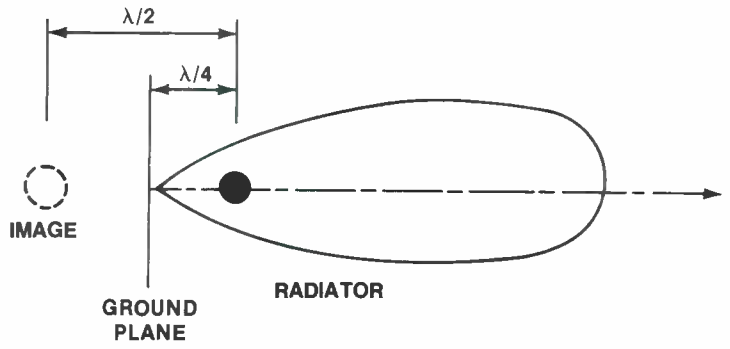


Fig. 28. Examples of azimuth patterns of an H panel low band antenna on a 3.2 meter tower.



shapes can be obtained by controlling the position and power fed to each panel.

Traveling Wave Antenna

There is a large variety of traveling wave antennas now available.

The traveling wave slot antennas are either resonant (standing wave) or non-resonant (traveling wave). All are bottom fed. When the far end is shorted, an infinite standing wave is set up in the transmission line (either coax or waveguide). When the slots are appropriately sized and spaced, energy will be coupled out. The amplitude and phase developed across the aperture can result in a high gain antenna. The band width limits this technique to narrow band or UHF high channel application.

The most common bottom fed traveling wave array is the non-resonant array. The number of half wavelength slots arranged about the periphery is dependent on the shape of the pattern desired. The circumferential slots are usually displaced by $\lambda/4$ and spaced vertically one wavelength. The coupling from the bottom to the top increases since the power radiated successfully reduces the power on the line. This method produces an amplitude taper across the aperture hence null fill. With all non-resonant arrays, there is a small amount of energy left over. This is radiated in specially designed end-loaded slots or in the opposite polarization.

The zig-zag is essentially a strip transmission line mounted over a ground plane; the spacing controls the radiation. Each element is a $\lambda/2$ radiator, and because of the orientation, the vertical components cancel. The choice of pitch angle and length on circumferential the helix will result in very good horizontally polarized broad side radiation.

Circular polarization can be obtained by orienting successive slots at 90° and exciting them in phase quadrature.

The circular polarized spiral or multi-arm helix are multiple wires mounted around a large cylinder forming a current sheet. The optimum parameters are a complex function of the number of arms, the length of one coil, and the spacing to the support pole.

Excellent circularity can be obtained since in any heading the radiation is essentially that from a current ring.

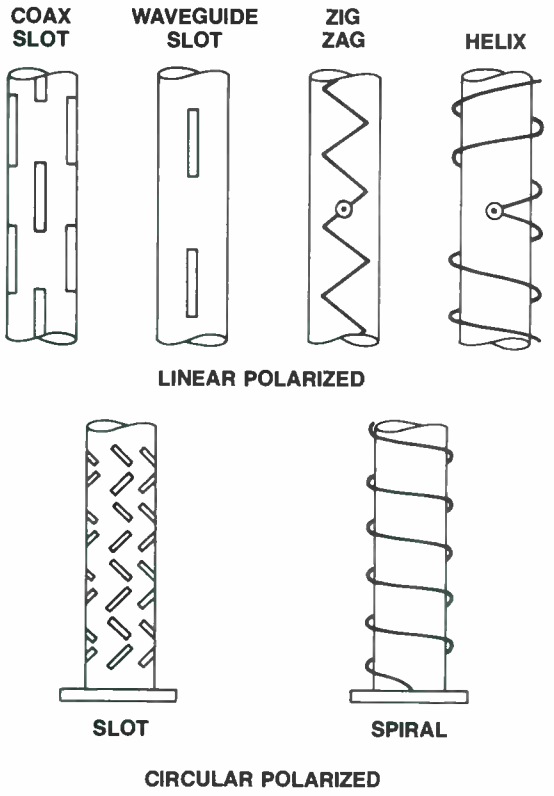


Fig. 29. Traveling wave antenna configurations.

Antenna Patterns

Azimuthal Patterns

In television, with the inherent limitations on coverage due to high-frequency propagation effects and the limitation on the number of stations with any area as set up in the existing allocation plan of the Federal Communications Com-

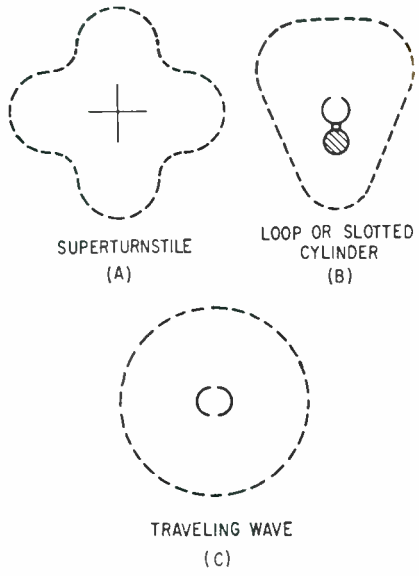


Fig. 30. Typical azimuthal patterns of well-known types of TV broadcast antennas.

mission, the large majority of requirements have been for omnidirectional antennas.

As is pointed out in the discussion of omnidirectional patterns, the primary criterion of a truly circular or omnidirectional pattern is the intent to make it omnidirectional. In the past, variations of 3 dB on each side of a true circle have been accepted as within the meaning of the word omnidirectional.

Since energy flows equally in all directions from a theoretical "point source," its horizontal pattern is a true circle. A thin dipole, vertical to the earth's surface (i.e., with vertical polarization), most nearly approaches this and has a similar azimuthal pattern. Except for these two cases, however, the finite physical size of television transmission antennas and the physical irregularities of their surfaces, due to the requirements of mechanical construction, result in the sum of the energies from various portions of the antenna as received in one direction varying from that received in another. Typical azimuthal patterns of some well-known antennas are shown in Fig. 30.

Except for the effects of supporting structures upon which they are mounted, rings or cylindrical antennas inherently have better circularity than other shapes. Ingenious methods have been used, however, to combine noncircular patterns of several radiators to obtain circularity. An illustration of this is the so-called turnstiling principle applied to dipoles. Fig. 31a shows the typical "figure-eight" horizontal pattern of a very small dipole. If a second dipole is placed at right angles to the first, the patterns will overlap, as shown in Fig. 31b. If both are fed in phase, addition of the radiated energies will result in a pattern such as is shown in Fig. 31c.

Other methods of obtaining omnidirectional patterns which have been used are the "clover leaf" of small loops (Fig. 32b), the triangle of folded dipoles (Fig. 32c), the small loop (Fig. 32d), the "supergain" with the dipoles backed by screens and fed in quadrature (as are the turnstiled dipoles) (Fig. 32e), and the helix wound around a tower structure with phase compensators to maintain correct phase relationship between successive turns of the helix (Fig. 32f).

Although omnidirectional antennas predominate in television broadcasting, there are locations where their use is impractical and even insufficient, and it becomes obviously desirable to direct the main portion of the radiated energy in both the horizontal and vertical planes to serve specific areas best. Examples in the United States are the Denver, Colo., area, where the presence of mountains to the rear of logical transmitting sites would set up undesirable reflections if the signal were allowed to radiate toward them, and the southeast coast of Florida, where the populated area borders the coast for great distances with only swamp immediately to the west.

Here the irregularities of the so-called omnidirectional patterns can be exploited to some extent, but truly "directional" patterns are more desirable. In order to obtain directional patterns,

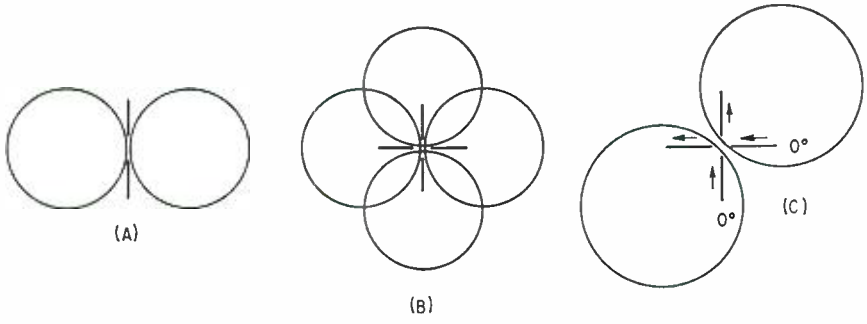


Fig. 31. Addition of fields of crossed dipoles. (A) Figure-eight pattern of a single dipole, (B) superposition of a second dipole at right angles, (C) pattern obtained when both dipoles are fed in phase.

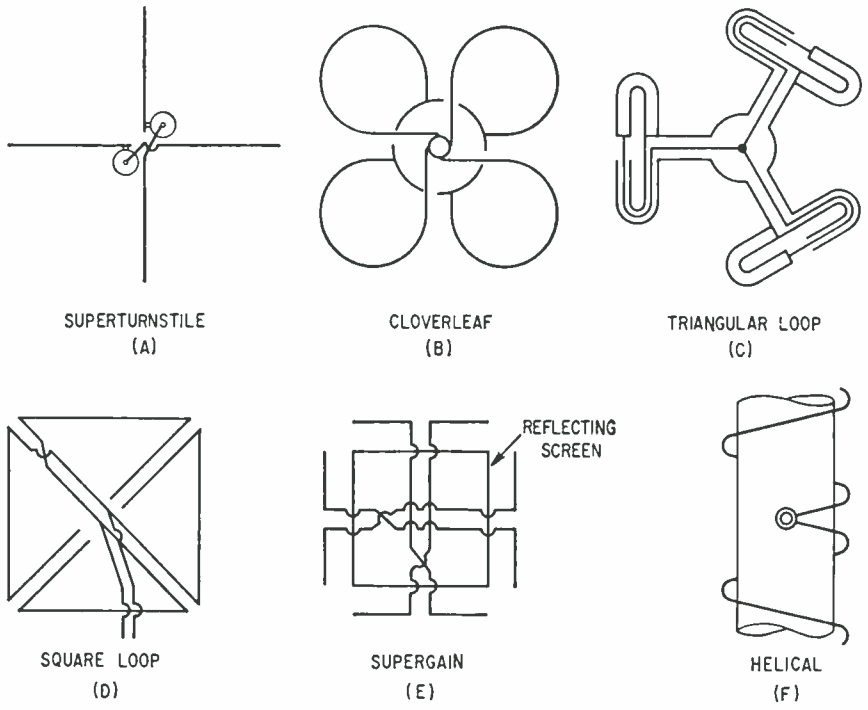


Fig. 32. Configuration of elements used to obtain omnidirectional patterns.

in either the vertical or the horizontal planes, correct relation in amplitude and phase of the signal coming from different portions of the antenna is necessary. This can be accomplished to some extent by physically spacing the radiating elements properly. For a given spacing, the pattern can be further modified by varying the phase and amplitude of the respective radiated signals. An example of this is shown in Fig. 33 where two point sources are fed in phase with each other but are spaced 180° apart. By the time the signal from *A* reaches *B*, the phase of the signal being radiated from *B* will have changed 180°. If the signals are equal in magnitude, they will cancel in the direction of the right. The same line of reasoning shows that no signal will be radiated to the left. Toward the top and bottom of the page, the signals will always be in phase.

The need for higher gain (see under Gain) than can be obtained with a single radiating element requires "stacking" the elements one above another. This, on the undesirable side, increases the condition of "lobing," or wide variations in the amplitude of the resultant radiation pattern in the vertical planes. On the desirable side, however, it provides more separate elements by control of which the patterns can be made nearly ideal for television broadcasting.

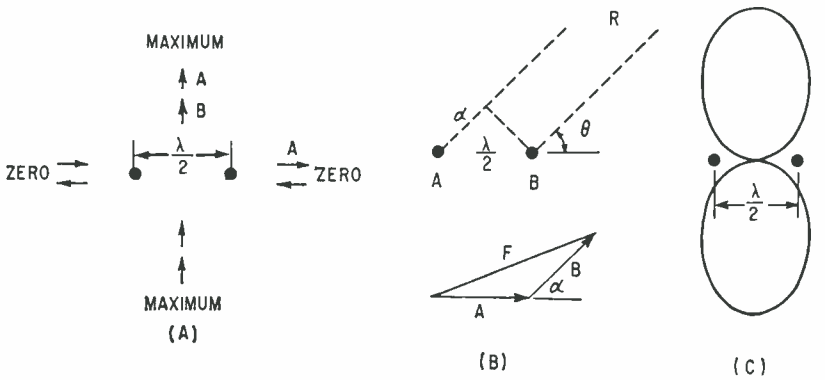


Fig. 33. Formation of field pattern from two souces placed a half wavelength apart, as shown in (a) and fed in phase. Leg of signal from source A in direction R is shown in (B) and the sum F of the signals from A and B are shown in (C).

Reference is made to the discussion of Azimuthal Patterns for an outline of the theory of pattern formation. The same principles apply in the vertical plane. Fig. 34A shows the vertical pattern of a point source or of a horizontal dipole. Fig. 34B and 34C show the effect to stacking two- and six-point sources one above another, a half wave apart, with currents of equal amplitude and phase. Fig. 30d shows the same information as Fig. 30c for the portion of the pattern between $\theta = 0°$ (horizontal) and $\theta = 270°$, on rectangular coordinates, with field intensities plotted against angle below the horizontal. This is the customary method of pattern representation, enabling one to see in convenient manner the relative field strength at any angle into the area served by a broadcast station down to the base of the antenna tower.

The presence of nulls in the pattern of a television broadcast antenna is undesirable, because receiving areas at the angles where nulls are indicated received either less than the required signal or one which is the sum of reflections from objects which lie outside the null area. This latter condition often results in multiple "echoes" in the received picture.

The angles at which nulls appear for the case of a vertical array of equally spaced radiators fed by signals of equal amplitude and phase can be approximately found by the relation

$$\theta = \arctan \frac{\pm K}{nd}$$

where K is the null in question (the one nearest the main beam having a K value of 1, the next one 2, and so on). The number of elements is given by n, and the spacing of elements in wavelengths by d.

A quick rule-of-thumb method to obtain the distance of a null is to multiply the antenna height by the antenna gain and divide by K, thus

$$d = \frac{hg}{K}$$

Various methods are used in the design of antennas to "fill in" the null axis. Single power division, whereby the upper or lower half of the elements are fed with a greater amount of power than the other half, results in the elimination of all odd-numbered nulls (see Fig. 35A).

A more complex power distribution was proposed by J.S. Stone, wherein successive elements are fed with amplitudes proportional to the coefficients of a binominal series. Thus for three elements the distribution would be in the relation 1, 2, 1, and for five 1, 4, 6, 4, 1. The result is an elimination of all minor lobes and all nulls except the ones directly at the base of the tower and directly above the antenna.

A similar result is obtained if the amplitude is exponentially tapered from one end of the antenna to the other, as in the traveling-wave antenna.

Still more elaborate is a combination of power division and phasing to obtain specific desired pattern shaping (see under UHF Antennas).

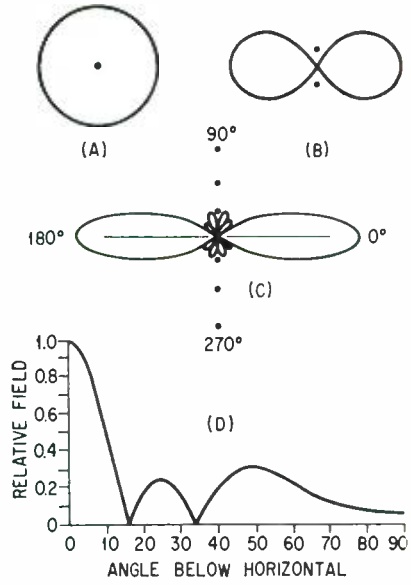


Fig. 34. Effect of stacking several point sources having equal currents and phase. (A) Vertical pattern of single source, (B) two sources, (C) six sources. Information given in (C) is shown in rectangular coordinate form in (D) for angles between horizontal (0°) and directly below the array (270°).

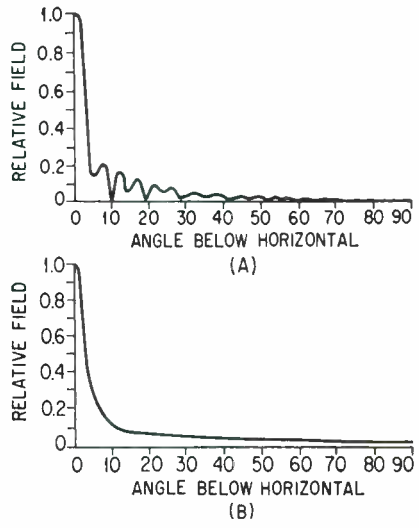


Fig. 35. (A) Vertical field pattern of antenna with a gain of 12 having twice as much power in the upper half as in the lower half. (B) Vertical field pattern of an antenna with many separate radiating elements with ideal phase and power distribution to obtain smooth pattern.

With the number of elements available in antennas having gains of 30 and upward, patterns have been obtained by these methods which are almost without a visible ripple (see Fig. 35B).

The filling of nulls, while highly desirable in cases where the area served would be otherwise affected, must be done at the expense of gain to some extent, since power is usually drawn from the main beam to furnish the filling signals. Proper pattern synthesis can, however, reduce this effect to a minimum, taking power instead from the portion of the pattern above the horizon, where it would otherwise serve no useful purpose.

Directionalizing the vertical pattern so as to direct the main lobe of energy at other than the horizontal direction is permitted by the Federal Communications Commission where it can be shown that the public can be more adequately served. Certain restrictions limit the type and amount of such directionalizing, however, namely:

1. The power radiated in the main lobe may not exceed that authorized for nondirectional operation for the particular area.
2. Power radiated in any direction above the horizontal may not exceed the power radiated in the horizontal after directionalizing.
3. Requirements for Class A and Class B coverage must still be met.

Directionalizing in the vertical planes is normally accomplished by variation in phasing among elements in the array. This may be a lumped effect, as when the lower half of an antenna is fed in such a way as to lag the upper half in phase, or it may be a smooth transition of progressive phasing throughout the length of the antenna. In either case, the net result is to tilt the main beam downward, so that it points to the horizon or below. Antennas on Mt. Wilson in California, serving the Los Angeles area, offer examples of this type of directionalizing to obtain maximum coverage of the area with the least loss of power over the ocean beyond.

Combinations of electrical and mechanical "tilt" are used when the antenna is on top of a plateau overlooking a city in which a strong signal is desired. When the electrical and mechanical tilt are made equal, the total tilt toward the city is double the electrical tilt alone, with no tilt in the opposite direction along the plateau.

In considering the formation of total patterns a word should perhaps be said on the effect of distance on this formation. With antennas having a length (or "aperture") of several wavelengths, there is a distance within which the shape of the pattern is found to vary. This occurs because the distance is so small that radiation from the separate elements comes to the receiving point at different angles from the source rather than along parallel paths. Movement changes the angles and the distances from the separate elements at an unequal rate, resulting in variations in the sums of the individual signals. The field within this region has not "stabilized," and calculations which assume parallel paths of the rays do not yield an accurate result. The region from the outer border of the near or "induction-field" zone to the point at which the rays become essentially parallel and the pattern stable is known as the Fresnel zone. Beyond this region the formed pattern takes the form investigated by Fraunhofer, and the region is known as the Fraunhofer zone. For practical purposes the distance of the boundary between the zones is

$$d = \frac{2a^2}{\lambda}$$

where a is the total aperture in wavelengths.

Gain

Directionalizing horizontal and vertical patterns has been discussed in previous sections. The object is to force the energy to radiate in directions in which it can be usefully employed. In television broadcasting, these directions involve all the region below a plane tangent to the earth's surface and passing through the antenna. The area with which we are concerned is from the base of the antenna out to points somewhat beyond the horizon. Power raidated above this region serves little useful purpose, and it is desirable to reduce it as much as possible.

To indicate the effectiveness of this directional process, the increase of signal intensity obtained thereby is related to the signal intensity which would be received from some standard reference antenna such as a half-wave dipole or an isotropic source having the same input power. The value of the ratio so obtained is called the "gain" of the antenna.

It should be noted that because of the fixed relationship between the shapes of the patterns of the two antennas commonly used for reference, a gain value as compared with a half-wave dipole can be converted to a corresponding value using an isotropic source as a base of comparison by use of a multiplying factor of 1.64.

An illustration of this in one plane only is given in Fig. 36. The circle contained the same area as the pattern being considered and represents the field pattern of an isotropic course with the same power input. The gain in the main lobe, ignoring losses, will be

$$G = \frac{E_A}{E_i}$$

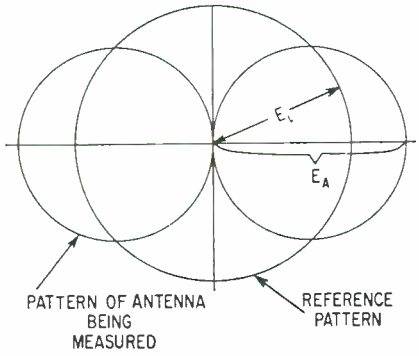


Fig. 36. Comparison of pattern of a measured antenna with circle of equal area to determine gain.

Impedance

Transmission-line theory tells us that maximum transfer of power takes place when a load terminating a line has the same impedance as the characteristic impedance of the line. Since the final load in a radiating system is space, it is desirable that the antenna match the impedance of space, or approximately 377 ohms, at the point of radiation.

The antenna therefore must transform 377 to that of the feed line.

The input impedance of a superturnstile antenna is about 150 ohms (both batwings together), of a helical antenna 100 ohms, of a resonant full wave slotted cylinder about 40 ohms, dipole is 73Ω.

A simple and effective method of matching for a narrow band of frequencies can be obtained by inserting between the impedances to be matched a quarter-wave section of line having a characteristic impedance equal to the geometric mean of the two impedances. That is,

$$Z_c \text{ (of transformer)} = \sqrt{Z_1 Z_2}$$

Since the length of the transformer is λ/4 for only one frequency, the bandwidth of the transformation is small. Matches over wider bandwidths can be obtained, however, by using several such transformers end to end.

Feed Systems

The feed system of a television broadcast antenna is commonly considered that portion of the transmission system having its input at the antenna terminal which is at the top of the vertical run of coaxial transmission line in the tower and its output at the radiating elements.

Most antenna gains in the manufacturers' literature take the losses of the feed system into account. Therefore, when system losses are calculated, the feed-system loss can be excluded.

Types

In the television broadcasting field, three types of feed systems are in wide use. They are the branching, standing-wave, and traveling-wave feed systems. Each meets a need peculiar to its own application. Frequencies vary from 54 to 806 MHz, power-handling-capacity requirements vary from 500 to 220,000 watts, gains vary from 0.5 to 60, and where pattern shapes vary between extreme limits, good economics dictates various types of feed system.

BRANCHING: This feed system progressive divides the power as shown in Fig. 37.

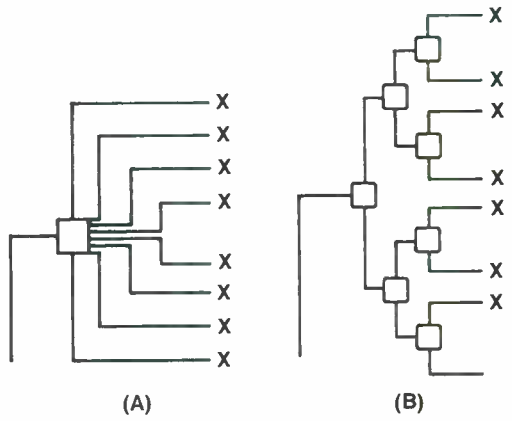
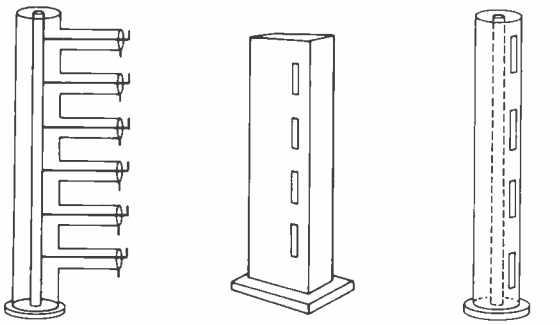


Fig. 37. Branching feed systems.

This feed system would be used when the radiators are individual elements each with their own terminal such a dipoles or panels. The system shown in Fig. 37A would have a narrower impedance bandwidth than Fig. 37B since for economy one 8-way power divider is used. The junction impedance is $Z_m/8$. If the element impedance is 50Ω, the power divider must transform 6.25Ω to 50Ω. The system shown in Fig. 37B uses only two way splitters. Although it has a broader bandwidth there are 7 power dividers with additional interconnect cable. Null fill and beam tilt in both of the above are accomplished by changing the length of the feed cable or in some applications by unequal power dividers.

A problem with either of the above is the presence of the feed line in the aperture of the lower elements. The feed lines will cause reradiation and distort the azimuth pattern. The branching feed system can be effectively used with these antennas that require a center support tower or mast.

STANDING WAVE FEED SYSTEMS: A transmission line either coax or waveguide can be shorted at the far end resulting in standing wave along the length of the line. If slots or coupling probes are appropriately sized and positioned energy can be coupled and a desired ampli-



COAX DIPOLE ARRAY | WAVEGUIDE SLOT ARRAY | COAX SLOT ARRAY

tude and phase distribution across the aperture can be obtained. This resonant array structure has a desirable feature: all coupling parameters are the same and equally spaced. Its disadvantage is a narrow bandwidth and can only be used at UHF frequencies.

TRAVELING WAVE: The traveling-wave feed system operates on the principle of a gradual attenuation (radiation) of the input signal as it progresses from the input along the aperture of the antenna. An application of this principle is the spiral antenna or slot antenna known as the traveling-wave antenna.

Fig. 38A shows the principle of this feed system using short rod radiators to illustrate the theory. A number of radiators per wavelength uniformly spaced are loosely coupled to a coaxial line. Because of the number of radiators and the relatively slight reflection due to each, the effect is essentially that of a uniform loading. The result is a uniformly attenuated traveling wave in the line. Since a traveling wave has a linear-phrase characteristic, the excitation of each successive radiator will be lagging from the previous one by an amount which depends on the spacing between the radiators and the velocity of propagation in the line. If the radiators are alike, their currents will have the same phase relationship as the excitation. Thus the radiating currents will be successively lagging, and repetition of phase occurs after every guide wavelength.

To obtain an omni-directional pattern the radiators, instead of being in line, can be moved around the periphery to form a "spiral" as shown in Fig. 38B. For a horizontal main beam the pitch of the spiral has to be equal to the guide wavelength in the transmission line. In this arrangement all the radiators in any one vertical plane on one side are in phase and the phase difference between radiators in different planes equals the azimuth angle difference between the planes; that is, the phase rotates around the periphery. The rotating phase produces a rotating field which, because of the relatively small amount by which the magnitude of current changes from layer to layer, produces an omni-directional pattern.

A disadvantage with the traveling wave antenna or non-resonant array is the energy not radiated at the end of the array must be absorbed. This is accomplished with a special absorbing section at the top which will radiate the energy in the same or cross polarization.

The traveling wave (non-resonant) antenna is more broadband than the standing (resonant) wave antenna. Many antennas use a combination of branching and either of the above.

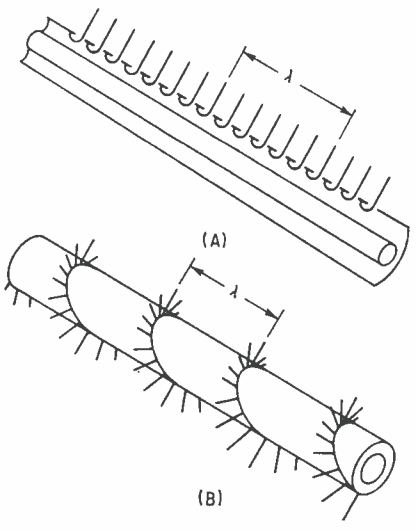


Fig. 38. Basic principles employed in the traveling-wave antenna feed system.

Bridge Diplexing

Antennas that use a single feed line must diplex the visual and aural signal together. Some antennas such as the turnstile/batwing can use either one or two lines. If separate antennas are used for visual and aural, two lines would be required.

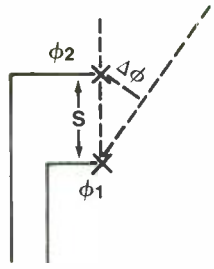
The bridge hybrid by virtue of its 3dB coupling properties will split the visual and aural signal between the N/S and E/W antennas.

With dual lines beam tilt can be affected by differential changes in the line length or propagation velocity. See Fig. 39.

Constant Impedance Notch Diplexers

Most antennas use a single feed line because of cost. Dual lines increase wind load on the tower. The cost of single large size lines for a tall tower can cost up to $250,000.

The most common diplexer used is the Constant Impedance Notch (CIN) Diplexer.



BEAM TILT = $\psi = \text{SIN}^{-1}\left(\frac{\Delta\phi}{S}\right)$

S = SPACING BETWEEN THE TWO ARRAY'S IN ELECTRICAL DEGREES

$\Delta\phi$ = PHASE CHANGE

$= \phi_2 d - \phi_1$

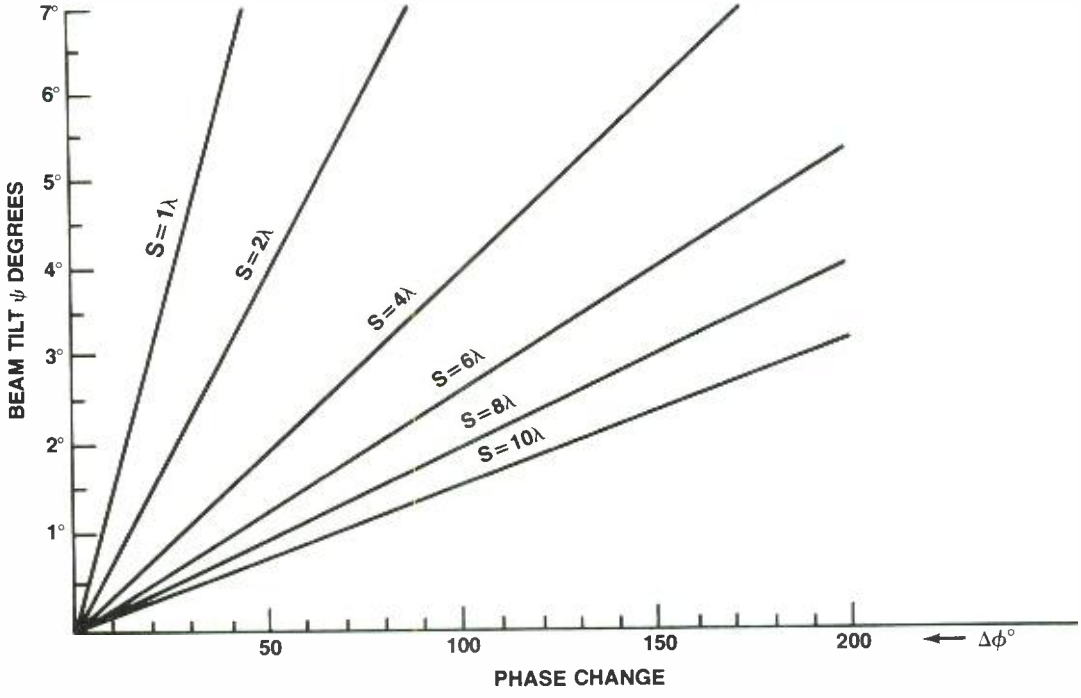
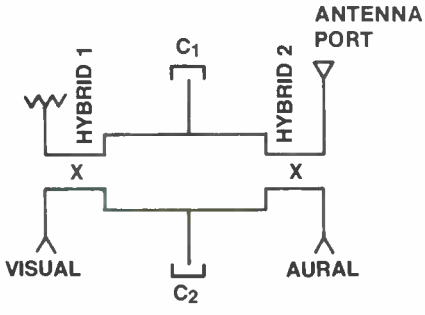


Fig. 39. Effect on beam tilt of differential phase change between elements of an array.

In the CIN type, the visual signal splits equally in the hybrid 1. The signal passes the cavity since they are tuned to resonate at the aural frequency. The signals are recombined in the second hybrid, and all the energy goes out the antenna port. The aural signal is split in hybrid 2, resonated in cavities C_1 and C_2, and reflected back toward hybrid 2. Because of the phase reversal, all the energy is coupled out the antenna port.



ATTENUATION @ +4.18 MHz	UHF (CH 5)			UHF (CH 64)		
	3 dB BW kHz	α dB	Q_L	3 dB BW kHz	α dB	Q_L
1 dB	400	.25	212	—	—	—
2 dB	500	.2	170	420	.9	1900
3 dB	600	.1	140	670	.4	1200
6 dB	—	—	—	1200	.2	650

Fig. 40. Diplexer cavity characteristics.

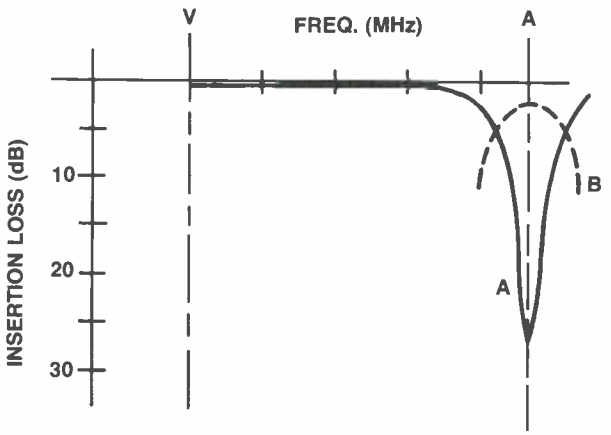


Fig. 41. System performance curve A would be the response between the visual and antenna port, and, curve B, the response between the aural and antenna port.

Since the cavities are tuned to the aural frequency (+4.5 MHz) and are very high Q resonant devices, the signal in the visual pass band (0 to 4.18 MHz) does not see the cavity reactance until the frequency approaches the resonant frequency of the cavity at 4.18 MHz. With non-MTS diplexers the cavity Q is adjusted so there is minimum loss at +4.5 MHz (aural carrier). The loss at +4.5 MHz is dependent on the ratio of Q loaded to Q unloaded.

Very high Q unloaded cavities are used. For VHF the cavities are usually re-entrant type. For UHF waveguide the cavities are either cylindrical or square operating in the TE_{11} mode.

The 3 dB bandwidth, insertion loss at resonance, and the cavity loaded Q are dependent on transmission loss at +4.18 MHz.

Typical performance would be as shown in Fig. 41. Curve A would be the response between the visual and antenna ports. Curve B would be the response between the aural and antenna port.

Insertion loss and group delay response characteristics of typical VHF diplexers are shown in Fig. 42.

MTS Diplexer

The diplexer used for mono-sound bandwidth is ±25 KHz. The bandwidth requirements for MTS (Multi Channel-Stereo Sound) should be ±200 KHz.

The bandwidth requirement for the MTS signal is shown below.

Signal	Base Band Freq.	Deviation	β	RF BW
Main	15 kHz	25 kHz	1.6	± 40 kHz
Stereo	48 kHz	50 kHz	1.04	± 90 kHz
SAP	90 kHz	15 kHz	0.16	±105 kHz
PRO	105 kHz	5 kHz	0.05	±112 kHz

The above assumes individual carriers—when multiple carriers are present a more complex situation exists and wider bandwidth may be required.

Ideally we would like the aural path to be transparent and not contribute any distortion. To accomplish this the bandwidth should be twice the RF band required.

The specifications for MTS diplexers due to the aforementioned restrictions would be, as follows:

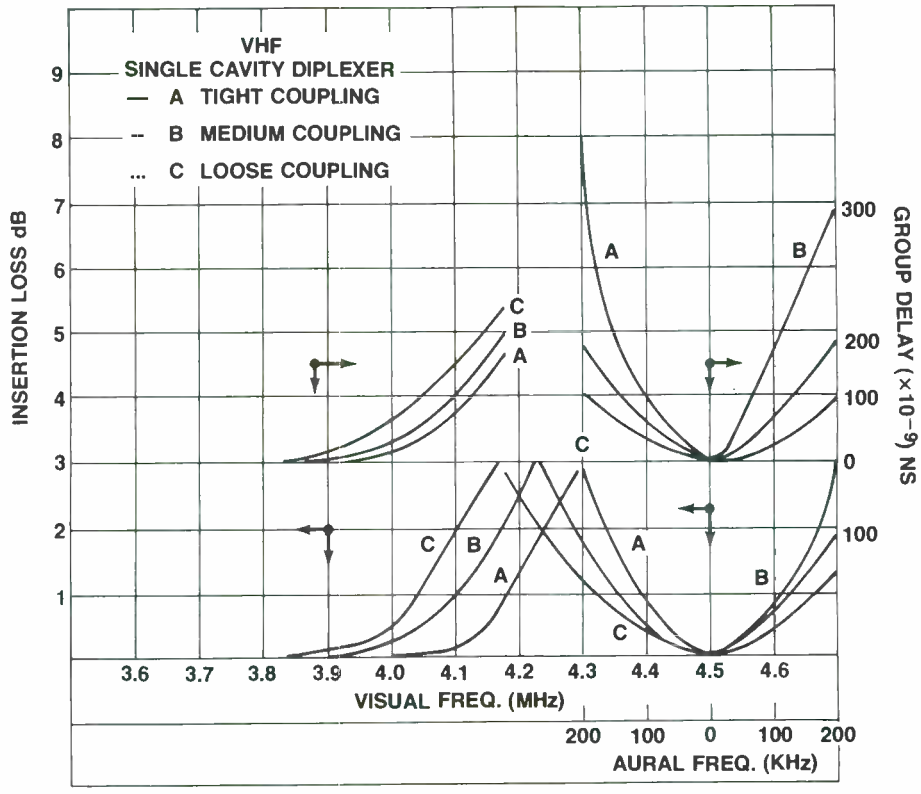


Fig. 42. Measured insertion loss and group delay response for some typical VHF diplexers.

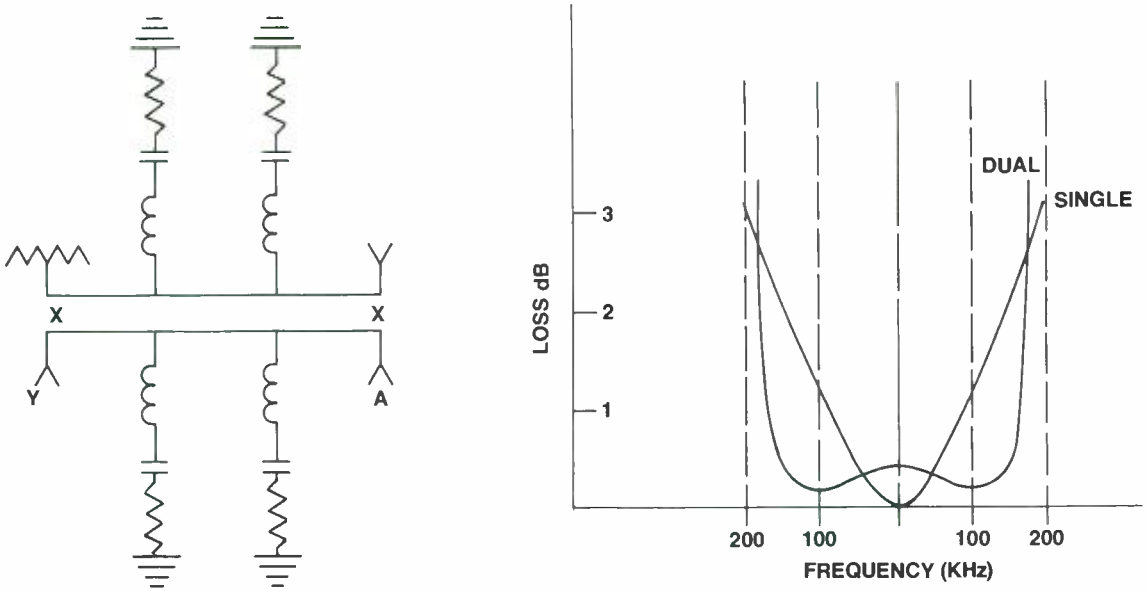


Fig. 43. Characteristics of cavity diplexers.

Bandwidth	±200 kHz
Insertion Loss	
Visual to Antenna @ +4.18 MHz	3 to 6 dB
Aural to Antenna @Aural Carrier	<0.4 dB
Over Aural Band	<3 dB
Amplitude Asymmetry	
Over Aural Band on	±0.2 dB
Group Delay Asymmetry	
Over Aural Band	<50 ns

MULTIPLE CAVITIES

To satisfy the wider bandwidth requirements some transmitter manufacturer's use lower Q cavities and pre-distort at the front end to lower the transmission loss and group delay.

It is also possible to increase the bandwidth without pre-distortion by using multiple cavities.

The advantages of using dual cavities are:

(1) Wider aural bandwidth with lower Q cavities.

(2) Lower insertion loss at the aural carrier.

(3) Lower Q will result in less sensitivity to detuning and less asymmetry.

(4) Steeper skirts in the vicinity of the +4.18 MHz will result in lower transmission loss in the visual pass band.

(5) Less group delay.

Multiple Antennas

In an area where two or more television stations are providing coverage, various advantages accrue to the broadcasters if they enter into what is referred to as a multiple-antenna installation. These advantages include reduced costs of individual tower and better reception, since all receiving antennas can be oriented toward the common source of radiation. Furthermore, the fact that tall towers can be located only in limited areas, owing to air-space restrictions, offers a further incentive for a common installation.

Systems Planning

Many times, the individual aspects of a television installation are meticulously scrutinized, and yet how they work together is given secondary consideration. An exhaustive check list would be almost endless. But a few important items are listed:

1. Detailed study of coverage taking terrain and competitive signals into account
2. Antenna location relative to population centers
3. Antenna vertical pattern design for best coverage
4. Antenna mounting methods
5. Layout of transmission lines
   a. In the vicinity of the tower top
   b. Main tower run
   c. Horizontal run to station
6. Transmitter and associated equipment locations
7. RF filter networks and load locations
8. Station layout
9. Emergency provisions
   a. Emergency antenna
   b. Emergency transmission lines
   c. Standby provisions
   d. RF switching features

A few of these will be discussed in more detail.

Propagation Study

In hilly terrain, especially at higher frequencies, shadow areas will occur which cannot be predicted from FCC curves.

Antenna Mounting Methods

Most antennas are flange mounted and manufacturers—either in their catalogues or upon request—will furnish mechanical and mounting data for their antennas. Standard mounting bolts are usually furnished with the antenna. If a special double plate design or other design is used in the tower top, the antenna manufacturer should be advised so that the proper bolts can be furnished. If a new antenna is substituted for an old one, an adaptor plate may have to be designed and furnished by the tower manufacturer.

Layout of Transmission Lines

In the vicinity of the tower top. Usually, it is desirable to avoid as many elbows in a system as possible. However, near the tower top, it has been found advisable to have from two to four elbows at the top of the vertical run in order to provide access to the system. It also provides a measure of mechanical flexibility, depending on the horizontal length of line between elbows. This flexibility is very desirable. The amount required is dependent on the movement, due to antenna sway, expected from the lines coming down from overhead.

Where complicated circuitry involving power-dividing Ts, transformers, phasing sections, and cut-over elbows (for an emergency feature) are used, considerable thought should be exercised in planning the hanger supports and line layout in cooperation with the tower designer.

Since mismatches at or near the antenna are the most potent source of echoes, any equipment in this area should be specially optimized to a VSWR value of 1.015 or lower.

Main tower run. Normally, in tower-transmission-line runs composed of 20 ft. sections or 12 foot waveguide sections, the top section is supported with two fixed hangers spaced 10 ft. apart and the sections below on spring hangers located on 10-ft. centers. Care must be applied at installation to locate the transmission-line sections so that the hanger springs do not cross over or rub against the transmission-line flanges. When the spring hangers are installed, they should be stretched according to the chart supplied by the manufacturer. If this is not done properly, it may require an excessive pull to separate the line in hot weather and the line may not be supported adequately by the springs in cold water. At the base of the tower, clearance must be provided to accommodate the differential expansion of the steel tower and copper transmission line.

Horizontal run to station—The length of the vertical run—which determines the amount of differential expansion between the copper transmission line and the steel tower and the length and size of the horizontal run—which determines the amount the line can bend without damage—must be taken into account. Transmission line manufacturers usually furnish curves or nomographs which provide this information. If the horizontal run is too short, it may be necessary to anchor the line near the transmitter rather than at the station wall which introduced complications. The length of the horizontal run required is an important item in the overall planning.

The horizontal run should have a protective shield from falling ice where such a condition exists.

RF Filter Networks and Load Location

The diplexer, filterplexer, and similar networks should be located with sufficient clearance so that easy access to all portions for servicing and cleaning is possible. While ceiling mounting conserves floor space, accessibility of all elements should still be a consideration. Since many of these devices use cavities which cannot be pressurized, a clean atmosphere is important, since dust accumulation inside the cavity will eventually cause trouble. Cavities should be arranged so that they are in the same ambient temperature. A difference in height when a high-temperature gradient exists or sun heating of one cavity may result in imbalance. Since hot air is less dense than cooler air, a hot location will reduce the safety factor for voltage breakdowns.

Emergency Provisions

It has always been the desire of the broadcaster to keep the ratio of nonscheduled "off-the-air" time to schedule "on-the-air" time as small as possible—preferably zero. An efficient maintenance procedure is excellent insurance. Emergency facilities can also help to keep this ratio small. A great variety of items are available. A word of caution—do not make the emergency provisions too complex and check their operation periodically.

Emergency Antenna. The simplest emergency-antenna provision is that found in the superturnstile, where, if one portion of the antenna fails, the power going to that half can be absorbed in a load while the other half continues to provide some measure of service with a figure-eight pattern. In various antenna designs the power is distributed to the upper and lower halves through combining networks mounted at the tower top. Simple change-over equipment permits the selection of either the upper or lower half for emergency service. Relatively low-gain antennas have been used mounted on the sides of towers and some inside towers for emergency use. It must be remembered that the tower will distort the antenna pattern.

Emergency transmission line. One extra provision of insurance can be provided by the installation of a spare transmission line so located that it can be inserted in place of the main run with a minimum of change-over connections at the input and output. It is wise to use gas stops at both ends and keep it pressurized.

Standby provisions. How much insurance one wishes to buy in the form of standby equipment can be based on the losses incurred by interrupted service. Where broadcasters have expanded their operations to higher power, the replaced transmitters have been retained for standby use. In some new installations broadcasters have obtained duplicate transmitters and worked them both on alternate schedules. In addition to this excellent emergency feature, a large portion of maintenance work can be scheduled during regular working hours. A standby Diesel generator set, duplicate microwave equipment, duplicate RF networks, and duplicate tower and antenna all contribute to potentially more reliable service.

RF switching features. Perhaps the most common emergency feature is the cutback circuit from transmitter amplifier to driver. This usually is performed quite rapidly using motor-driven RF switches. Where a standby system, including transmitter and RF networks, is available but a common antenna is used, motor-driven RF switches can be inserted to transfer the input of the antenna from the main transmitter to the standby system. Many elaborate cutover and cutback systems have been proposed.

In many switching applications the speed of the motor-driven switch is not required and a manual

transfer panel is adequate. To terminate various points in the RF system with a dummy load, it has been found convenient to install a single-pole double-throw switch to break open a line so that the load termination can be made by way of a separate multiposition manual-transfer panel.

TYPES OF ANTENNA

The types of antennas available can be grouped into the following categories:

(A) LoV, HiV, UHF
(B) Top or side mounted
(C) Horizontal Linear, or Circular Polarization

All of the above parameters affect the basic design concept.

The prime purpose of the tower is to support the antenna that has the required radiation characteristics in order to deliver a satisfactory signal to the viewer. Since it is desired to cover as large a viewing area as possible, tall towers are used. It is not uncommon for antennas to be mounted on 1,000 ft., 1500 ft., or 2000 ft. towers. These tall towers are guyed triangular towers with face dimensions 5, 7, 10 ft. The design and cost of the tower is dependent on the wind load (overturning moment) of the antenna.

The physical dimensions of the antenna are related to the channel (wavelength) and the gain requirements.

	λ	Length for maximum gain	Maximum gain
LoV	16 ft.	100 ft.	6
HiV	5 ft.	90 ft.	18
UHF	2 ft.	120 ft.	60

The ideal omni-directional antenna would be a smaller diameter*, infinitely stiff pole. The smallest cross section that can resonate would have to be $\lambda/2$.

At LoV frequencies the resonant element of 8 ft. is sufficiently large so that a support pole can be used in the center with the antenna mounted outside (batwing). On the other hand at UHF frequencies the resonant length of 1 ft. is so small that the resonant elements must be outside the support pole or the support pole itself must radiate like a slotted coax or waveguide array.

Ideally, omni-directional antennas should be fed from the bottom so there are no feed lines in the aperture of the antenna to distort the pattern. If feed lines are required for the upper elements, they should be on the inside. A conflicting requirement is that the diameter of the feed line be large enough to satisfy the power handling requirements, yet small enough not to create pattern distortion.

Omni-directional antennas are difficult to make directional, whereas directional antenna such as panels are difficult to make omni-directional. Some antennas require a large enough support structure so they can be side mounted. Only one antenna can be top mounted unless candelabras are used. This permits the use of multiple antenna installations. Some circular polarized antennas such as cross or basket dipoles require a large enough support structure so that they can be side mounted directly to the tower.

VHF—Horizontal Polarized

Superturnstile/Batwing

The first antenna developed for commercial service was the Superturnstile.[7] It consists of a central sectionalized steel pole upon which are mounted the individual radiators, or "batwing." These radiators are mounted in groups of four around the pole in north-south and east-west planes to form a "section," and the sections are stacked one above the other to obtain the desired gain. Fig. 45 illustrates this construction.

In this type, each of the radiators is fed separately by its own feed line to whose impedance that of the radiator is carefully matched. The feed lines, in turn, are combined at junction boxes, which perform the dual function of feeding power simultaneously to all feed lines and of transforming the combined impedance of these lines to that of the transmission line which carries the power from the base of the antenna. This latter function is achieved by the use of three-stage transformers immediately below the junction box.

At the base of the antenna at the tower top, a combining network is used when there are more than two junction boxes. These networks accomplish power division between portions of the antenna if so desired. These antennas are manufactured in various gains from 3 to 12 for Channels 2 to 6 and 6 to 18 for Channels 7 to 13.[8] They can also be obtained for various types of null fill[9] (see under Vertical Patterns) and wind loading. They have also been used in stack and candelabra

*Round shapes have less wind load and present a constant drag coefficient to the wind.

[7] R.W. Masters, The Superturnstile Antenna, *Broadcast News*, January, 1946.

[8] H.H. Westcott, New 50 KW VHF Superturnstiles, *Broadcast News*, May-June, 1953.

[9] Irl T. Newton, Jr., and H.H. Westcott, The New 12BH High Gain Antenna, *Broadcast News*, March-April, 1954.

	HORIZONTAL POLARIZATION		CIRCULAR POLARIZATION	
	MOUNTING			
	TOP	SIDE	TOP	SIDE
VHF-LOW BAND	BATWING	BUTTERFLY DIPOLE PANEL	SPIRAL CROSS DIPOLE	BASKET DIPOLE RING PANEL
VHF-HIGH BAND	HELIX TRAVELING WAVE	DIPOLE PANEL ZIG-ZAG	CROSS DIPOLE	RING PANEL
UHF	COAX SLOT	DIPOLE PANEL	SPIRAL	
	WAVEGUIDE SLOT	ZIG-ZAG	H/V SLOTS	
	LONG SLOT WITH RELECTORS		45° SLOTS	

Fig. 44. Commonly used types of televison transmitting antennas.

installations.[10] Antennas can be split by the use of additional junction boxes for emergency use and for other purposes. Elliptical azimuthal pattern can be obtained by changing the power division between the north-south and east-west planes. This antenna can also be used for two channels. A number of them are operating at Channels 4 and 5 and also in various combinations in the Channel 7–13 range. Copper feed lines instead of aluminum are available in areas where salt incrustation occurs but where there is insufficient rain to wash it off. Feed lines in both ¾-in. and ⅞-in. sizes are available depending upon the power rating required. Special antennas can be built for higher power ratings.

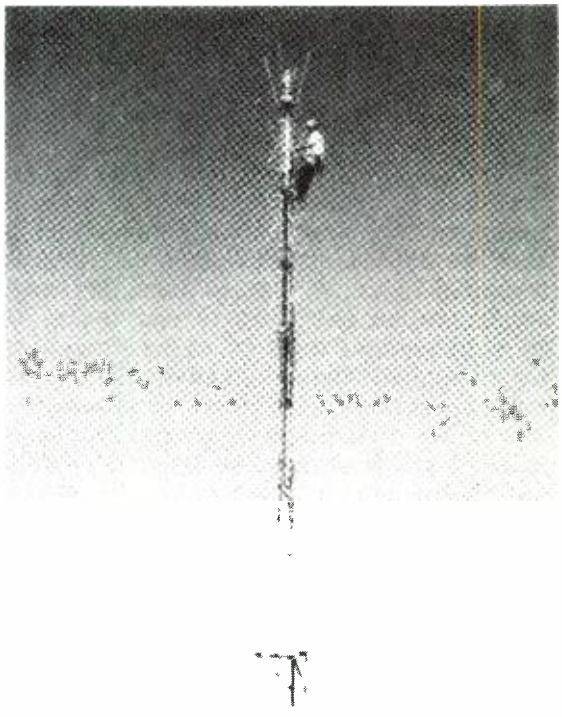


Fig. 45. Six Bay Channel 9 Superturnstile Antenna (Cetec Photograph).

Delta-Dipole Antenna

The delta-dipole antenna (see Fig. 47) consists of specially shaped, broadband dipoles mounted on reflecting panels. This special shape, which gives the dipole a delta-wing appearance, increases the effective area of the dipole arms, thereby increasing the bandwidth of the dipole without substantially increasing its resistance to wind pressure. Groups of dipoles and panels are arranged as required, both horizontally and vertically, so as to produce the desired horizontal and vertical radiation patterns.

This antenna lends itself to situations where it is necessary to mount an antenna around a tower or to stack several antennas one above the other. Because of its bandwidth, the delta-dipole also lends itself to situations where it is desirable to combine more than one channel in a single antenna. Both omni-directional and directional horizontal radiation patterns may be achieved by the proper choice of power division and element phasing between dipoles in any given layer.

Because the distance between the radiating element of the dipole and the reflecting panel is large (of the order of one-quarter wavelength), ice on

[10] Matti Siukola, Predicting Performance of Candelabra Antenna by Mathematical Analysis, *Broadcast News*, October, 1957. R.H. Wright and J.V. Hyde, the Hill-Tower Antenna System, *RCA Engr.*, August-September, 1955.

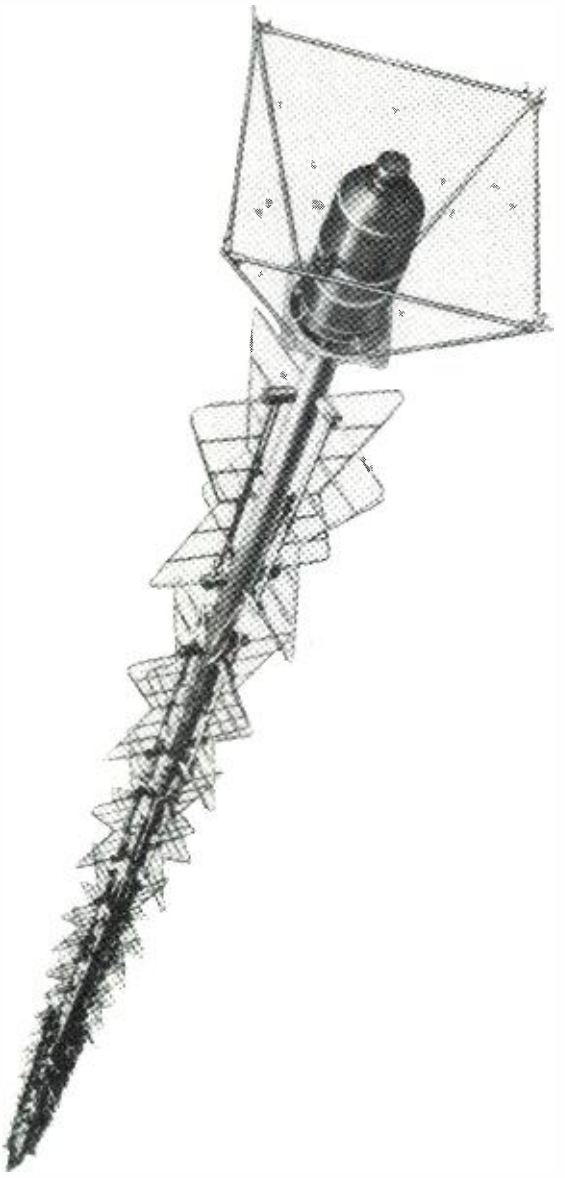


Fig. 46. RCA Superturnstile.

the reflecting panel has no significant effect on the operation of the antenna, and only parts of the dipole itself require deicing.

Traveling-wave Antenna

The traveling-wave antenna* embodies principles found in the operation of the superturnstile, the slot antenna, and the helix employs these principles in a manner which results in its being different from any of them.

In form the antenna is a coaxial line, with pairs of slots in the outer conductor spaced at intervals of a quarter wavelength throughout its length. Probes at the center of each slot distort the field within the line to place voltages across

*The majority of antennas in service are traveling-wave antennas.

Fig. 47. Delta Dipole Antenna (Alford Photograph).

the slots. These, in turn, drive currents on the periphery, setting up a radiated field. Attenuation of the signal by withdrawal of a portion of the power at each slot reduces it to a very low value at the upper end of the antenna. There, a special pair of slots, designed to match the line, extracts the remaining portion and radiates it.

Fig. 48 shows the physical shape of the antenna. The signal, entering through the input section (normally in the buried portion below the tower top), is progressively attenuated as it passes through the main aperture. The portion reaching the top is radiated from the "top-loading" section.

Fig. 49 shows cross sections of the antenna in the three main portions. It will be noted that the entire inner connector is supported by the base plate of the antenna and can be removed through this base.

Operation of the antenna can be better understood if the section of the aperture having pairs of slots are recognized as being, in effect, dipoles. Fig. 50 shows this similarity.

Successive pairs of slots are alternately in one plane and in another at 90° to it, so that the antenna can be simulated by stacked dipoles with a 90° angle between successive layers.

In a given plane, reversal of the direction of feed every half wavelength (by placing the probes on opposite side of the slots), together with the half-wave change in phase of the signal as it passes along the aperture through this distance, results in all the "dipoles" in that plane being fed in phase. The same action takes place in the other plane except that they are fed 90° out of phase with the first plane owing to their 90° displacement along the antenna. The result is shown in Fig. 51.

Each plane of dipoles radiates essentially a figure-eight pattern. Since the planes are fed in

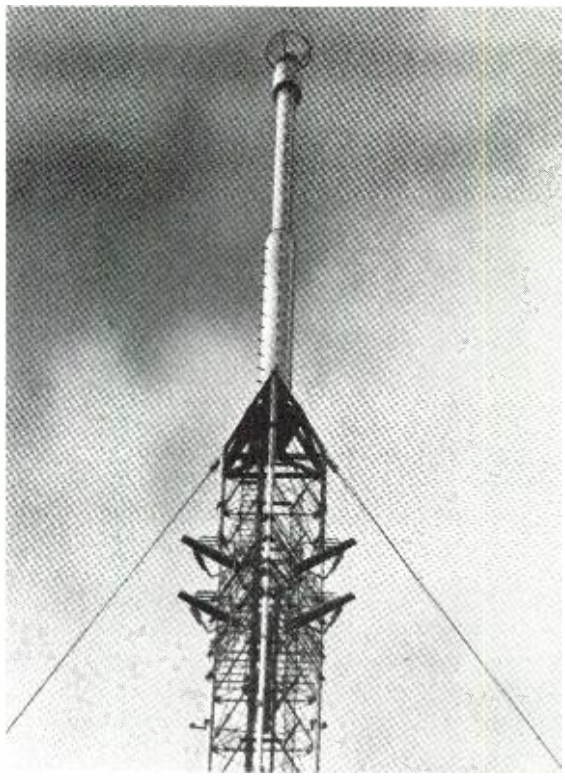


Fig. 48. The traveling-wave antenna-external appearance. (RCA Photograph)

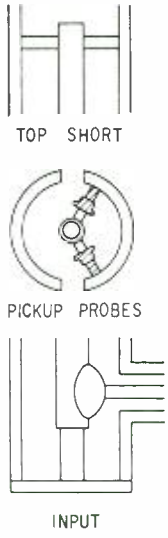


Fig. 49. Cross section of traveling-wave antenna at input, aperture, and top.

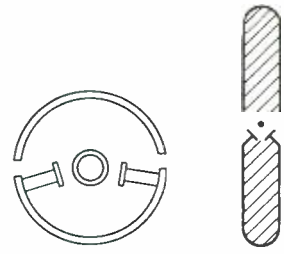


Fig. 50. Cross section of traveling-wave antenna at a slot pair level, showing resemblance to a dipole.

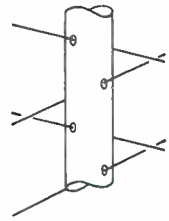


Fig. 51. Stack of half-wave dipoles which traveling-wave antenna resembles in operation.

quadrature, addition of the patterns results in a circular pattern, as outlined under Azimuthal Patterns. Because of the circular cross section and the lack of obstructing radiators, the resulting horizontal pattern is almost a true circle, varying from circular by only about 0.5 dB in a typical case.

As slot spacing is actually 90° only for a specific frequency in the channel, variation in frequency across the channel would be expected to result in a progressive lag or lead in the signal as radiated from successive slots inasmuch as the

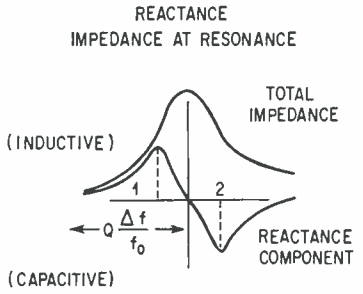


Fig. 52. Universal curve (high-Q parallel-resonant circuit).

spacing becomes greater than 90° for higher frequencies and less than 90° for lower frequencies. Correction for this effect would obviously be accomplished if, at each slot pair position, another circuit element were added which, with change of frequency, had the opposite effect on the phase.

Such an element is available in the form of a parallel-resonant circuit with resistive loading with its familiar reactance characteristics (Fig. 52). The resistive portion is the radiation resistance.

In the region between 1 and 2 (Fig. 52), increasing frequency results in a lower inductance (higher capacity) while decreasing frequency yields a more inductive circuit. If this circuit is placed across the transmission line at a slot position, the effect will be to cause the voltage at this position to lead the voltage at the preceding slot at high frequencies and to lag it at lower frequencies within the frequency range 1 to 2 (Fig. 52).

By adjustment of the values of inductance and capacity the slope of the response curve can be changed until a compensation is obtained over a considerable frequency range for the apparent change in line length between slot pairs due to frequency change.

The above circuit is obtained by shaping the slots to obtain the required value of inductance and capacity, the length of the slot and the shape of the end portions controlling for former and the width of the slot at the center of the latter.

A further control of the phase at each slot is obtained by the insertion between slots of compensating probes. By means of these, the phase can be made progressively more lagging from top to bottom, bringing about a downward tilt of the main beam if desired.

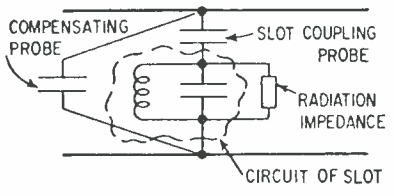


Fig. 53. Equivalent circuit of one slot pair section of traveling-wave antenna.

Omission of particular slot pairs is a method which has been used to obtain special effects such as reduction of signal at a particular angle in the vertical plane to "protect" areas where radiation is undesirable. Such a situation has arisen where important radio-frequency measurements on equipment being manufactured in a particular location would have been disturbed by the reception of television signals.

This equivalent circuit of each layer is shown in Fig. 53.

The coupling probes are all set at the same depth. As a result, the same percentage of power arriving at the slot location is picked up and radiated at each slot. The amount of power so radiated is therefore decreased exponentially from the bottom to the top of the antenna, giving the effect of a constantly changing power division except for the elimination of slots necessary for the insertion of flanges, and for the change at the top-loading slots. The result is a smooth vertical pattern without any nulls. The flanges and top loading cause a small ripple in the pattern, but the effect is slight. Fig. 54 shows a typical vertical pattern of a traveling-wave antenna with a gain of 12.

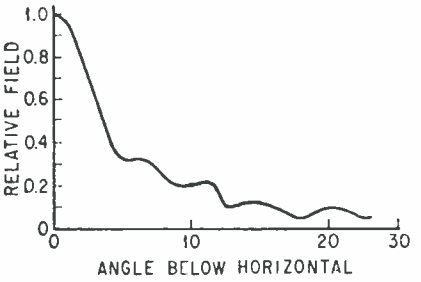


Fig. 54. Vertical field pattern of traveling-wave antenna with gain of 12.

Because the slots are a quarter wave apart, giving an impedance-compensating effect similar to that of insulators similarly spaced in a coaxial transmission line, and because the slots are only lightly coupled into the line, there is almost no reflected energy returning to the input of the antenna. The action of the top loading further reduces the chance of energy reflection. As a result the standing-wave ratio at the input is inherently low, and no input-matching transformers are required to broadband the impedance.

As the antenna is primarily a large-size transmission line, the power-handling capacity is very high.

The antenna tubing is of steel, hot-dip galvanized. The inner conductor is copper tubing. Hardware is of stainless steel with the exception of the

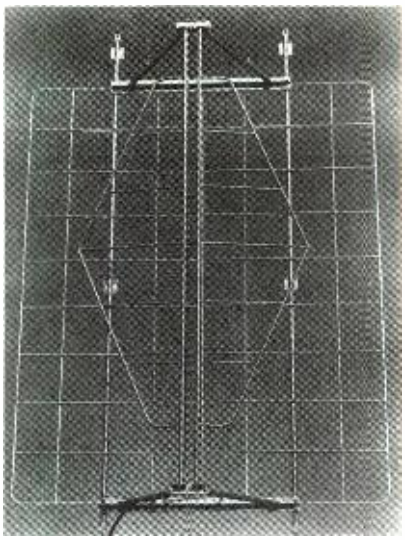


Fig. 55. RCA THP Panel Antenna, single panel.

probes, which are of aluminum treated to resist atmospheric corrosion. The slots are covered with polyethylene covers to keep out rain, snow and ice.

Fig 55. shows a portion of a traveling-wave antenna being lifted to the test platform for a check of the attenuation and phase velocity. This type of high support is used to ensure that no errors are introduced by reflection from the ground. The shape of the slots employed to obtain the electrical compensation referred to above is shown.

Rhombic/Butterfly Panels

The rhombic/butterfly panels are broad band dipoles mounted in front of a ground plane.

The individual panel tends to radiate $\cos^2(\theta)$ element pattern in both the azimuth and elevation plane. For omnidirectional pattern a four-sided tower would be required. The panel dimension would be $0.8\lambda \times 0.9\lambda$. For low VHF they are physically large enough to wrap around a relatively large tower.

The elements are mounted $\lambda/4$ in front of the panel and are fed via a balun. The wide band impedance can be further improved by feeding the panels in rotational phase. This will permit multiplexing several channels into one antenna. Directional azimuth pattern can be obtained by changing the power feed to the four panels.

VHF Antenna Circular Polarized

Fan-Vee Antenna

The Fan Vee is a top mounted circular polarized antenna. The antenna consists of horizontal and vertical radiating elements interleaved, spaced one wavelength and fed in phase quadrature. The horizontal polarized element is the standard batwing fed in rotational phase. The vertical polarized element is four back-to-back tilted dipoles in a V configuration. A branching type feed system is used for each radiator and the full array.

CPV Antenna

The CPV antenna is a circular polarized top mounted antenna consisting of three cross vee dipoles mounted at 120° intervals around a vertical mast. The dipoles are segmented by three vertical grids like a corner reflector used both for isolation and to shape the element for good circularity. The cross dipoles are fed in phase quad-

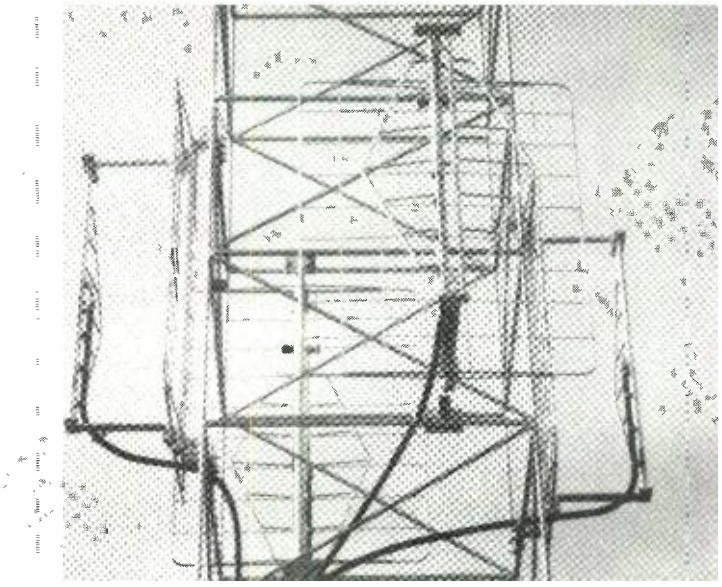


Fig. 56. RCA THP Panel Antenna, single layer on tower.

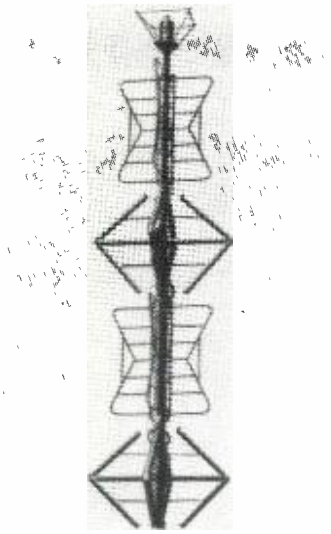


Fig. 57. The RCA Fan Vee top mounted circular polarized antenna.

rature radiate circular polarization from each element.

A branching feed system is used with the lines fed up the mast. Null fill and beam tilt is accomplished by changing the electrical length of the feed cables.

TDM Antenna

The TDM is a top mounted circular polarized antenna. The antenna consists of three slanted dipole (45°) mounted on a common phase center (support pole). Short studs are used to compensate for the distortion caused by the support pole. A branching feed system with a single feed point is used. Null fill and beam tilt is accomplished by adjusting the length (phase) of the feed cable.

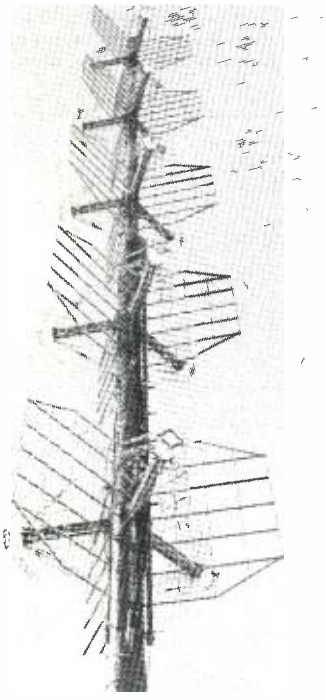


Fig. 58. The Harris CPV antenna with three cross vee dipoles mounted at 120° intervals around a vertical mast.

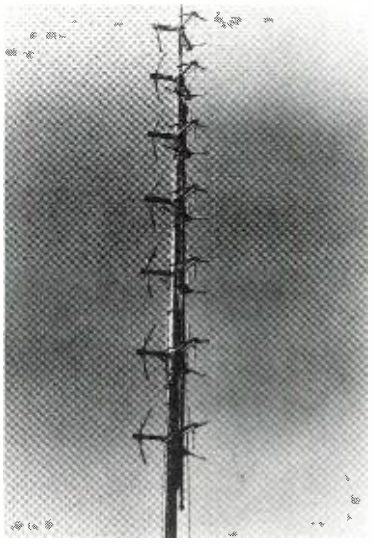


Fig. 59. RCA TDM antenna, top mounted.

Spiral Antenna

The spiral antenna is a top mounted antenna consisting of four spirals (coils) wound around a mast. The coils are fed in such a manner that in any vertical plane the combination of fields from the four coils radiate a circular polarized wave. The multiple coils are essentially a circular current sheet and have excellent omni-directional characteristics. Each section is fed from the bot-

Fig. 60. Three section spiral antenna, top mounted. (Cetec photograph)

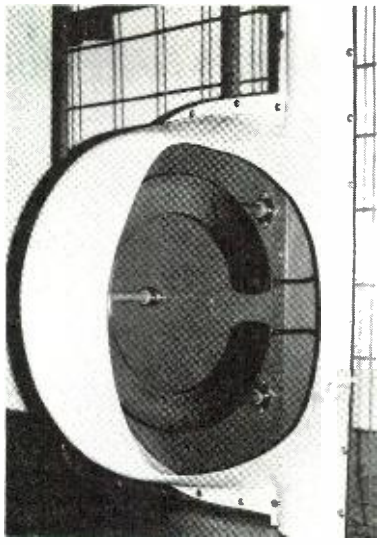


Fig. 61. Cetec ring panel.

tom as a traveling wave non-resonant antenna. Radiating coils are used as end loads at the top of each section to attenuate the remaining energy.

Ring Panel

The ring panel is designed for either top or side mounting tower. Each panel radiates a circular polarized wave. Four panels are wrapped around the tower to produce the desired azimuth radiation pattern. The panel is a traveling wave antenna of several panels with each ring spaced one wavelength.

Cloverleaf Panel

The TCP is a basket type panel radiating a circular polarized wave. It is designed to mount around the tower four panels per day. The radiating elements are fat cross dipoles in a cloverleaf configuration fed in phase quadrature for circular polarization. The panels are fed after power division in a branching line feed system.

Fig. 62. Cloverleaf panel. (RCA photograph)

Fig. 63. Harris TPC antenna.

The cavity backed radiator is a similar antenna and is generally built for 3-sided towers.

UHF Antenna
Linear Polarized

Pylon-UHF

The UHF Pylon Antenna is a coaxial transmission line with radiating slots in the outer conductor. The number of slots (per layer) around the circumference is determined by the horizontal pattern such as one slot for a skull-shaped pattern, two for a peanut-shaped pattern, three for a "trilobe" pattern and four or more slots, depending on outer cylinder diameter, for an omnidirectional pattern. The layers are located at one-wavelength spacings along the antenna with the number of layers determined by the vertical gain and pattern. The radiation parameters of phase and amplitude are determined basically by a combination of slot length and coupler bar diameter.

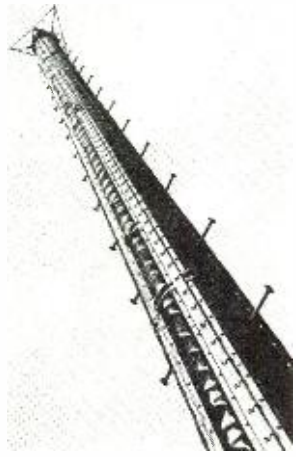


Fig. 64. RCA pylon antenna.

This feature allows discreet control of the illumination along the antenna aperture at every wavelength resulting in vertical pattern control and shaping. It also allows for maximum aperture efficiency and, in conjunction with the extremely low cross-polarized radiation component of a slot, produces the highest vertical gain for a given antenna length.

The antenna is a bottom fed travelling wave resonant antenna. Some antenna launch the energy into the coax line at the bottom. Others feed the coax radiating section at the center. The bottom coax feed is located inside the radiating coax feed.

The pylon uses radome covering the radiating slots only.

The Trasar antenna is similar except it is bottom-fed and is a non-resonant structure with a cylindrical pressurized radome covering the complete antenna.

Wave Star (Omni)

The wave star omni antenna is a bottom fed traveling wave waveguide slot antenna for top mounting. Since it is waveguide, no inner conductor is required. The signal propagates in the TM_{01} mode. The resultant current rings on the inside wall are interrupted by six rows of slots cut in the wall. The slots have radiome covers.

The wave star cardioid designed to radiate a cardioid pattern has a single row of slots. This is also a bottom fed traveling wave waveguide array only operating in the TE_{01} mode. This is built by exciting the fields in a rectangular waveguide and rolling the wave guide into a cylinder.

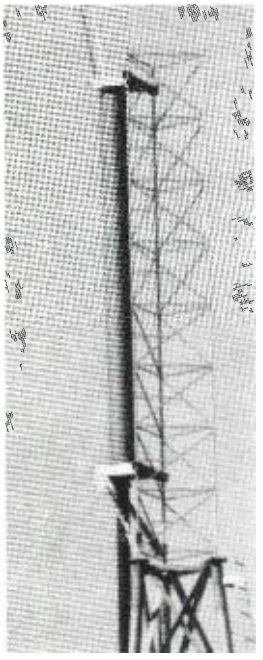


Fig. 65. Andrew Trasar antenna.

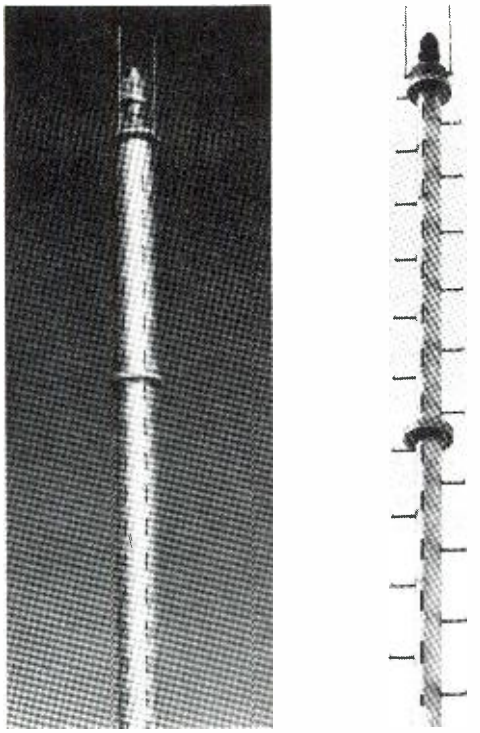


Fig. 66. Harris WaveStar antennas: left is omnidirectional; right is cardioid.

Zig-Zag

The zig-zag is a four-sided, linear polarized panel type antenna. The panels are mounted on a square mast with the complete antenna randome-covered. Each panel is traveling wave structure center fed. The panel length is approximately 8λ so the panels have to be stacked to provide the desired gain. The panels are fed in a branching manner.

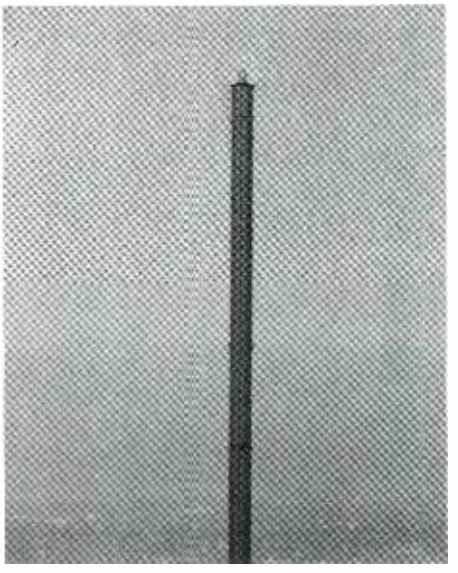


Fig. 67. Zigzag antenna. (Harris photograph)

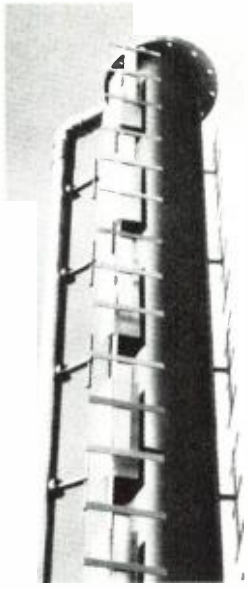


Fig. 68. Bogner slot-director antenna.

Slot-Director Antenna

The slot-director antenna is a linear polarized single row of slots with directors to fill in the low signal on the opposite side of the slots.

The slots are one wavelength long on one wavelength center line. Each is fed directly at the slot from a high power strip line feed. Each section is up to 8λ's and four sections are usually stacked for the desired gain.

Each section is branch fed while the slots in each section are fed in a traveling wave manner.

Pylon Circular Polarized

The traveling wave pylon is bottom fed for top mounting. Circular polarization is obtained by slots slanted left and right at approximately 45°. Successive slots are excited 90° in phase quadrature.

Trasar-Circular Polarized

The circular polarized Trasar antenna uses the same horizontally polarized slots as in the linear

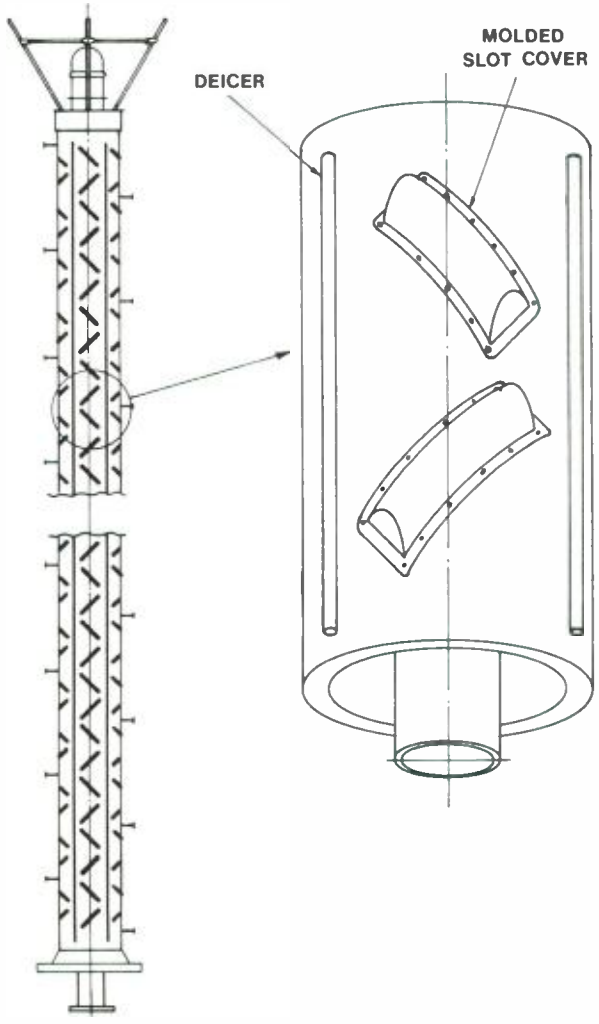


Fig. 69. RCA circular polarized pylon.

polarized antenna. The difference is that the end elements are vertically polarized slots radiating in phase quadrature.

ANTENNA TESTS

Before Shipment

Antennas are tested to meet the necessary requirements for impedance and patterns. This is usually done for all prototype antennas but not necessarily on the repeat antennas of the same type before shipment.

Custom antennas are usually impedance tested before shipment. As noted above under Antenna Specifications, the impedance is adjusted by the manufacturer to assure himself that the antenna will meet the 3 percent RF Pulse System Specification. These measurements are made under ideal conditions at the manufacturers plant to be certain that they are not influenced by other objects or the earth. From a Smith Chart Plot a judgment can be made by an experienced engineer to determine the percentage of reflection. It can also be determined by using a computer program as discussed under System Specifications.

Pattern Tests

The object of a pattern test is twofold. One of the objectives is to determine the gain as compared with a dipole for which perhaps a substitution method could be used. The other objective, however, is to determine the amount of radiation at all vertical and horizontal angles which have an influence on the coverage. Both objectives can be accomplished by taking patterns as described under Gain, since the gains can be determined by integrating all the power flow through an imaginary sphere.

To pattern-test the antenna it can be placed upon a wooden turntable which has a speed-controlled motor drive. From the reciprocity theorem it is possible to use the antenna as a receiving antenna as well as a transmitting antenna and obtain the same resulting pattern. This is done for the sake of convenience, since it permits the pattern recorder and the antenna under test to be located at the same point, thus allowing quick analysis of the results. The transmitting dipole is placed in the far field which is $2a^2/\lambda$ in feet where "a" is aperture of the antenna in feet and "λ" is the wavelength in feet. Since the antenna is in a horizontal position on the turntable, the transmitting dipole must be placed in a vertical plane. The received signal is amplified and the patterns drawn out on the recorder. To determine gain all of the energy going through an imaginary sphere with the antenna at its center must be accounted for. Usually the area of interest in a pattern lies from about 3° above the horizontal (+3°) to about 11° below the horizontal (−11°). However, for gain determination, all energy from +90° to −90° must be taken into account. Also since some types of antennas have a degree of unwanted vertically polarized energy in addition to the desired horizontally polarized energy, this factor must also be considered. Ohmic losses in the feed system must also be considered in determining the gain.

After Shipment, Before Erection

After the antenna is erected, the difficulties of working on it are greatly compounded. Since few engineers climb, the work must be done entirely by riggers, who do not have the background to do electrical testing. Furthermore, the time during which work can be performed on the antenna is very limited, owing to both scheduled operation and the weather, which frequently prevents work or even climbing. Hence, it is extremely important that tests be made on the ground before erection. Both electrical and mechanical tests should be made.

A thorough mechanical inspection should be made to see that the required components are in their proper places and securely fastened using the specified fastening materials. The pressurized portions should be pressure-tested for a long enough period to be certain that there are no slow leaks. A loss of over 2 lb. in 24 hr. should be investigated. The fit of major mechanical assemblies should be checked on the ground, since any discrepancies during the rigging operation can become major problems.

Depending upon the antenna type, it is generally good practice to make some electrical measurements on the ground before erection. The primary purpose is to determine if anything has happened to the antenna during the shipping and reassembly process. Hence, it is basically a qualitative test rather than a quantitative one since the ideal conditions at the vendors site may not be duplicated.

The test normally used is an impedance, or VSWR, measurement made every megacycle over the television channel. Closer measurements are not necessary since for a broad-band antenna the impedance varies quite slowly with frequency.

The practice would vary with VHF antennas and UHF antennas. It is usually necessary to be above the ground by about three wavelengths to obtain meaningful measurements. Hence at UHF, a height of 6 ft. is readily achievable. Often the antenna can be tested on the shipping trestles if they are close to this height and made of wood.

For VHF, the heights required above ground are about 15 feet from Channels 7-13, and 35 ft

or so for Channels 2-6. It is manifestly impractical to provide trestles of this height for field tests. Since these antennas often have branching type feed systems, other means can be used. In the case of a Superturnstile Antenna, the E-W system and the N-S system can be separately measured for impedance at a low height by placing the plane of the radiators under measurement in a vertical plane so that the maximum field is parallel to the ground rather than into it. Since the radiators are still quite close to the ground, ideal measuremnets cannot be obtained and a judgement factor is required. Final touch-up of the impedance after erection can usually be made by using a variable transformer.

It should be noted, however, that the further the variable transformer is from the point in the antenna where the best match across the band exists, the more difficult it is to lower the reflected pulse value. This point is at or near the radiators for a Superturnstile antenna or after the last transformer when broadbanding techniques are used.

The action of the variable transformer is to insert a negative bump to counteract the positive bump due to the remaining mismatch at the antenna. If the negative bump is displaced in time, by too long an intervening transmission line, it can only partially reduce the positive bump. If it is displaced more than a 100 ft. or about 0.1 microsecond it serves no purpose and only introduces a second unwanted bump.

The use of a variable transformer could in the case of a factory assembled antenna eliminate the ground test if a good mechanical inspection is made. For antennas of the Traveling Wave type for Channels 7-13, the construction is extremely rugged and a mechanical inspection only is required. This antenna has a built-in variable transformer.

When impedance measurements are made on antennas at the customer's site, there may be site factors involved such as fences, building materials, towers and other objects in the field. If the readings are of the same order, or if the Smith chart plot is about the same but displaced, the antenna can be considered to be in good condition. To make any corrections in such a situation could correct the antenna for the site conditions which would not be present at the tower top and hence worsen the impedance. As noted above the check is qualitative to discover possible damage during shipment and not a quantitative compliance test.

The remarks above are also applicable to panel type antennas. Where possible, it is always desirable to ship antennas in one piece even though special permits and shipping arrangements are necessary.

After Erection

Overall Test

See antenna specification considerations under "System Specification Performance after Erection."

Reflectometer Test

In order to protect antenna and line components properly it is mandatory that a reflectometer be used on both visual and aural transmitters to interrupt power when the VSWR exceeds a predetermined value. If an arc occurs in the antenna system, it usually loads the transmitter so that meter readings may fail to give a warning resulting in major damage to the antenna system.

Hence, before application of power to the antenna system the reflectometers should be checked for proper operation.

INSTALLATION

Advance Planning

The instruction book for a particular antenna usually contains considerable useful information which should be carefully read and followed. There are a number of items, however, common to most antennas which will be discussed.

Preinstallation Procedure

Usually it is advisable to have the manufacturer's serviceman take care of assembly supervision and testing. Some detailed procedure is outlined below.

Antenna Mounting Trestles

Most antennas are impedance-tested on the ground before erection. This is a wise precaution, since any corrective work, if required, is extremely difficult to accomplish once the antenna is at the tower top. The impedance of the antenna is affected by the ground, and trestles are required to obtain adequate clearance. Usually the furnishing of the trestles is the responsibility of the station, although the design is furnished by the manufacturer. They should be on hand when the antenna arrives located on reasonably level ground close enough to the base of the tower so that the antenna can be hoisted directly but far enough away so that assembly work can be done on the antenna without danger of falling objects from the tower while the riggers are working on it. The antenna should be placed so that the tower is not in the radiated field of the antenna, which would affect the impedance during the ground test. This will vary with the type of antenna and the frequency, and the manufacturer's recommendation should be obtained.

Precautions during Unpacking and Assembly

Antennas are usually heavy and appear to be quite rugged. Riggers used to handling heavy, rugged components often overestimate the ruggedness of the antenna, since many of the components can be damaged by rough handling.

If lifting lugs are not provided, the usual practice is to use cable wrapped around the mast with a 2 by 4 "corset" to protect feed lines, slot covers, or other components mounted on the pole. Special oak 2 by 4 lumber should be used for this purpose, since regular lumber crushes, causing damage to components.

Long poles can be given a "set" or internal components damaged if the pole is not properly supported over its entire length when it is lifted from a horizontal position. Strains can be set up under this condition which exceed the maximum wind-load conditions.

To ensure proper handling, a qualified rigger who has a reputation for making successful antenna installations is desirable. Some manufacturers will, if the customer desires, provide a "package" for the tower, line, antenna, and all installation work. This avoids split responsibilities and has many other advantages.

Checking Shipment

It is a wise precaution to check the shipment in detail against packing lists and see that no damage has occurred during shipment. The per diem rate for a crew of riggers is costly, and any delays due to missing or damaged parts will prove expensive. If there is any damage or shortage, the shipper should be notified immediately.

Pressurized Equipment

Equipment that is normally pressurized should be either stored in a dry place or kept under pressure during storage. The latter will also establish whether any leaks have resulted from shipment.

Assembly

Usually the manufacturer furnishes detailed instruction for the assembly which should be carefully followed.

Special tools are sometimes furnished or called for in certain operations which should be used.

Since the antenna is primarily a piece of electrical equipment, cleanliness at points of electrical contact is mandatory.

Electrolysis can occur if proper hardware specified is not used.

Forcing parts into place will usually result in future difficulties. The reason should be investigated.

All hardware should be right and secure.

If anything does not appear to be correct, consult the manufacturer rather than take a chance.

If any field welding is required, certified welders should be used, since failure could result in loss of human life.

Tests before Erection

It is extremely important that certain tests both mechanical and electrical be performed before the antenna is erected, since the difficulties of working on it after erection are greatly compounded. These tests are described under After Shipment, before Erection.

Erection

The erection procedure should be left in the hands of a qualified rigger. It is highly desirable to erect the antenna in one piece when this is feasible. If not, the rigger must be thoroughly instructed in the assembly procedure. The orientation of the antenna should be carefully established and well marked so that there is no misunderstanding.

In some antennas when transmission lines pass through the top plate of the tower, orientation is doubly important.

Vertical Alignment

For flange mounting triangularly shaped stainless steel shims should be used fitted between the mounting bolts. Vertical alignment is best checked with transits from several directions. Allowance must be made for wind deflection and sun benching. Accurate vertical alignment is especially important at UHF, where beamwidths are much narrower owing to the use of higher gain antennas.

Tests before Application of Power

These tests are important to ensure that the over-all requirements are met and also to be certain that the system is ready to receive power. Much damage can be done if there are loose or open connections or if the reflectometer circuits in the transmitter are not properly adjusted.

MAINTENANCE

Daily Operation

A drop in gas pressure* (in excess of 2 lb. in 24 hr.), an increase in VSWR as indicated by the reflectometer, or the appearance of an echo on the monitor indicates an unusual condition in the antenna system.

*A pressure-tight system is defined as less than a 20% change in 24 hours.

Gas leaks can usually be located by sectionalizing parts of the system. An increase in VSWR may denote icing or a change or failure of some part of the system. Power should be reduced when the VSWR rises, since the power-handling capability is inversely proportional to the standingwave ratio.

The appearance of an echo is a symptom of some change in the system which sould be investigated. New pulse techniques will make the location of faults much simpler.

Semiannually

A qualified rigger who is thoroughly familiar with all the aspects of the line and antenna should inspect the system. He should inspect for signs of corrosion, loose clamps or hardware, condition of slot covers, need for paint, physical damage, etc., as the particular antenna requires.

In superturnstile antennas it is advisable to take resistance readings between the inner and outer conductor for each side of the line. Any significant change from the initial readings should be investigated.

As a general guideline, no work should be performed on an antenna while power is on. In the case of a multiple antenna system where antennas are at the same level, the power should be off for all antennas on the platform.

RF fields from UHF antennas are particularly dangerous for two reasons: due to the shorter wavelength, local heating in the body is more likely to occur without an awareness that it is happening and could have serious results. Also, since a maximum power of five megawatts can be radiated, UHF stations are now approaching this value which is 16 times as high as for the Channel 7-13 range, and 50 times as high as for the Channel 2-6 range.

2.7

The Measurement of FM and TV Field Strengths (54 MHz-806 MHz)

Howard T. Head
Joseph W. Stielper
A. D. Ring & Associates
Washington, DC

MEASUREMENT OBJECTIVES

Television and FM broadcast field strengths may be measured to accomplish several objectives. These include: (1) Determination of measured coverage contours instead of relying only on predictions of coverage; (2) Evaluation of the performance of transmitting systems; (3) Measurement of spurious emission; (4) Special studies including propagation studies to evaluate the effect of factors such as terrain and vegetation on field strength. Special studies that require field strength measurements are also used for purposes such as interference and allocations.

Before the start of measurements, a plan should be designed considering the objectives of the field strength survey. For example, the constraints imposed by a survey to determine coverage of a station are different and generally less restrictive than those imposed by propagation studies. Design of a program to evaluate the performance of transmitting systems is likely to be the most difficult and require even more careful planning than programs for other purposes. Suggestions for designing measurement programs for each of the above objectives are presented in the following sections, as well as a discussion of the techniques of actual field strength measurement.

NOTE: Superscript numbers refer to Footnotes and References at end of the chapter.

There are several basic considerations, affecting all types of measurement programs, that should be addressed. These include the choice of antenna height for the measurements and allowance for factors such as weather that are beyond the control of the engineer.

The FCC Rules require measurements using a 9 meter (30 foot) receiving antenna height. This height should be used unless there are very good reasons for using another height. The bulk of reliable data were taken at 30 feet and the broadcast coverage contours are based upon the 9 meter (30 foot) height. Thus, a 9 meter (30 foot) receiving antenna height must be used for filing with the FCC, for direct coverage measurement or for direct comparison with other data. Use of a 9 meter (30 foot) high antenna raises several practical problems including safety. These are discussed in a later section.

Field strength varies with time and location. The variations are caused by factors such as terrain, man made structures, vegetation and weather. The effect of each of these on the measurements should be considered when designing the program. Except for the unusual case of measurements designed to evaluate time variation factors, the effect of weather or climate on measurements should be minimized. Variations of field strength with time are generally greatest near or just beyond the radio horizon. A more detailed discussion of this problem is included in a later section.

Measurement of Coverage

The coverage of a broadcasting station and the technical quality of the service provided are determined by the received signal and field strengths. Presently available methods of estimating field strengths within the service ranges of FM and television stations are only approximate, and even the best methods of calculating field strengths often fail to take into account variations due to important local conditions. For operating stations the best determination of station coverage is provided by properly made field strength measurements.

This section describes measurement programs for measuring field strengths to determine coverage of FM and television broadcasting stations.

The quality of service is related to field strength by considerations of receiver sensitivity and noise figure, receiving antenna gain and transmission-line loss, and tolerable signal-to-noise ratios. The required fields vary with the class of service and frequency assignment. Table I lists the frequencies employed by television and FM broadcast stations. Interfering signals from other transmitters on the same or adjacent channels may limit service to higher values of field strength.

Table II lists values of median field strength required for various grades of FM and television service in the absence of interfering signals as established by the Federal Communications Commission's Technical Standards.[1] There are also included revised estimates of the fields required in the television bands to provide acceptable grades of service based on the practical experience of operating stations and the findings of the Television Allocations Study Organization (TASO).[2] These latter have not as of the present date (Sept. 1, 1984) been officially adopted by the Commission. A number of changes in the definition of television coverage grades based upon the TASO studies and other data have been proposed from time to time since the adoption of the present definitions. None of these proposed changes have been adopted. A review of the rationale for the VHF contour definitions and some potential revisions is presented in the FCC Report FCC/OCE RS 77-01.[3]

Service is defined in Table II in terms of the median field with respect to both location and time, at a receiving antenna at a height of 9 meter (30 feet) above ground. Thus, field strength measurements to be filed with the FCC must be taken using a 9 meter (30 foot) receiving antenna height. In these frequency bands, field strength usually varies appreciably with antenna height, generally tending to increase with increasing antenna height. However, the variation in field with height may not follow simple laws, as discussed more fully in subsequent paragraphs.

It may not be necessary or even desirable to employ a 9 meter (30 foot) antenna height for measurements that will not be filed with the FCC. For example, if comparative coverage of several stations is desired and receiving antenna heights in the area are less than 30 feet, it may be appropriate to use a lower height. Measurements taken at a lower height may be, if necessary, adjusted to reflect the standard 9 meter (30 foot) height. Because of the uncertainty of the magnitude of the adjustment, the adjusted results are ordinarily less precise than measurements taken at 9 meters (30 feet). Adjustment factors are discussed in subsequent sections.

The presence of trees, buildings, and terrain irregularities[4-9] often results in considerable variation in field strength from one location to another, even within relatively small areas. The variation in field strength with location must be taken into account in measuring field strength as well as in specifying service. Service is usually defined in

TABLE I

Frequencies Employed for FM and Television Broadcasting

Service	Frequencies, MHz	Channel Nos.	Channel Bandwidth
TV	54-72	2-4	6 MHz
TV	76-88	5-6	6 MHz
FM	87.9-108	200-300	200 kHz
TV	174-216	7-13	6 MHz
TV	470-806	14-69	6 MHz

TABLE II

Median Field Strengths Required for Various Grades of Service in the Absence of Interfering Signals

FM Broadcasting (All Channels)

Grade of Service	μv/m	dBu[a]
Principal City	3,160	70
Urban	1,000	60

Television Broadcasting (FCC Technical Standards)

Gr. of Service	Ch. 2-6		Ch. 7-13		Ch. 14-83	
	μv/m	dBu	μv/m	dBu	μv/m	dBu
Principal City	5,000	74	7,000	77	10,000	80
Grade A	2,500	68	3,500	71	5,000	74
Grade B	225	47	650	56	1,600	64
(Based on TASO Data)						
Primary	250	48	1,400	63	7,500	75
Secondary	50	34	200	46	630	56
Fringe	20	26	55	35	180	45

[a]This abbreviation was coined by the FCC for television service and signifies the field strength in decibels above 1 μv/m. 0 dBu = 1 μv/m.

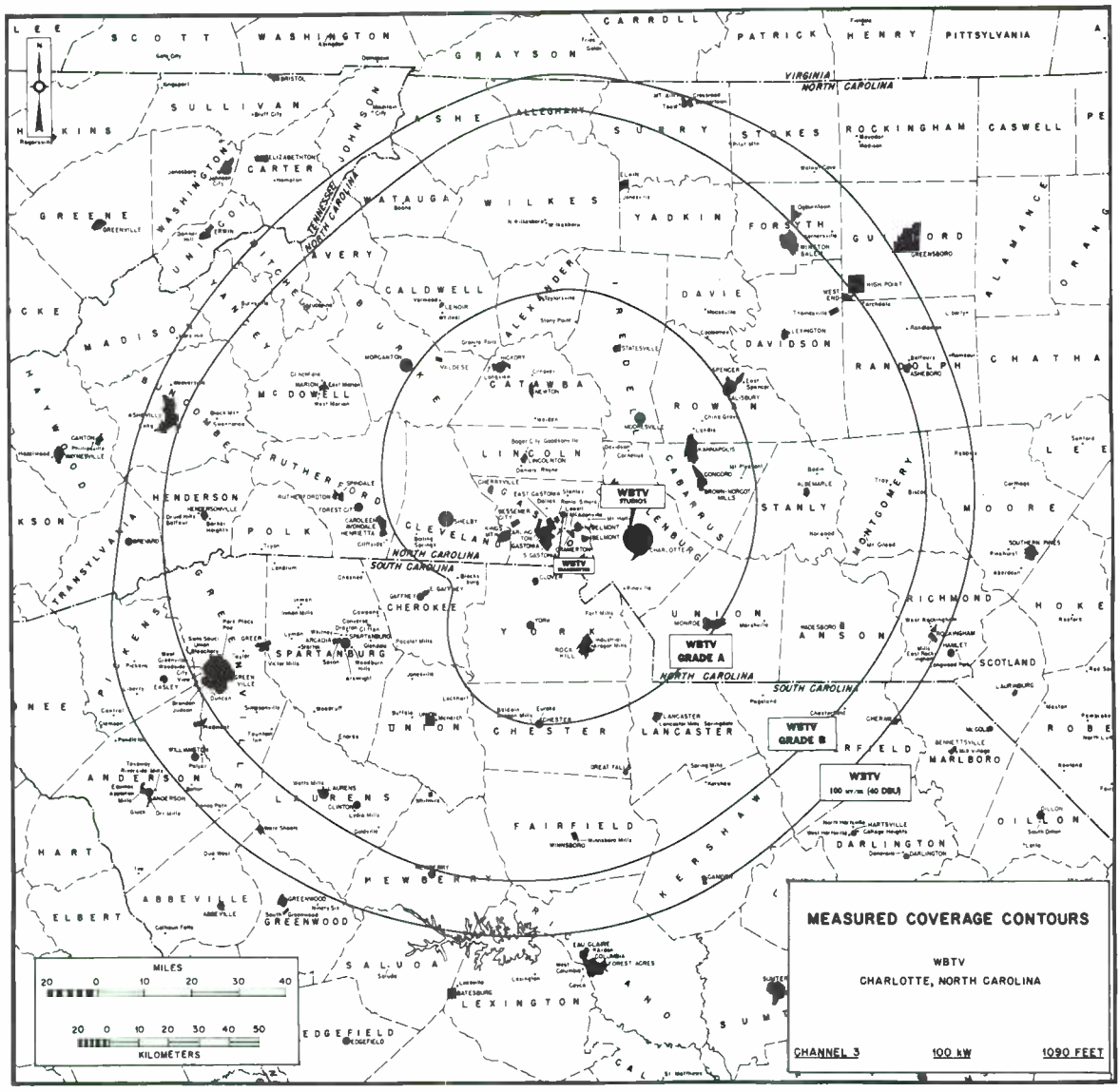


Fig. 1. Map showing measured service contours for an operating television station. (Courtesy of Jefferson-Pilot Broadcasting Company)

terms of the median value of field strength, which is the value exceeded for at least 50 percent of the time at the best 50 percent of the receiving locations.

The results of field strength coverage surveys are customarily presented as contour maps, showing lines of constant median field strength which represent the outer limits of various grades of service. A typical map of measured television station coverage is shown in Fig. 1. Methods of preparing contour maps are described in detail under the heading "Analysis of Measurements to Depict Coverage".

Much of the present knowledge of wave propagation in these frequency bands has been derived from field-strength-coverage surveys on operational FM and television stations. The information gained from these commercial coverage surveys has added to the body of scientific knowledge, but field-strength measurement surveys employing special techniques are often needed to supply data for special problems. Examples of such special techniques are discussed under other headings in this article.

The measurement program to determine coverage may be laid out according to the radial route method of the FCC Rules as described for propagation studies. Unless the results will be filed with the FCC, there is no need to maintain the precision required by the FCC. The precision required by the FCC Rules is primarily intended to insure statistical randomness for propagation studies and to assure that the propagation path is a true radial. For "in house" coverage studies there is general-

ly no need for the measurement location to be "exactly" on a true radial route at random 2 mile increments as required by the FCC Rules. Since many FM and TV transmitting sites are located near the center of cities it is often convenient to take measurements along more or less radial roads. Selection of measurement location need not be random but may be influenced by population density or the desire to obtain data in particular areas.

Sections 73.314(c) and 73.686(c) of the FCC Rules describe the procedures for the measurement of service to specific communities for FM and TV stations, respectively. These rules outline a measurement pattern that is in the form of a rectangular geographic grid overlying a map of the community. The grid must encompass the boundaries of the community. Measurements are made at the intersecting points on the grid.

The number of measurement points must be at least 15 or 0.1 $\sqrt{P}$ (whichever is greater) where P is the population of the community in thousands. Additional requirements describing documentation and calibration are contained in the rules.

The rules also contain a statistical procedure to analyze field strength. This method fits the measurement data to a normal distribution and yields the median or average field strength in a community. This result is not completely compatible with other FCC Rules. The principal city coverage rule for example, is based upon the determination of the location of coverage contours. This difficulty can be eliminated by using a grid that is not truly rectangular but consists of radials and perpendicular arcs. This plan permits both radial and grid analysis. Since the resulting grid is not perfectly rectangular, use of this plan should be cleared with appropriate FCC personnel before undertaking measurements when the results will be filed with the Commission.

Transmitting System Evaluation

Field strength measurements are occasionaly used to assess the performance of a station's transmitting system, particularly the operation of the transmitting antenna. The difficulty in this case is that of separating the effect of propagation factors from the effect of the transmission system. Comparisons of measured data with standard propagation curves such as the FCC Rules curves or smooth earth curves must be used with caution. The standard deviation of measured data used to draw the FCC curves compared with the curves is 7.7 dB at low VHF, 6.8 dB at high VHF, and 9.3 dB at UHF after adjustment for terrain[10]. Even in smooth terrain field strength is affected by other factors such as trees, buildings and atmospheric variations.

In hilly terrain, the effect of clutter, terrain and atmospheric variations can be minimized by selecting sites near the transmitting antenna to minimize atmospheric effects and where ray path clearance over all obstacles obtains. This clearance should be at least 0.6 Fresnel zone. The radius of a full Fresnel zone is given by:

$$H_o = 2280 \sqrt{\frac{d_1 \, d_2}{f(d_1 + d_2)}} \qquad [1]$$

Where: H_o = Fresnel zone radius in feet
d_1 = distance from transmitting antenna to obstacle in miles
d_2 = distance from receiving antenna to obstacle in miles
f = transmitting frequency in MHz

Application of this criterion is illustrated by Fig. 2.

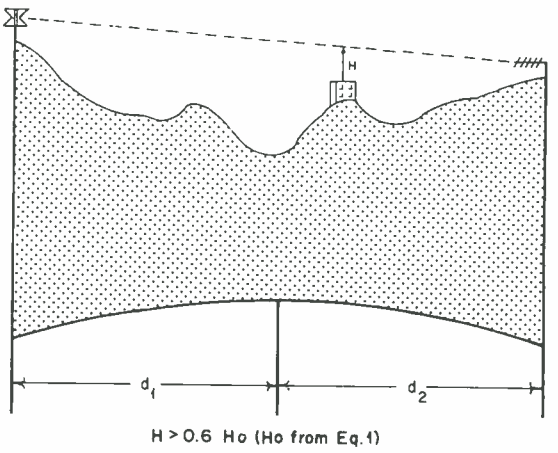


Fig. 2. Illustration of required ray clearance to avoid obstacle loss.

Even if such ray clearance over all obstacles can be obtained, reflections from terrain may often modify field strength. Allowance for reflections can only be achieved by taking measurements at a large number of locations to "average out" reflection effects.

Field strength measurements intended to evaluate system performance are sometimes taken in a helicopter in an attempt to reduce terrain effects. However, there are several problems associated with helicopter measurements, including: 1) Determination of the actual location of the helicopter relative to the transmitting system under test, 2) constraints on the design imposed by the helicopter's performance, 3) mounting of the receiving antenna on the helicopter to minimize the effect of the helicopter on receiving antenna pattern without creating a hazard, 4) uncertainties, such as actual path loss, that limit the accuracy of the measurement of absolute gain of the transmitting system under test.

PROPAGATION AND OTHER SPECIAL STUDIES

Sections 73.314 and 73.686 of the FCC Rules of the FCC describes the procedures to be employed for field strength measurements for propagation studies. This procedure is basically the technique developed by TASO. The actual field strength measurement procedure is discussed later in this article. The FCC procedure is intended primarily to yield data that may be analyzed to study the effect of terrain and other local influences on field strength. Measurement programs intended for other purposes may require substantially different plans. For example, measurements primarily intended to determine the effects of "clutter" such as trees and buildings should be taken if possible, in smooth terrain to eliminate the effect of terrain.

Measured field strength for propagation studies may be compared to calculated field strength for a number of propagation models.[10-13].

Measurement programs have been conducted to evaluate field strength time variation factors. In this case field strength measurements are recorded at fixed locations and over a period of time.

Field strength measurements may be an integral part of special field tests particularly with regard to interference allocations and changes in FM or TV operation. Examples of such field tests include those on VHF/TV Land Mobile channel sharing, tests relating to the problem of educational FM interference to Channel 6 and on circular polarization for television. Detailed discussion of special projects is beyond the scope of this article; however, the basic techniques of field strength measurement discussed herein are valid for special programs. In addition, many of the topics discussed in planning coverage, transmission equipment evaluation and pure propagation tests are appropriate for use in special tests.

Measurement of Spurious Emission

It is occasionally necessary to measure spurious radiated field strength from FM and TV broadcast facilities to show compliance with FCC cabinet radiation rules after installation. Requirements of the level of spurious signals relative to carrier level is specified in Sections 73.317 and 73.687 of the FCC Rules for FM and TV transmitting systems respectively. Such field strength measurements are nominally regulated by Section 2.993 of the Commission's Rules.

This section is quite vague and it is recommended that the person intending to take measurements determine acceptable procedures from FCC Laboratory personnel before undertaking the measurements.

BASIC EQUIPMENT PRINCIPLES

Field strengths in the VHF and UHF bands (30 to 3,000 MHz) are ordinarily measured by determining the voltage which the field induces in a half-wave dipole. The basic relationships can be expressed in several forms. The power transferred between two half-wave dipoles in free space separated by a distance, d, is given by

$$\frac{P_r}{P_t} = \frac{1.64\lambda^2}{4\pi d} \quad [2]$$

Where: P_r = receiver power
P_t = transmitted power
λ = wavelength in same units as d

In terms of the field at the receiving dipole, the power delivered to a matched load by a half-wave dipole in a field of E volts/m is

$$P_r = (0.0186E\lambda)^2 \text{ watts} \quad [3a]$$

where λ is expressed in meters.

Or alternately in dB relative to one Watt (dBW)

$$P_r = F - 20\log f - 105.1 \quad [3b]$$

where f is the frequency in MHz and the field strength F is in dBu.

For a resistive load of R ohms, the voltage V developed across a matched load by a dipole in a field E is

$$V = \frac{E\lambda\sqrt{R}}{53.7} \quad [4]$$

The fundamental problem presented, therefore, is that of measuring the developed RF voltage by a practical instrument of acceptable accuracy.

The voltage measuring device is ordinarily separated from the antenna by a length of cable. The cable may introduce losses, and any impedance mismatch must be sufficiently small that calibration errors are not introduced by differences between the antenna and cable impedance and the internal impedance of the calibrating oscillator.

The following paragraphs describe the basic components used for field strength measurement using the standard FCC methods. The system described is the conventional system using chart recorders and manual analysis of recorded data. Digital sampling, recording and analysis techniques may be used to replace, at least in part, manual techniques. At this time an engineer conducting field strength measurements is most likely to use conventional equipment. Therefore, the

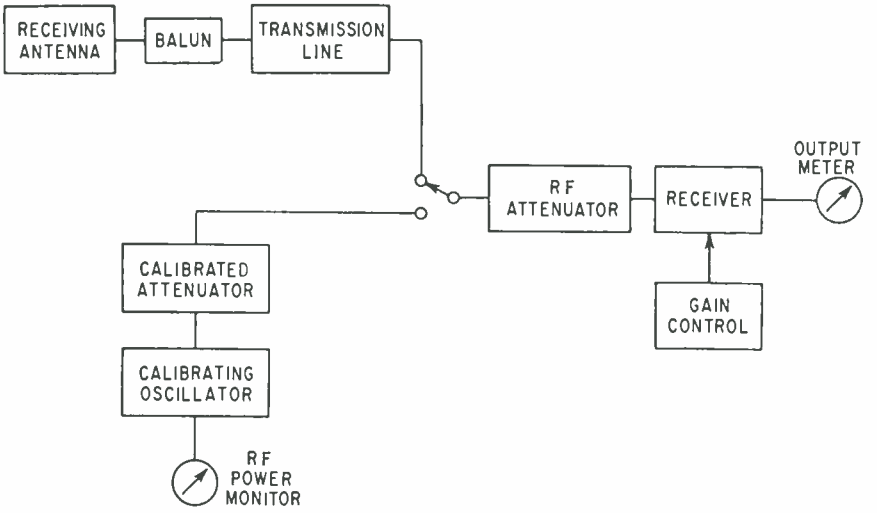


Fig. 3. Block diagram of practical field-strength meter.

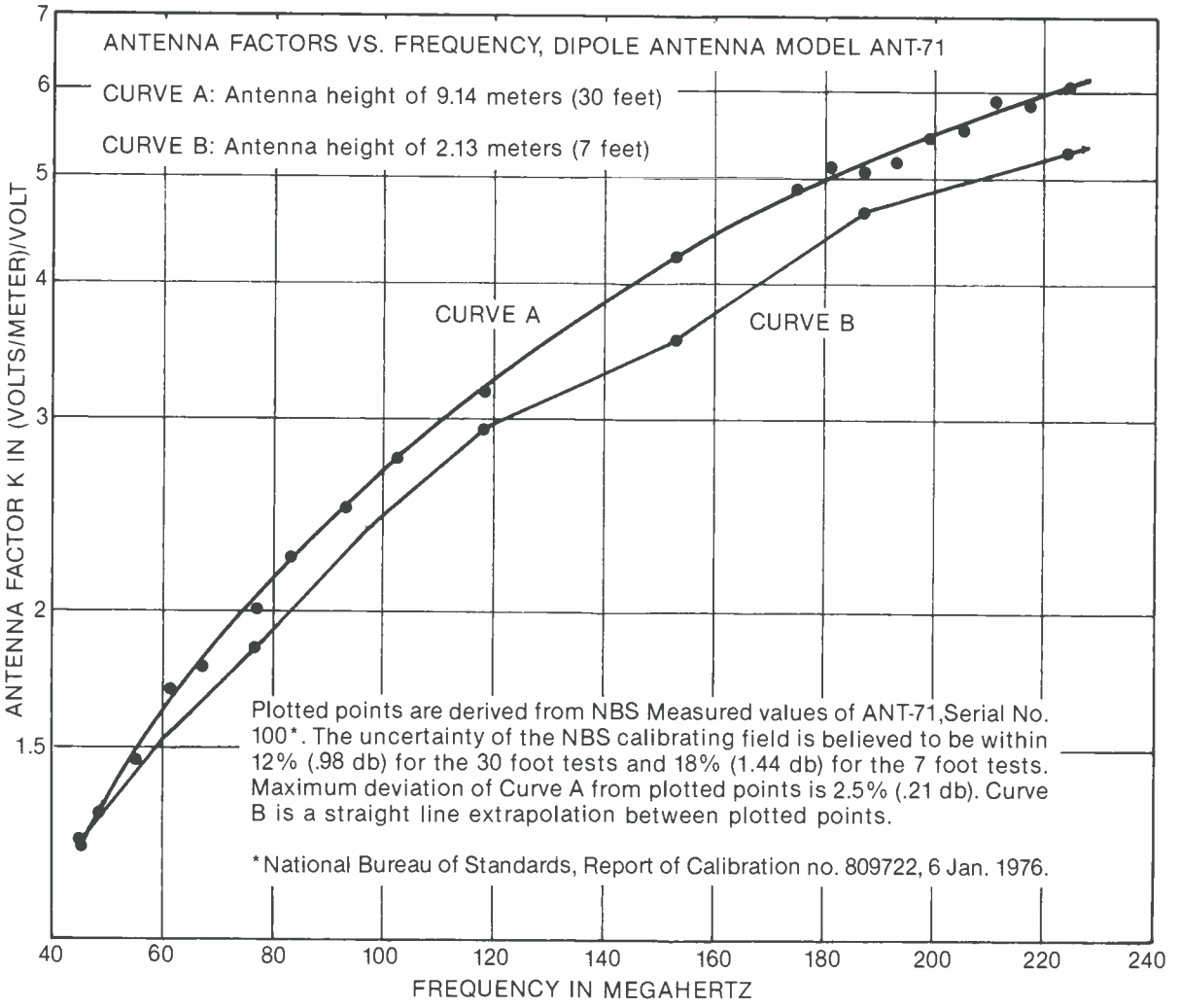


Fig. 4. Graph of K for a Typical VHF field strength meter.
(Courtesy of Potomac Instruments, Inc.)

following paragraphs will only discuss conventional equipment. However, the principles of the measurement procedure also apply to digital equipment and a discussion of conventional equipment will illustrate these principles more clearly.

Practical Field Strength Meters

Field strength meters are calibrated receivers that fall into three basic categories: (1) Receivers that contain a precision oscillator and attenuator and use direct comparison between meter readings produced by the received power and the output of the oscillator. (2) Receivers that use a precision oscillator to adjust receiver gain to produce a direct reading meter. (3) Receivers that are direct reading but do not contain a calibrating oscillator. Field strength meters of Type 3 are not considered suitable for precision field strength measurements.

Fig. 3 is a block diagram of a practical Type 1 field-strength meter. Type 2 meters are more often used presently; however, the purpose of the following discussion is to illustrate measurement principles. The Type 1 meter is more suitable for this purpose. The antenna delivers its received power to a transmission line leading to the receiver input. If the receiver input is unbalanced to ground, a balance-to-unbalance transformer ("balun") is required. The transmission line between the antenna and the receiver is shielded to avoid stray pickup.

The RF attenuator shown serves two purposes: to avoid overloading of the receiver input on strong signals and to improve the impedance match when the receiver input impedance is substantially different from the characteristic impedance of the transmission line. It is frequently omitted when not required for either of these purposes.

The signal at the receiver input is amplified and converted to the intermediate frequency. Amplification and attenuation at the intermediate frequency permit operation over a wide range of field strengths; further range is provided by the receiver gain control. The rectified receiver output operates the indicating meter.

In operation, the attenuators and gain control are adjusted to provide an on-scale reading of the indicating meter. The receiver input is then switched between the output of the transmission line and the output of the calibrating oscillator, which is tuned to the frequency being measured. The output of the calibrating oscillator is adjusted to a predetermined fixed value using the RF power monitor, and the calibrated attenuator is adjusted until the indicating meter deflection is the same as that obtained from the antenna and transmission line.

For this condition, the voltage at the output of the calibrated attenuator is the same as that from the antenna and transmission line. By taking line and balun losses into account and applying Eq. 4 above, the field at the antenna required to produce this voltage can be determined. The relationship between field strength and receiver input voltage is usually expressed as $E = KV$, where K is a function of frequency. Fig. 4 is a typical graph showing values of K for a VHF field-strength meter.

A typical commercial field-strength meter of professional quality is shown in Fig. 5. The instrument shown is a Potomac Instruments type F1M-71 covering the VHF, FM and television band from 54 to 216 MHz. A companion instrument, similar in appearance, covers the UHF television band from 470 to 806 MHz.

Accurate instrument calibration is essential in measuring RF fields. During use, the calibration of the instrument described is provided by the calibrating RF voltage source, which is usually an integral part of the field-strength meter (see Fig. 5). The calibration of the oscillator and the overall calibration of the instrument as a whole must in turn be established and maintained by reference to laboratory standards.

The most direct laboratory calibration of the complete field-strength meter is established by generating a known standard field in which the receiving antenna is placed. Standard-field ranges have been developed and constructed at both UHF and VHF[14-15] and are sometimes used in primary calibration of field strength meters. Most commercial laboratory calibrations, however, are made by removing the dipole elements from the standard antenna and applying a known RF voltage at the proper frequency to the dipole terminals in series with an impedance equal to the receiving-antenna impedance. The calibration of the balun, line, and receiver is established in terms of this applied voltage, which is then related to field strength through Eq. 4.

The calibration of the internal reference oscillator section includes the calibration of both the

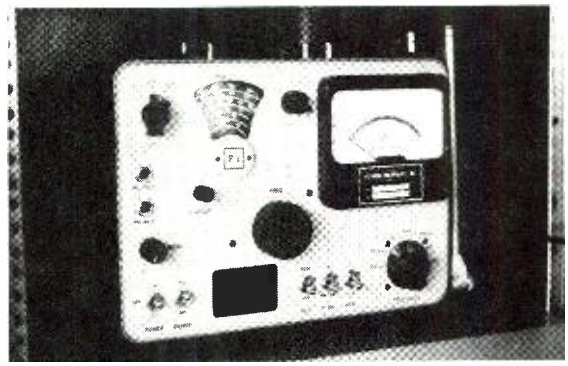


Fig. 5. A VHF meter of professional quality.

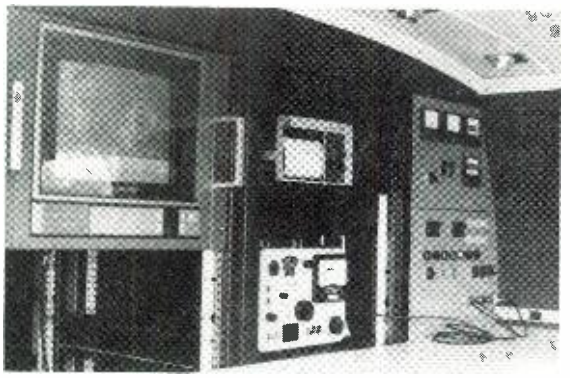


Fig. 6. Equipment set up for field strength measurement.

oscillator proper and the variable-output attenuator, if employed. The attenuator is usually of the inductively coupled piston type,[16] which depends only on its dimensions for proper functioning; this can be checked against the correct dimensions or against a laboratory standard attenuator. The oscillator can be compared with a standard oscillator, or its output can be measured with a laboratory standard such as a bolometer bridge.[17] This calibration is normally but not necessarily performed by the manufacturer.

If measurements are made on the visual carrier of a television station, the difference between the peak and average powers of the transmission must be taken into account. This can be done by establishing a calibration in terms of average power for a still scene (such as test pattern or black picture), or a peak-reading voltmeter can be employed to indicate the level of the synchronizing peaks. Such peak-reading voltmeters are an integral part of professional commercial field-strength meters such as the one illustrated in Fig. 5.

In addition to the field strength meter, several accessory items are needed in making a field-strength survey. The principal items and their use are described in the following paragraphs and include (a) a special receiving antenna, (b) an antenna-supporting mast, (c) a chart recorder and (d) power supplies. Fig. 6 shows the field strength meter, chart recorder and some additional equipment for a survey. The size and weight of the equipment usually dictate that it be mounted in an automobile or light truck. As discussed in Appendix A, all of this equipment including the field strength meter should be grounded to the vehicle frame. Fig. 7 shows a van with elevated mast supporting a UHF antenna and containing the mounted equipment of Fig. 6.

In addition to taking field strength measurements, it is often desired to use other equipment such as the television monitor shown in Fig. 6. A vehicle devoted to general field test

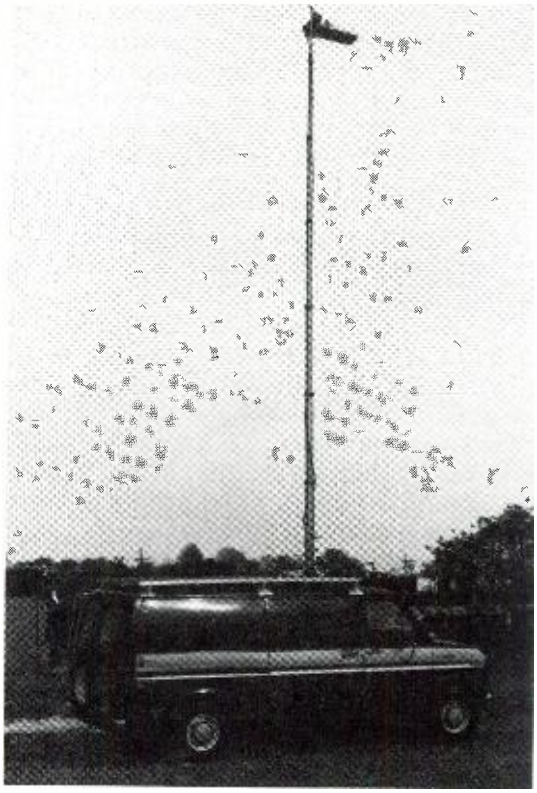


Fig. 7. Van equipped for making field strength measurements with 30 foot antenna height.

programs should have sufficient space available for special equipment including monitors, waveform scopes and magnetic recorders.

Receiving Antennas

Horizontally polarized receiving antennas are normally used for field strength measurements. At the present time, the FCC Rules require that FM and TV stations operate with horizontal only, or dual, circular polarization. If measurements on the vertically polarized components of a dual polarized field are desired, precautions must be taken to reduce the effect of coupling between the vertically polarized antenna and the supporting mast and vertical run of transmission line. If the standard antenna furnished with the field strength meter is used for measurement or calibration of another antenna, the standard antenna should be mounted at least one wavelength from all metallic vertical components. This requirement presents a mechanical problem at the lower VHF frequencies.

The measurement survey can be made by employing the standard dipole antenna furnished with the field-strength meter, or other antennas can be utilized. It is often desirable to use an

antenna other than the standard antenna for actual measurements. Standard antennas are usually not mechanically sturdy. If measurements are to be taken at a large number of locations, especially with extensive driving between locations, it is desirable to use a rugged or readilly replaceable antenna and thus minimize the probability of damaging the standard antenna.

An antenna which is essentially omnidirectional in the horizontal plane does not require orientation as the vehicle is moved; however, it is generally desirable to use a receiving antenna with directivity. Directional receiving antennas possess gain which is useful principally for UHF measurements, and their directivity is useful to eliminate unwanted signals from sources other than the transmitter being measured.

The antenna employed for the measurements must be calibrated on the measurement vehicle because of ground and vehicle proximity effects.[18] The difference in the calibration curves of Fig. 4 is caused by ground proximity effects and by differences in transmission line losses. The received field is first measured using the standard dipole antenna mounted on the vehicle at the measurement height. The antenna to be used in making the survey is then mounted on the vehicle at the height to be employed in making the survey, and the receiver input voltage determined with the receiving antenna at the same spot in the field. If an omnidirectional receiving antenna is employed, the circularity of the pattern of the antenna as mounted on the vehicle must be determined. The antenna pattern is best established by rotating the vehicle with the antenna mounted as for measurements, and recording field strength and measuring antenna gain as above. If the vehicle cannot be rotated an alternate, comparable procedure must be followed.

The gain of a directional service antenna can be established relative to the dipole antenna by means of measurements with the antennas stationary, but more consistent results are often obtained by making short mobile runs over identical paths and recording the signals from the two antennas. In either case a location essentially free of standing waves should be used. For either procedure, the voltage gain of the service antenna G_s relative to the standard dipole antenna G_d is $G_s/G_d = V_s/V_d$, where V_s and V_d are the voltages delivered to the receiver input using the service and standard dipole antennas, respectively.

If the transmission line or balun between the antenna and receiver is different from the standard cable and balun supplied with the instrument, the antenna calibration must include the measurement system cables and baluns.

Antenna Supporting Mast

The receiving antenna is ordinarily supported at a height of 3 to 9 meters (10 to 30 feet) above ground, depending on the measuring technique employed. For the short heights, a simple mast of metal tubing can be used. For the standard 9 meter (30-foot) height, a special mast is required to raise and lower the antenna, and the mast arrangement should permit the vehicle to move over limited distances with the mast elevated.

The measuring unit shown in Fig. 7 employs a telescoping mast constructed of aluminum tubing elevated by compressed air or nitrogen; the mast descends under gravity when the pressure is relieved. A handle inside the vehicle permits the mast to be rotated to orient the receiving antenna.

Operation with an elevated antenna involves a number of safety hazards including the avoidance of overhead obstructions and potential traffic hazards posed by the measurement vehicle. Power lines are the principal overhead obstruction of concern. The avoidance of these hazards, equipment grounding and operation after encountering a hazard are discussed in Appendix A. These safety procedures were taken from the TASO Report[2] with minor modifications that update the procedures and descriptions.

Chart Recorder

For measurements made with the vehicle in motion, a chart recorder is employed. The chart can be driven from the vehicle speedometer or a clock drive motor. Excitation of the recorder is provided by a dc amplifier, which usually is built into the field strength meter or may be a separate accessory.

When the chart recorder is employed, the recorder pen element must be calibrated against the receiver output indicator of the field strength meter. The dc recorder is adjusted for balance at the ends of the meter scale, and a calibration curve is prepared for intermediate values.

Power Supplies

The power drain of the measuring equipment can be fairly substantial, especially if much accessory equipment is employed. It is usually preferable to provide a power source for the measuring equipment separate from the vehicle battery. This may consist of a separate battery bank to operate the meter and accessories, or a separate 115-v. ac alternator may be mounted in the vehicle. The latter is employed to operate the ancillary equipment shown in Fig. 6.

MEASURING PROCEDURES AND TECHNIQUES

The FCC FM and TV Technical Standards prescribe measuring methods to be employed in making measurements to be submitted to the Commission. These or similar methods are also usually employed in making other surveys such as for the measurements on station coverage. Variations from the official procedure are frequently taken; some of these variations are discussed under earlier headings. The following paragraphs summarize the present requirements of the Commission's Standards.

FCC Standard Method For the Collection of Propagation Data

The following discussion summarizes the FCC procedure in making field strength measurements for propagation studies. The forms for recording and submission of data and other technical requirements are presented in Section 73.314(b) and 73.686(b) of the Rules for FM and TV respectively.

The Commission's Technical Standards require field strength measurement surveys to be made with mobile equipment along at least eight radial lines from the transmitter. The radials need not be laid out along bearings separated by 45°, beginning with true North as is standard for contour prediction. Measurements are required to be taken from 16 kilometers (10 miles) in increments of 3 kilometers (2.0 miles) in each direction. If it is desired to establish contour location, the distance should extend somewhat beyond the field strength contour which it is desired to establish. The routes are selected to encounter representative terrain and to permit reasonable interpolation between adjoining radials. A precise radial line is laid out from the transmitter on topographic maps to the distance to which measurements are to be made. Along this radial line, measuring locations are marked at exact 3-kilometer (2-mile) intervals, beginning at exactly 16 kilometers (10 miles) from the transmitting antenna. The actual measurements are made precisely on the radial, at locations as close as possible to the exact 3-kilometer (2-mile) marks established as described. The ground elevation of the actual measurement location should be the same as that of the intended location.

The individual measurements consist of short mobile runs (at least 30 meters (100 feet) along the road) at each location so chosen, with the receiving antenna at the 9 meter (30 foot) height. If measurements are made on multiple stations for comparison purposes, it is desirable to mark the beginning or end points for each run to insure that the run is made over identical paths on each channel. Before making the measurement run, the gain of the field strength meter is adjusted to the meter reading and chart recorder indicating the initial calibration.

The chart recorder is used to record the field strength meter output, and the median, minimum, and maximum values of the field for each recording are determined from the chart recording. Precise determination of the median is usually made after completion of the survey; however, it is useful to use the meter's calibrating oscillator to make a trace of an estimated median value on the chart paper after each run. The median of the run is estimated and the output of a precision attenuator may be adjusted to the estimated median. This provides an additional calibration check and permits a rapid preliminary calculation of field strength that is often useful to monitor the progress of a survey.

Fig. 8 shows a sample of a typical chart recording obtained by this method. With field strength meters such as the one shown on Fig. 5 there is no built-in adjustable attenuator; however, there is an oscillator output which may be fed through an external attenuator to the input to achieve this calibration.

The chart median values are then converted to received field strength by combining the individual calibrations of the antenna, transmission line, field strength meter, dc amplifier, and chart recorder as discussed above.

Analysis of Measurements to Depict Coverage

If a measurement height of other than 9 meters (30 feet) was used, the received fields must be adjusted to the field expected at a receiving antenna height of 9 meter (30 feet) above ground if it is desired to obtain the location of standard contours. An antenna height of approximately 10 feet is often used when the results will not be filed

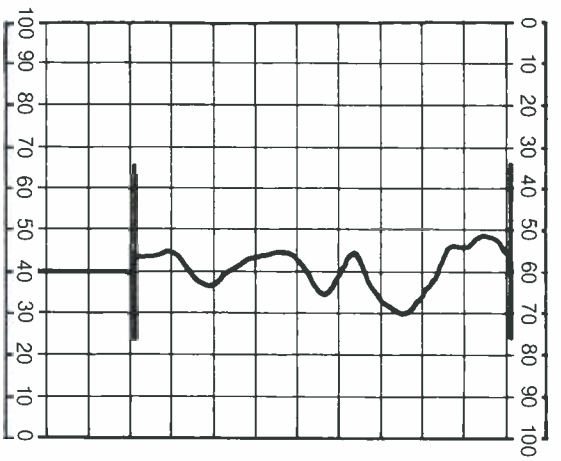


Fig. 8. Sample of field strength chart recording of a short mobile run showing traces marking beginning, ending and calibration.

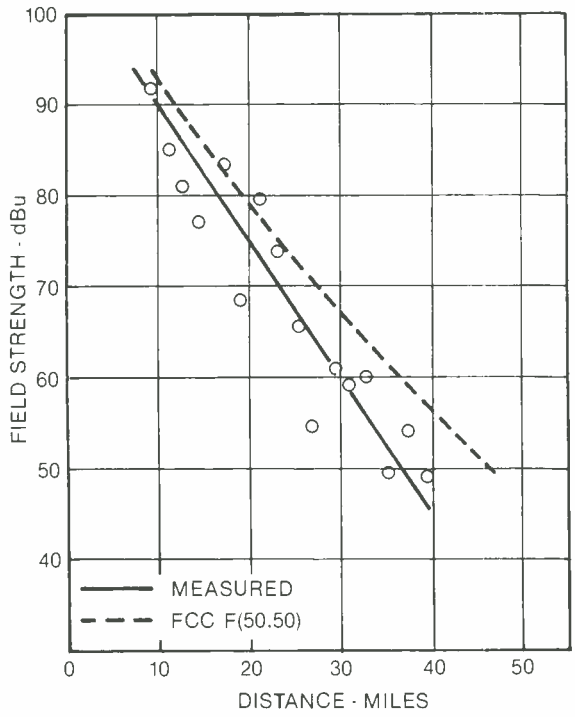


Fig. 9. Graph of measured field strength versus distance for a typical radial series of measurements. The results of each mobile run are shown. The solid line is best fit curve through the points. The dashed line is the predicted field strength from the FCC curves.

with the FCC. It has been common practice to assume the field strengths to increase linearly with antenna height, as indicated by classical plane earth propagation theory. For this assumption the relationship between the field, E30, which would be expected at 30 feet and the field EH, which would be expected at 30 feet and the field EH, measured at a receiving antenna height Hr is E30/EH = 30/Hr. For example, the ratio of the field at 30 feet to the field at 10 feet is 30/10 = 3.0, or 9.5 db.

The application of the linear height-gain function discussed above is recommended only in relatively flat terrain. In rolling or rough terrain the following height-gain factors (in decibels) were recommended by TASO to convert from 3 meter (10-foot) to 9 meter (30-foot) fields. The values were preliminary and are not based upon measurement programs designed for this purpose.

Channel	Smooth Unobstructed Terrain	Rolling Hilly Terrain	Rough Terrain
2-6	9.5 dB	8 dB	7 dB
7-13	9.5	7	5
14-83	9.5	5	2

The median fields as established in accordance with a radial or modified radial procedure described above are plotted as a function of distance from the transmitter, and a smooth curve is drawn through the plotted points. Fig. 9 is a typical graph showing the plotted field strengths as a function of distance from the transmitter, together with the smooth curve through the plotted points. The dashed curve in Fig. 9 is the predicted field strength calculated using the propagation curves and prediction methods specified in the FCC Television Broadcast Technical Standards.[19]

Individual graphs of median field strength versus distance as shown in Fig. 9 are prepared for each of the directions along which the measurements were made; the distances to the desired field strength contours, selected from Table II, are determined in each direction. These distances are then plotted on a suitable map, and contours are drawn to produce a finished map such as shown in Fig. 1.

PRACTICAL PROBLEMS ENCOUNTERED IN MAKING FIELD-STRENGTH SURVEYS

Before any field strength measurement survey is undertaken, the radiated power of the transmitting installation must be established as closely as possible. The transmitter output power should be determined by means of the dummy load and maintained as closely as possible to the proper value throughout the survey. The radiated power is established from the measured transmitter output power, taking into account the antenna power gain and the transmission line and diplexer losses.

The use of a 9 meter (30-foot) receiving antenna mounted on a vehicle requires special permission from police or highway authorities in most states. These requirements vary among the individual states, but full details can be obtained from the state police or highway headquarters in the various state capitals.

The operation of a 9 meter (30-foot) mast presents safety hazards which require the exercise of utmost caution in the use of an elevated mast. In addition to proper grounding discussed earlier, the TASO field-strength measuring specification includes a special appendix (included here as Appendix A) dealing with overall safety requirements. When measurements are made with an elevated antenna, the need for caution must be borne in mind at all times.

Time Variation of Field Strength

Fairly substantial variations in field strength with time are frequently noted particularly near and beyond the radio horizon although significant variations occur at other distances. Factors for time variation are included in several refer-

ences.[10-12] These variations may be relatively rapid, occurring over a period of a few minutes, or slow variations may appear over periods of several hours. There are also long term seasonal variations. Average field strengths in this region are usually lowest during winter afternoons, and higher average fields may be observed during the evening hours and during summer. The variations in field strengths with the passage of time must be taken into account in planning and making field strength coverage surveys.

The observed fluctuation of the field near the horizon is believed to be due principally to variations in the refractivity gradient of the lower atmosphere, which in turn is determined by the temperature, humidity, and barometric-pressure gradients. Measurements for coverage surveys should not be made beyond the radio horizon during periods when unusual conditions of temperature, humidity, and barometric pressure are believed to prevail. In particular, such measurements should not be made during changing weather conditions or if weather fronts are known to be in the area.

The variations in field strength with time often result from causes which are not readily apparent, and it is frequently difficult to determine whether typical propagation conditions prevail. One method which has been proposed and tried with some success is that of establishing fixed recording stations in one or more directions, at locations near the expected outer limit of the measurement program and recording the received signal over a period of several days. These recordings will give an indication of the signal to be expected under average conditions; the coverage survey measurements beyond the horizon can be made during a period when the recordings indicate propagation conditions to be typical. Measurements should not be made on days when these recordings indicate excessively high or excessively low field strengths.

APPENDIX A

Safety Precautions Recommended by TASO for Mobile Field Strength Measurements With Antennas Elevated 30 Feet Above Ground.

Some broadcast equipment uses high electrical voltages which are extremely dangerous to personnel that may come in contact with them. We have all been familiar with the locations of many of these high voltages in the past, particularly in radio and TV transmitters and, to a lesser appreciated but equally dangerous extent, video power supplies and some audio and test equipments. Personnel involved with the construction, operation or maintenance of these equipments should be fully aware at all times of the potential danger. One should never take chances with these high voltages. It has been demonstrated through a series of unfortunate accidents that the measuring of field strength at television frequencies can also be extremely dangerous where observations are made at a 30 foot level. The danger here is not with the field strength measuring equipment being used but with hazards of contact with primary electrical power circuits and, to a lesser extent, potential traffic hazards. In view of the dangers associated with the field strength measuring work outlined above, there are certain general precautions everyone should take in addition to the specific precautions included within this memo for safety in operation of the field strength measuring vehicle. These general precautions include the following:

(1) Never take chances.

(2) Do not service or work on equipment when the power is turned on.

(3) Never work on electrical equipment containing high voltages unless there are at least two persons present.

(4) If in doubt keep one hand in a pocket at all times.

(5) Everyone who has occasion to work on such electrical equipment must have a knowledge of the best methods of artificial respiration.

I. EMERGENCY PROCEDURE

If the procedures outlined in this memorandum for the safe operation of field strength measuring vehicles are followed, there should be no need for emergency procedures. In spite of this, it is felt worthwhile to outline some emergency procedures to be followed in the event of some unforeseen accident. Assuming that some accident has arisen involving overhead obstructions, the following precautions should be observed:

(1) The obstruction you are entangled which may carry HIGH VOLTAGE.

(2) The vehicle you are in may be at a high potential with respect to ground, so STOP AND THINK.

(3) Under no circumstances should the transmission line (associated with the field strength measuring gear) be touched. The grounding connections may have broken due to mechanical strain or have burned up due to extremely high currents.

(4) The precautions you have taken in inspecting the vehicle before starting the day's work should prevent any high voltage from entering the vehicle.

2.8

AM Field Strength Measurements and Proof of Performance

Donald G. Everist
Cohen and Dippell, P.C.
Washington, District of Columbia

INTRODUCTION

The directional antenna is composed of two or more radiating elements. These elements are arranged in a specific physical configuration and energized with RF energy of known magnitude and phase relations. The electrical and physical arrangement causes the individual fields of each element to interact, adding and cancelling, to produce the desired directional pattern shape. Each directional pattern is customized to provide the optimum service to the desired area while rendering the required suppression in area(s) of protection to other stations' service area(s) in accordance with the FCC Rules.

The phase and current relationships are produced by the RF distribution system. The distribution system transfers the RF energy from the transmitter to the radiating tower. The RF distribution system outside the transmitter building is generally composed of a matching network at the base of each tower enclosed in a weatherproof environment and an RF transmission line extending from the input of each tower-matching network to the transmitter building. Inside the transmitter building, the transmission line is connected to other distribution and matching networks. These distribution and matching networks are usually housed in a metal cabinet. This item is usually designated as the 'phasor'. The ground system is connected securely (electrically and mechanically) to the phasor cabinet and its components and the tower matching networks. The phasor typically will incorporate a matching input network between the distribution circuits and the transmitter in order to present the transmitter with a suitable load impedance. This network will help provide the optimum RF energy transfer from the transmitter and allow adjustment of the common point impedance. It is at the common point that the power of the directional array is determined. For more information on the design and contruction of AM antenna systems, see Chapter 2.4, "AM Broadcast Antenna Systems." As described in Section 73.51 of the FCC Rules, directional arrays having a nominal power of 5 kW or less shall exceed the nominal power by 8%. This additional factor for power is an allowance for system losses. Nominal powers greater than 5 kW are permitted a system loss factor of 5.3%. This factor, multiplied by the nominal power, provides the value used in the determination of the license common point current.

The directional antenna parameters are monitored by a system composed of an antenna monitor, sampling line(s) and sampling devices. The antenna monitor requires FCC-type approval. Sample lines are used to transmit the energy from the sampling device to the antenna monitor. In planning and building a sampling system, care must be exercised in the selection of the sampling element and its placement and in the selection of the type of line, size, length, and its installation.

Appropriate grounding of the sample system with the station ground system is essential. This system must be built to provide reliable service, and proper installation will benefit the station in the long term.

The ground system about the bases of the towers must be installed in accordance with that proposed in the application authorized by the FCC. Typically, the ground system is copper; although in unique situations, other materials have been permitted by the FCC. All connections should be properly made using a recognized method of electrical RF connection. Silver solder is typically used since this type of connection will withstand years of service with a minimum amount of maintenance. Rosin or acid core solder is not acceptable. While installing a ground system, detailed plats should be prepared, and it is recommended that pictures be taken for future use. These pictures will assist in directing an investigation of various parts of the ground system in later years.

Deviation in ground system composition may require prior FCC approval or, at the minimum, alternate configurations will require advising the FCC in a letter or an FCC Form 302 with supporting information.

If the radiating elements are guyed, then the electrical continuity of each guy wire must be interrupted with insulators at intervals sufficient to permit the antenna to act as a free-standing radiator.

The selection of a point to serve as a monitor point along each radial specified in the construction permit is required. Each point must be reachable in inclement weather and must be free of surrounding objects, such as underground pipes and overhead wires. Schoolyards, churches, and cemeteries often provide useful monitor-point locations because the surrounding area generally is free from alteration. Prior to the submission to the FCC, possible sites for monitor-point selections should be observed over a period of time until a degree of confidence in the measured field strength values has been established. The reading at each point must be in the direction of the station. The direction of the station can be established by using a U.S. Geological quadrangle or by switching the pattern to the non-directional mode (if available).

Once the directional array is operating, one of the often overlooked items is the monitoring of the area for new construction. Vertical structure construction or new construction authorized by governmental authorities is often very difficult to detect in the advance stage of planning. New power-line construction and construction of other communication structures can act as additional, parasitic reradiators of the directional energy if placed sufficiently close to the array. Such reradiated energy can lead to situations whereby the directional pattern is altered.

Security (especially if the transmitting site is remote controlled or is located in a remote area) is definitely an item that should be considered. The location of a transmitter building in a secluded area without adequate security is an invitation for all kinds of crime or vandalism. Fences, including those about the tower bases, should be of rugged construction to serve as a deterrent. It is recommended that adequate night lighting be positioned around vulnerable areas, and an alarm system may be installed to warn of unauthorized entry and fire. Local authorities such as police and fire can be a great source of assistance in matters of security and fire prevention in individual situations.

Requirements to conform with the FCC Rules are broader for directional than non-directional operations; however, regardless of the operational mode, the FCC Rules must be observed. One approach is the acquisition of the current edition of the AM & FM Broadcast Station Checklist from the FCC field office having jurisdictional responsibility. The booklet is useful in identifying non-technical as well as technical areas of the FCC Rules where compliance must be maintained. The 1985 edition is reproduced at the end of Chapter 1.2, "FCC Field Operations Bureau," of this *Handbook*.

One item of importance, regardless of the power level or the status of the operation, is the evaluation of exposure to radio frequency energy. The FCC, in General Docket 79-144, released a Report and Order that specified that human exposure would be an area for consideration of potential environmental impact. While Docket 79-144 deals with FCC responsibility in considering effects for human exposure to radio frequency energy, the Report and Order specified that the 1982 protection guidelines of the American National Standards Institute be used in evaluating compliance.

The Rule, which became effective January 1, 1986, in general requires the broadcast station to demonstrate its effect on its surroundings at the time when the applicant or licensee applies for a construction permit and when a licensee files for renewal.

The FCC has released an OST Bulletin No. 65 entitled, "Evaluating Compliance with FCC-Specified Guidelines for Human Exposure to Radio Frequency Radiation." The bulletin covers different areas and can be of assistance in determining the facilities' potential impact. Accompanying the release of that document was an FCC Public Notice entitled, "Environmental Processing Rules for Broadcasters". A copy of that Public Notice is provided on page 2.8-233.

(5) Study your predicament carefully to determine your best course of action. It may be one of the following:
   (a) Back the vehicle up.
   (b) Drive the vehicle ahead.
   (c) Lower the mast.
   (d) Raise the mast further.
   (e) Get away from the car—IF YOU DO THIS, REMEMBER THE CAR MAY BE AT A HIGH POTENTIAL WITH RESPECT TO GROUND SO DO NOT TAKE CHANCES—JUMP CLEAR.

(6) Be sure no one else approaches the scene or comes in contact with the vehicle.

II. CONSTRUCTION SAFETY PRECAUTIONS

Since there is a remote possibility of the mast or antenna of the measuring vehicle coming in contact with extremely high voltages, the construction of the vehicle should be such as to reduce to the absolute minimum, the possibility of these electrical voltages entering the vehicle. The secure electrical bonds referred to herein must be made with a view towards the hundreds or thousands of amperes that may be involved in the event of an accident. The first of these precautions have to do with external features of the vehicle.

(1) All antenna elements which are directly connected to the transmission line must have a secure electrical bond to the mast.

(2) The outer conductor of all transmission lines used with the mast must have a secure electrical bond to the top of the mast.

(3) The vehicle shall be operated with blinking hazard lights when the mast is elevated.

The additional constructional details to be observed with the vehicle are as follows:

(1) The outer conductor of all transmission lines must have a secure electrical bond to the vehicle as soon after entering the vehicle as practical.

(2) All electrical equipment (field strength meters, recorders, receivers and signal generators) must have secure electrical bonding to the vehicle.

(3) The vehicle shall be equipped with a light readily visible to the vehicle driver which indicates that the mast is under pressure or up and/or the vehicle shall have a window in the roof from where the driver and engineer, if feasible, can directly view the mast and antenna.

The vehicle shall also be supplied with certain safety equipment as follows:

(1) A pair of high voltage rubber gloves with protecting leather gauntlets. The rubber gloves should be tested at least once a year and a memo including the date of test and the testing organization shall be included in the carrying box for the gloves. All major power companies have provisions for making these tests.

(2) A non-metallic safety pole 8 foot minimum for handling hot wires.

(3) A CO2 fire extinguisher. This should be checked annually.

III. OPERATIONAL SAFETY PRECAUTIONS

The foregoing equipment safety precautions are believed to be adequate to make the inside of the vehicle safe in the event of some unforeseen accident. These precautions will only be effective as long as the equipment is in good working condition. Therefore, it is important that all safety precautions outlined in the foregoing paragraph be checked each morning before beginning the day's work. In addition to have a safe vehicle, it must be operated in a safe manner. Therefore, the following precautions must be observed when the car is used:

(1) No night work is permitted without prior written approval. In the event this permission is given, it will include additional detailed precautions for the specific job for which the approval is given.

(2) The mast must not be erected unless two operators are present.

(3) The location for elevating the mast must be carefully chosen both to prevent contact with overhead obstructions and to avoid being a traffic hazard. The mast must not be elevated on busy urban streets or heavily traveled rural highways. The chosen area must be reasonably level and, if a mobile run is contemplated, the vehicle must traverse the path before the mast is raised.

(4) Having selected the location for measuring, the following procedure shall be used for elevating the mast. The driver and the engineer will both step out of the vehicle and examine the overhead area for obstructions. The engineer may then return to the vehicle and elevate the mast. If a mobile run is to be made, the driver must walk ahead, examining the path for overhead obstructions and leave a marker at the end of the chosen path. If

repeated measurements are to be made along the same path, the starting point should also be marked so that neither end of the examined path is passed. The vehicle may then be driven between the markers.

(5) When the measurements are completed, the driver shall, without stepping out of the vehicle, determine that the overhead area is free for the lowering of the mast. The driver must also make a personal observation that the mast has been fully retracted before driving to the next measuring area.

FOOTNOTES AND REFERENCES

1. Federal Communications Commission: FM Technical Standards, Sec. 73.311(c); TV Technical Standards, Secs. 73.683(a) and 73.685(a).
2. "Engineering Aspects of Television Allocations," Report of the Television Allocations Study Organization to the Federal Communications Commission, Mar. 16, 1959.
3. Kalagian, G.S. "A Review of the Technical Planning Factors for the VHF Television Service FCC/OCE RS 77-01," March 1, 1977.
4. LaGrone, Alfred H.: "Forecasting Television Service Fields", Proc. IRE, June 1960, vol. 48, no. 6, pp 1009-1018.
5. Brown, G. H. J. Epstein, and D. W. Peterson: "Comparative Propagation measurements; Television Transmitters at 67.25, 288, 510 and 910 Megacycles", RCA Rev., vol. 9, no. 2, pp 177-202, June 1948.
6. Bullington, K.: "Radio Propagation Fundamentals", Bell System Tech. J., May, 1957 vol. 36, no. 3, pp. 593-626.
7. Peterson, D. W., and J. Epstein: "A Method of Predicting the Coverage of a Television Station", RCA Rev., December, 1956, vol. 17, no. 4, pp. 571-582.
8. Head, H. T.: "The Influence of Trees on Television Field Strengths at Ultra-High Frequencies." Proc. IRE June, 1960, vol. 48, no. 6, pp 1016-1020.
9. Kinase, Akira, "Influences of Terrain Irregularities and Environmental Surroundings on the Propagation of Broadcasting Waves in the UHF and VHF Bands." Japan Broadcasting Corporation (NHK) Tech. Monograph No. 14, March 1969.
10. Damelin, J., W. A. Daniel, H. Fine, and G. V. Waldo, "Development of VHF and UHF Propagation Curves for TV and FM Broadcasting" FCC Report No. R-6602, September 7, 1966.
11. Norton, K. A. "The Calculation of Ground Wave Field Intensity over a Finitely Conducting Spherical Earth", Proc. IRE, vol. 29, December, 1941.
12. Rice, P. L., A. G. Longley, K. A. Norton and A. P. Barsis "Transmission Loss Predictions for Tropospheric Communication Circuits", NBS Technical Note No. 101, January 1, 1963.
13. Reed, H.R. and Russell C. M. *Ultra-High Frequency Propagation,* John Wiley and Sons, 1953.
14. Greene, Frank M.: "Calibration of Commercial Radio Field Strength Meters at the National Bureau of Standards," Natl. Bur. Standards Circ. 517, December, 1951.
15. Green, Frank M., and Max Solow: "Development of Very-high Frequency Field intensity Standards", Natl. Bur. Standards Research Paper RP2100, vol. 44, May, 1950.
16. Terman, F.E.: *Radio Engineers' Handbook,* McGraw-Hill Book Company, Inc., New York, 1943.
17. Schrack, R.A.: "Radio-frequency Power Measurements", Natl. Bur. Standards Circ. 536, Mar. 16, 1953.
18. Greene, Frank M.: "Influence of the Ground on the Calibration and Use of VHF Field Intensity Meters", Natl. Bur. Standards Research Paper RP2062, vol. 44, February, 1950.
19. Federal Communications Commission's Rules, Sec. 73.684.

each of the radials defined in the reference proof. The partial proof must contain an arithmetic or logarithmic ratio analysis of the measurement data so obtained. It must demonstrate that the antenna system is operating within its instrument of authorization. Generally speaking, the measurements should be made at an interval of 3 to 16 kilometers (2 to 10 miles). A statement that the impedance of the common point has been measured and is unchanged from the licensed value prior to making measurements should be provided. A change in common point impedance at the operating frequency requires an appropriate submission to the FCC and is to be requested, using FCC Form 302.

GENERAL REQUIREMENTS FOR MEASUREMENTS

All measurements should be made during the daylight hours in the absence of interference, and special temporary authority may be required prior to the commencement of measurements for a new authorization. For established stations, the FCC Rules permit considerable flexibility in operation during periods of making antenna system field strength measurements.

It is FCC policy that the measurement observations to be recorded and utilized as a basis of analysis of the inverse distance radiation values are those observed with the field strength meter oriented towards the station. The maximum indication can occur when the meter is oriented away from the transmitting source. This phenomenon can be caused by many factors including null depth on the measured radial. These factors vary from local effects surrounding or adjacent to the measuring point, non-uniform conditions inherent in the propagation path and can be affected by the position of the observation point on a rapidly changing portion of the directional pattern.

A record must be kept of the measurement data, including each point number, the field strength observations, dates and times of the measurements, the pattern under investigation, a description of each point location, the name of the individual taking the measurements, the general weather conditions, the field strength instrument utilized and the date of its last calibration. A sample form is provided for tabulating the field measurement data.

Graphical Analysis

The inverse distance field or unattenuated field strength at a reference distance kilometer (1 km) is the field strength predicted at that distance from the transmitting antenna if the earth were to behave as a perfect conductor. As the wave energy travels away from the antenna, the unattenuated field strength reduces by the inverse proportion to the distance from the antenna. For example, if the value of the unattenuated field at 1 km is 100 mV/m, its value at 2 km will be one-half that value or 50 mV/m, and at 10 km, its value will be one-tenth of the 1 km value or 10 mV/m. The effects of attenuation on field strength are shown by families of curves for field strength vs distance for various values of ground conductivity. These graphs are included in Section 73.184 of the FCC Rules. The actual field will be diminished by this inverse distance factor as well as the losses attributable to ground conductivity.

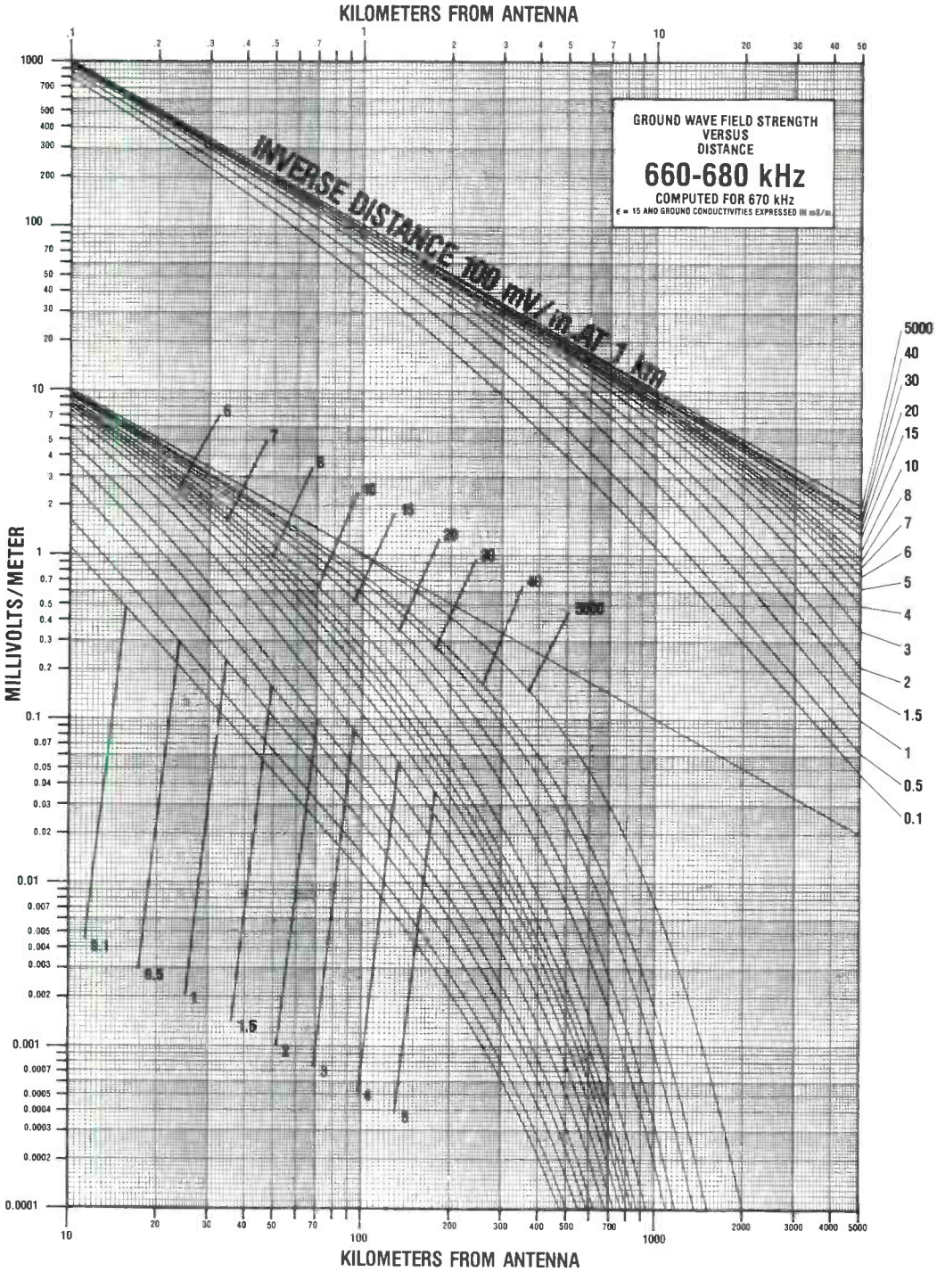
The FCC, in its conversion to the metric system, redetermined the frequency curves. In addition, the FCC used its computer program and determined additional conductivity values for each frequency chart. The dielectric constant for all curves except for sea water, is 15. For sea water the calculations are based upon a dielectric constant of 80.

There are 19 sets of frequency dependent propagation graphs that encompass the frequencies from 540 to 1610 kHz. Curves for each frequency group are drawn on two graphs. One graph shows the uppermost portion with conductivity curves normalized for 100 mV/m/km from one-tenth to 50 km and the bottom portion reflects the conductivity curves for 10 to 5000 km. The second graph is an expanded version of the uppermost portion of the first graph to allow for easier determination of the inverse distance field and conductivity values for measurements less than 50 km from the transmitting antenna.

After the distances from the transmitting antenna to each of the measuring points have been determined and tabulated opposite the observed field strength values, the measured field strength values can be plotted on log-log graph paper. The ordinate (vertical scale) is field strength, expressed in mV/m, and the abscissa (horizontal scale) is distance in kilometers. Data can be plotted on groundwave field intensity graph paper available through NAB. This paper has the same logarithmic scale as the expanded version of the FCC curves.

Plotting Data

For the logarithmic coordinate system, (log-log graph paper) the inverse distance field strength plots as a straight line. The conductivity curves are drawn for the case of an inverse distance field of 100 mV/m at 1 km, but their use is not limited to that value. If an inverse distance field strength is 200 mV/m (twice the reference value) or 50 mV/m (one-half the reference number) or some other value at 1 km, and if all points on the curve are multiplied by the ratio of the actual inverse distance field strength to 100 mV/m, the effect would be the equivalent of moving the curves by



GRAPH 5

Ground Wave Field Strength versus Distance
660-680 kHz

that amount on the logarithmic coordinate paper. This is the basis on which field strength measurements are analyzed. The appropriate conductivity values for the frequency involved are made by matching the abscissa of the data with that of the FCC graph and sliding the ordinate information data vertically to obtain the "best fit" of measured field strength values to the conductivity curves. By this method, both the unattenuated field at 1 km and the conductivity values along the radial path can be determined. The use of a light table will assist in aligning and moving the two sheets of paper.

An individual attempting to analyze measurement data for the first time and without the benefit of experienced supervision can find this a frustrating experience. One approach is to take log-log graph paper for the appropriate frequency (either the regular or expanded scale) and plot the measurement point values normalized to 100 mV/km. For example, if the non-directional 0.25 kW operation is expected to possess an RMS field at 1 kW of 91 mV/m (70 degrees [0.194 of a wavelength] electrical height tower with a normal ground system—see Figure 8, Section 73.190 of the FCC Rules), it has a field 91/100 less than the FCC log-log conductivity graph. Therefore, multiply all values (divide all values if the expected field is greater than 100 mV/m) of the measurement data by the ratio of 100/91 to normalize it to 100 mV/m. Plot the normalized data. The plotted values can be viewed in relation to the conductivity values if the assumption of the inverse distance field is correct. If the normalized data appear to be over the inverse distance line, then the radiation value is higher than assumed and conversely if the normalized data appear abnormally low, the assumed radiation value selected is too high.

This approach can be useful when the non-directional measurements out to 3 km in the various directions have been taken and a quick evaluation of the conductivity values/radiation efficiency around the site is desired. It also will help to assess whether or not the non-directional radiation pattern is being influenced by other adjacent towers in the directional antenna system.

Special Temporary Authority

Special temporary authority will generally be required with any operation which has not received prior authorization from the Federal Communications Commission. Section 73.1635 of the FCC Rules provides that special temporary authorization be requested in writing (an original and two copies) to the FCC in Washington, D.C. The authorization request should delineate the station frequency, location, and authorizing construction permit number. The request must contain the non-directional power requested. The letter should indicate the capacity of the requesting individual and his phone number so that the FCC can request additional information informally, if required.

For licensed operations, the FCC Rules provide that a non-directional operation that has been authorized in a proof-of-performance for a daytime only station, a station with a single pattern or more than one directional pattern for day and night, etc., can utilize the non-directional power set forth in the latest proof-of-performance without further authorization from the FCC. However, this privilege is permitted only for the time field strength measurements are being made. In addition, the FCC permits, without further authorization, operation of a nighttime pattern during daytime hours when field intensity measurements are being taken.

Antenna Monitor System Approval

For each new station, details of the antenna monitor system components and installation must be contained in the proof-of-performance report in order to obtain the necessary recognition from the FCC that the antenna monitor system conforms to the FCC Rules. An antenna monitor system request accompanying a partial proof should be, for prompt consideration, filed in a separate submission. During construction or revision of the monitoring system, special temporary authority for variance of parameters may be required for existing stations. This authority can be obtained by submitting a request (original and two copies) to the FCC. The purpose of the request as well as its duration should be provided. For specific situations, reference should be made to Section 73.68 of the Rules; however, with the revision in Docket 85-90, the FCC is less specific as to the detail of sampling system construction. The FCC indicates, as a matter of policy, that the procedural methods outlined in the Rules, as modified by MM Docket 83-16, would receive continued FCC acceptance. Other, less conventional methods may be subject to rigorous scrutiny, including observations over a period of time and partial proof-of-performance. For convenience, Section 73.68 of the FCC Rules is provided prior to alteration by Docket 85-90.

Whether contained in the proof-of-performance or otherwise, the request for approval must indicate information sufficient to determine compliance with the FCC Rules concerning the method of sample, type of sample line, and its electrical length and whether the sample lines are under similar environmental conditions. The submission should incorporate other descriptions as may be required to demonstrate compliance with the FCC Rules and Policy and must be accom-

panied by a signature of authority from the station organization. A station with an approved sampling system is permitted to establish its own schedule of monitor-point measurements based on its operating conditions.

FCC FORM FOR LICENSE

Each proof-of-performance must include the information requested in FCC Form 302. It must comply with the provisions and intent of the FCC Rules including Section 73.186 regarding the number of measurement radials, the number of non-directional and directional measurements made along each radial, the mathematical or graphical analysis, if utilized, the plot of the field versus distance measurements on semi-log or log-log graph paper, and reproductions of the quadrangle maps (or other maps as required) showing the radials along which measurements were made and locations used in making the measurements. Section 73.186 of the FCC Rules also dictates the form for the submission of non-directional antenna impedance measurements as well as the common point impedance measurements with the required graphical plots.

Furthermore, descriptions of the monitoring points as specified by the construction permit, complete with the monitor-point photographs and a route diagram must be supplied (see Section 73.158 of the FCC Rules). The station must also comply with all other conditions of the construction permit.

A diagram of the phasor, associated RF feed system, and matching network, as constructed, is to be provided. Plots of the inverse distance field at 1 km for the non-directional as well as each directional mode are to be supplied for each measured radial, showing the interpretation of the measurement data. The measured directional pattern field strength must not exceed the authorized pattern in any direction and must have the requisite RMS. In certain situations for new stations or revisions of existing facilities requiring a new reference proof-of-performance, the FCC will permit an adjustment of directional power which can be effected at the time of the license application. The FCC policy statement concerning such power adjustment is provided in its entirety, see page 2.8-229.

For each directional operation, the parameters as indicated by the antenna monitor for both loop and phase (including SIGN), as well as the base currents and the ratios are to be furnished. Each field strength instrument and its type number, make, model, and date of the last calibration should be listed. If more than one instrument is utilized, a comparison of the accuracy observed for each instrument should be made. The name, address and qualifications of the engineer making the measurements must also be provided.

LICENSE

The FCC license specifies, among other things, the licensee name; the term of the license; the station location; the main studio location, if not at the transmitter or within the boundaries of the principal community; the remote control location; the transmitter location and its coordinates; the type of antenna and ground system, if non-directional; the frequency; the nominal power; the hours of operation and any special conditions. For stations using a directional antenna system, the second page will provide a description of the directional antenna system; the spacing, orientation and height of the towers; and a description of the ground system. Also provided are the theoretical specifications authorized by the latest FCC construction permit and operating specifications determined from the most recent partial or full proof-of-performance. The descriptions of the monitor points and the maximum limits that the points must not exceed are contained on the following page(s) of the license.

Changes and modifications of any of these items require appropriate notification to and concurrence by the FCC. When a new license is received, it should be inspected for correctness as compared with the information used as a basis for the license application.

The operating parameters must be maintained in accordance with Section 73.62 of the FCC Rules and the directional antenna must be maintained with indicated relative amplitude of the antenna base currents and antenna monitor currents within 5% of the values specified in the license, unless other tolerances are specified. In addition, the directional antenna relative phase angles must be maintained within ± 3 degrees of the values specified in the license unless other tolerances are required.

Monitor-point values must be maintained within the values specified in the license. An increase in an existing monitor point(s) maximum allowed value can only be accomplished by submission of a partial proof-of-performance to the FCC. A change in monitor point location requires submission of a photograph, route diagram, description of the new monitor point and a minimum of 10 field strength measurements at locations used in the last reference proof-of-performance on the radial, including the newly-designated monitor point between 2 and 10 miles that is shown in the latest reference proof. This information is to be submitted to the FCC. The FCC policy for the assignment of monitor-point values is attached.

FCC POLICY STATEMENT ENTITLED "CRITERIA FOR APPROVAL OF SAMPLE SYSTEMS FOR DIRECTIONAL AM BROADCAST STATIONS" DATED DECEMBER 9, 1985

On October 31, 1985, the Commission adopted a Report and Order in MM Docket 85-90 concerning the antenna sampling systems and proofs-of-performance for directional AM broadcast stations. The new rules are based upon performance standards in terms of accuracy and stability rather than upon construction specifications. This Notice clarifies the information required for directional AM sampling system approval under the new provisions of Section 73.68(a) of the Rules. As before, stations constructing new antenna systems pursuant to a construction permit must obtain approval of their sample system when filing for a covering license. Existing stations may obtain approval by informal request to the FCC in Washington, D.C.

To obtain antenna system approval, applicants may follow either of the procedures set forth in Paragraphs A or B below:

A. Demonstrate that the system complies with the provisions of Section 73.68(a) of the Rules in effect prior to January 1, 1986.

B. Demonstrate stability of operation by submission of the following information:

(1) A detailed and complete description of the antenna monitoring system installation.

(2) Field strength readings taken on a monthly basis at each of the monitoring points specified in the instrument of authorization for a one year period prior to the date of the application.

(3) The following readings taken daily for each directional pattern use during the thirty-day period prior to the filing of the application:
   a. Common point current.
   b. Base currents and their calculated ratios.
   c. Antenna monitor sample current ratios.
   d. Antenna monitor phase readings.
   e. Final amplifier DC input voltage and current.

(4) The results of either a partial proof-of-performance (Section 73.154) or a full proof (Section 73.186) conducted no longer than 3 months prior to the filing of the application and the common point impedance at the operating frequency measured at the time of the proof.

Additional sampling system components and configurations found by the Commission to be accurate and stable over a wide range of environmental and operational conditions will be included as acceptable under Paragraph A above and announced periodically via public notice.

Questions concerning sampling system approval may be directed to John Sadler (202) 632-7010 and questions concerning the Report and Order in MM Docket 85-90 may be directed to John Reiser (202) 632-9660.

SECTION 73.68(a) OF THE FCC RULES IN EFFECT PRIOR TO JANUARY 1, 1986-SAMPLING SYSTEMS FOR ANTENNA MONITORS

(See text on page 2.8-223)

(a) The following requirements govern the installation of systems employed to extract samples of the currents flowing in the elements of a directional antenna, and to deliver these samples, to the antenna monitor. Each new station issued a construction permit, each existing station issued a construction permit authorizing tower construction, and any existing station undertaking modification or reconstruction of its sampling system must install the system meeting the following requirements. The application for license or modification of license must describe the system in sufficient detail to demonstrate its compliance with the following:

(1) All coaxial cable from the sampling elements to the antenna monitor, including cable used in the construction of isolation coils, except short lengths of flexible cable connecting the transmitter house sampling line termination to the monitor, must have a solid outer conductor and have uniform physical and electrical characteristics. The dialectric must be either predominantly pressurized air or other inert gas, or foamed polyethylene.

(i) All sampling lines for a critical antenna array (i.e., an array for which the station authorization requires the maintenance of phase and current relationships within specified tolerances) must be of the same electrical length, with corresponding lengths of all lines exposed to equivalent environmental conditions.

(ii) For other arrays, lines of differing length may be employed, provided that the difference in length between the longest and the shortest line is not so great that, over the range of temperatures to which the system is exposed, predicted errors in indicated phase difference resulting from such temperature changes will exceed 0.5 degrees.

(iii) A sampling line mounted on a tower must be adequately supported to prevent displacement, and must be protected against physical damage. Where feasible, sampling line sections between each tower base and the transmitter house is to be jacketed and buried: lines run above ground must be firmly supported, and protected against physical damage, with the outer conductor strapped to the station's ground system at such points as found necessary to minimize currents induced by antenna radiation.

(iv) All necessary connections and outdoor cable terminations must be made with waterproof fittings designed for use with the type of cable employed.

(v) For determining the permissible differences in the line lengths that may be installed, the total difference between the highest listed normal daily maximum and lowest listed normal daily minimum temperatures as shown for the nearest location shown in the most recent issue of "Local Climatological Data Annual Summaries" shall be used in the calculations. This publication is available from:

National Climatic Center
National Oceanic and Atmospheric Administration
Asheville, North Carolina 28801

(vi) The provisions of this subparagraph do not preclude the use of a centrally located impedance-matched radio frequency relay or a remotely controlled switch to provide a relative sampling currents to the antenna monitor over a single transmission line. However, the reference sampling line and the relative sampling line from the switching point to the antenna monitor must be identical in type and electrical length, and must be exposed to the same environment. The sampling line from each sampling element to the relay must conform to all relevant requirements indicated in this subparagraph. Alternatively, when such a relay is used to select signal samples from any of two or more sampling devices installed either on the tower or at its base and feed the sample to the antenna monitor through a single sampling line, the length of cable from each device to the relay shall be equal. Additionally, a licensee may install the antenna monitor at a centrally located or otherwise convenient location provided that the temperature and humidity of the operating environment are maintained within the tolerances specified by the antenna monitor manufacturer. When such an antenna monitor is to be remotely controlled and read, installation shall conform to the requirements of Section 73.67 of this Part.

(2) Except as provided below, sampling

elements must be single turn, unshielded loops of extremely rigid construction, with ample, firmly positioned gaps at the open loop end, mounted on towers at a fixed orientation. Loops must be installed to operate at tower potential, provided that for towers less than 130 degrees in electrical height, loops operating at ground potential may be used. Each loop must be mounted on the tower near the point of maximum tower current, but in no case less than three meters (10 feet) above ground.

(3) Shielded current transformers may be used in lieu of unshielded loops to extract samples from antenna feed lines at the base of each tower having a uniform cross-section and 110 degrees or less in electrical height, or a self-supporting tower 110 degrees or less in electrical height, provided it has a common feedpoint for all tower legs.

(4) Shielded current transformers may be used in lieu of unshielded loops to extract samples from the antenna feed line at the base of each tower having a uniform cross-section more than 110 degrees but not greater than 130 degrees in electrical height, self-supporting towers not exceeding 130 degrees in electrical height and having a central common feedpoint for all tower legs, and folded unipole antennas of any height having a base driving point resistance and reactance not exceeding 70 ohms, provided the following conditions are met:

(i) Stability of operation during a test period of 30 continuous days using the current transformers must demonstrate that the antenna monitor sample current ratios do not exceed five percent of those specified on the station authorization and that the relative phase indictions are with ± 3 degrees of the values specified on the station authorization, unless a more stringent tolerance is specified therein.

(ii) The following parameters shall be read and recorded as indicated during the 30 day test period for each antenna pattern:

(A) Indications at each monitoring point specified in the station authorization, weekly.

(B) Base currents and their calculated ratios, weekly.

(C) Common point current, daily.

(D) Antenna monitor sample current amplitudes and their ratios, daily.

(E) Antenna monitor phase indications, daily.

(iii) Failure to meet the stability requirement specified in paragraph (a)(4)(i) of this Section will require that the licensee seek special temporary authority to operate at variance with the terms of the station instrument of authorization until the problem can be corrected.

(iv) A certification by the licensee that the sampling system meets the stability requirement specified in this paragraph must be included in the request for approval of the monitor sampling system together with the information specified in paragraph (c) of this Section.

(v) Shielded current transformers may be used in lieu of unshielded loops to extract samples from the antenna feed line at the base of each tower greater than 130 degrees in electrical height provided the requirements set forth in subparagraphs (a)(4)(i) through (iii) of this Section are satisfied and the resulting data is included in the request for approval of the monitor sampling system together with the information specified in paragraph (c) of this Section.

(vi) The FCC may request the licensee to conduct such other tests, or measurements, or submit additional data it deems necessary to determine the stability of the antenna sampling system.

(b) Each license or modified license issued pursuant to an application containing a satisfactory showing that a sampling system has been constructed complying with the requirements set forth in subparagraphs (a)(1) and (2) of this section, and that an antenna monitor of a make and type approved or notified by the FCC has been installed, will be conditioned to exempt the

licensee from compliance with the rules which require:

(1) The routine reading and logging of base currents in the array elements.

(2) That monitoring point measurements can be made more frequently than at average intervals.

(3) The readings and station log entries specified in Section 73.1830(a)(2) be made.

(4) The skeleton proof-of-performance measurements required by Section 73.61. Note not required.

(c) Any existing station with an antenna monitor sampling system meeting the specifications of paragraphs (a)(1) and (2) of this section, wishing to be exempted from the logging and measurement requirements listed in paragraph (b) may send an informal request to the FCC in Washington, D.C. The request must be signed by the licensee or officer of the licensee and contain sufficient information to show compliance with the requirements of paragraph (a), including the following:

(1) The brand and type number of the coaxial sampling line cable, with a description of the dielectric material and electrical characteristics.,

(2) The overall length of each sampling line. If cables of different length are installed, the calculations to show that the phase difference of signals at the monitor are less than 0.5 degrees between the shortest and longest cable length.

(3) A description of the sampling elements (loops or current transformers) and the position of their installation, and when loops are installed, whether bonded or insulated mounting is used.

(d) In the event that the antenna monitor sampling system is temporarily out of service, the station may be operated pending completion of repairs for a period not exceeding 60 days without further authority from the FCC, if,

(1) The base currents, their ratios, and the deviations of those ratios, in percent, from the values specified in the station authorization are determined for each radiation pattern used, as often as necessary to ensure proper directional antenna system operation and,

(2) Field strength measurements, at each monitoring point specified in the station's authorization, are read at least once each calendar week.

(e) If the antenna sampling system is modified or components of the sampling are replaced, the following procedure shall be followed:

(1) Temporary authority shall be requested and obtained from the Commission in Washington to operate with parameters at variance with licensed values pending issuance of a modified license specifying parameters subsequent to modification or replacement of components.

(2) Immediately prior to modification or replacement of components of the sampling system not on the towers, and after a verification that all monitoring point values, base current ratios and operating parameters are within the limits or tolerances specified in the instrument of authorization or the pertinent rules, the following indications must be read for each radiation pattern: Final plate current and plate voltage, common point current, base currents and their ratios, antenna monitor phase and current indications, and the field strength at each monitoring point. Subsequent to these modifications or changes the above procedure must be repeated.

(3) If that portion of the sampling system above the base of the towers is modified or components replaced, a partial proof-of-performance shall be executed subsequent to these changes consisting of at least 10 field strength measurements on each of the radials established in the latest complete proof-of-performance of the antenna system. These measurements shall be made at locations, all with 3 to 16 kilometers (2 to 10 miles) from the antenna which was utilized in such proof, including, on each radial, the location, if any, designated as a monitoring point in the station authorization. Measurements shall be analyzed in the manner prescribed in Section 73.186. The partial proof-of-performance shall be accompanied by common point impedance measurements made in accordance with Section 73.54.

(4) Request for modification of license shall be submitted to the Commission in Washington, D.C., within 30 days of the date of sampling system modification or replacement. Such request shall specify the transmitter plate voltage, and plate current, common point current, base currents and their ratios, antenna monitor phase and current indications, and all other data obtained pursuant to this paragraph (E).

(e) If an existing sampling system is found to be patently of marginal construction, or where the performance of a directional antenna is found to be unsatisfactory, and this deficiency reasonably may be attributed, in whole or in part, to inadequacies in the antenna monitoring system, the FCC may require the reconstruction of the sampling system in accordance with requirements specified above.

FCC POLICY STATEMENT ENTITLED "THE APPLICATION PROCESS AND THE USE OF NON-DISCRETE POWER LEVELS FOR AM STATIONS" DATED OCTOBER 11, 1985

By Commission Report and Order dated April 24, 1985, changes were made in the FCC Rules which eliminated the requirement that AM stations file for facilities using power levels at a limited number of discrete values (e.g.: 0.25 kW, 1.0 kW, 5.0 kW, etc.). These modifications were intended to provide greater flexibility for AM applicants. However, details regarding implementation of certain provisions of the new rules need to be further addressed.

Under the new rules, a single value will be designated for the nominal power and the antenna input power (excluding the directional antenna supplement allowed under Section 73.51(b)(1) and (b)(2)). In the past, a radiation value less than the theoretically predicted amount could be achieved by applying a power level less than the nominal value to the antenna to provide compensation and both the nominal and antenna input powers would be licensed. With the removal of the discrete power level requirement, the power actually delivered to the antenna becomes the licensed nominal power, barring the above-mentioned exclusion. Several examples of how the application process will operate under these new rules are discussed below.

Consider first, applications which propose non-directional antennas. In the case of a new station, the power will be directly derived from the proposed radiation for that allocation. The radiation will be first extracted from Figure 8 of Section 73.190 of the FCC Rules (based upon antenna height and ground system), and then, that value adjusted by the square root of the proposed power to produce the proposed radiation. Alternatively, the proposed power will be derived from the square of the ratio of the proposed radiation to the Figure 8 predicted value. For an existing station proposing a change of facilities, these same methods apply. This is a departure from the former treatment where, if, for instance, an AM antenna height was being increased to accommodate an FM antenna and the AM radiation was to be maintained at the licensed value, then the station would retain its nominal power but reduce its antenna input power and would be licensed with a restricted radiation. Under the new rules, restricted radiations are being eliminated as they are encountered in formal applications that propose changes in the antenna systems. Thus, any such application must specify the actual power to be applied to the antenna and the end result will be a licensed operation with an apparent power reduction, but, in reality, coverage and radiation equivalent to the previous operation.

For directional operations involving a new station or a proposal utilizing a new antenna system (in particular, site relocations), the provisions of Section 73.150(b)(1)(i) shall be observed and the pattern RMS shall be developed using an assumed loss of one ohm per tower and the power adjusted to meet that RMS value. Patterns proposed under these circumstances that do not meet this criterion will result in a request to the applicant for a corrective amendment.

Directional applications that propose only slight modifications of existing arrays may have a sufficient history of antenna perfor-

mance and measurement data which can, in many cases, be used to demonstrate whether a particular system operates with an inherently greater loss than the one ohm method may approximate. For these specific systems, when the application proposes to modify only the theoretical parameters of the existing operation and leaves the overall system geometry unchanged, exemption from the RMS/power relationship based upon one ohm loss can be entertained. Should it become apparent after filing of the license application that a reduction of the input power is necessary to meet the pattern requirements, then that new power level will become the licensed power and any reference to the old nominal power will be deleted.

Additionally, there may be situations where a newly constructed directional antenna has been completed, and a license application has been submitted and it is demonstrated, based upon proof data, that the antenna system, due to its intrinsic shortcomings, does not perform to the level expected by use of one ohm per tower loss assumption. In such cases, an upward power adjustment can be affected at the time of license application. Such adjustment is to be made based upon a direct mathematical escalation applied to the measured values of inverse distance field while providing assurance that no adjusted value in any direction shall exceed the authorized standard pattern limitation. Requests for augmentation of the standard pattern to accommodate additional expansion once the requirements of Section 73.151(a) [regarding minimum RMS (85%)] have been met will be categorically denied. In no event will a power adjustment be allowed that would result in a power level in excess of the maximum value specified for that class of station. Upon Commission approval of the adjusted power, such value will become the licensed value and appropriate domestic and international notification procedures and data base updating will be initiated by the FCC staff. Also, at such time, the new power will be placed on FCC Public Notice. In most cases, the increase of power would normally affect the calculation of the standard pattern 'Q' factor as defined by Section 73.150(a)(1)(i) of the FCC Rules. However, since the purpose of the power adjustment is to allow for the actual performance of a constructed antenna system within the constraints of the proposed pattern, the original array design parameters should not require reconsideration. Therefore, the value of 'Q' as authorized in the construction permit will be retained and will subsequently be carried on the station license along with the modified value of nominal power. Similarly, this unchanged, but now non-standard, 'Q' value will undergo the proper international notification and data base updating processes.

Therefore, with the preponderant consideration given under the new Rules to the pattern RMS values and radiation efficiencies and their relationship to expected coverage area, no loss of service should be experienced, even though unfamiliar power levels begin to appear upon station licenses.

Related to the methods described within this Notice, examples are presented which depict some of the more frequently experienced applicational scenarios. These are included as an appendix to this document.

Further information on the matters discussed in this Notice may be obtained from James G. Ballis (202) 632-7010, or Henry A. Straube (202) 632-7010 both at the AM Branch of the Audio Services Division of the Mass Media Bureau.

EXAMPLES

Situation 1:

An existing non-directional station with a nominal power of 5 kilowatts, an antenna input power of 5 kilowatts, and an effective field of 300 mV/m/kW at one kilometer increases its antenna height while restricting radiation to the present value instead of achieving an effective field of 325 mV/m/kW at one kilometer for the new height. When the CP is issued, the nominal and antenna input power will be 4.3 kilowatts. [(300/325) squared x 5]

Situation 2:

A permittee for a new directional station with a nominal power of 5 kilowatts, a standard RMS of 700 mV/m at one kilometer, and and a Q of 25.0 mV/m at one kilometer determines via the proof-of-performance that the measured RMS is actually 800 mV/m at one kilometer. When the covering license is issued, the nominal power will be 3.8 kilowatts, the antenna input power will be 4.1 kilowatts, the standard RMS will remain at 700 mV/m, and the Q will remain at 25.0 mV/m. [(700/800) squared x 5 with an 8 percent adjustment pursuant to Section 73.51(b)(1) of the Rules]

Situation 3:

A permittee for a new Class II directional station with a nominal power of 5 kilowatts,

a standard RMS of 750 mV/m at one kilometer, and a Q of 25.0 mV/m at one kilometer determines via the proof-of-performance that the measured RMS is actually 630 mV/m at one kilometer. When the covering license is issued, the nominal power will be 7.1 kilowatts, the antenna input power will be 7.5 kilowatts, the standard RMS will remain at 750 mV/m, and the Q will remain at 25.0 mV/m. [(750/630) squared x 5 with a 5.3 percent adjustment pursuant to Section 73.51(b)(2) of the Rules]

Situation 4:

A permittee for a new Class III directional station with a nominal power of 5 kilowatts, a standard RMS of 750 mV/m at one kilometer, and a Q of 25.0 mV/m at one kilometer determines via the proof-of-performance that the measured RMS is actually 630 mV/m at one kilometer. The permittee must apply for a modification of construction permit to reduce the standard RMS to 630 mV/m so that the power to be authorized does not exceed 5 kilowatts.

FCC POLICY AS PUBLISHED IN BC DOCKET NUMBER 78-28 AND MM DOCKET NUMBER 83-16 CONCERNING THE ESTABLISHMENT OF MAXIMUM MONITOR POINT VALUE

The following item addresses the current FCC Policy governing assignment of monitor point limits and has been abstracted from the Docket released December 20, 1983. The policy is in the form of a letter dated December 6, 1979 and results from a series of informal meetings with the FCC engineering staff and the Association of Federal Communications Consulting Engineers. It was signed by Richard Shiben, Chief of the Broadcast Bureau, and is included in its entirety as the FCC provides a background, essence and discussion of its views and the relationship of the monitor point in the licensing process. The policy was also formally published in Docket 78-28 released December 20, 1983. It reads as follows:

"I have your letter of October 22, written on behalf of your committee, requesting modification of certain Commission engineering practices used in assigning monitoring point limits to AM directional broadcast stations. Your letter formalizes suggestions developed in a series of meetings, begun well over a year ago, between your committee and members of the Broadcast Facilities Division's engineering staff concerning the policies and procedures governing the preparation and processing of various types of applications. The interest shown throughout this period by your committee in helping improve our processing procedures has been helpful and is greatly appreciated.

Specifically, your committee feels that, under the present policy, monitoring point limits are often assigned which are unnecessarily restrictive and urges the adoption of a policy whereby the assignment of these limits is based on the "direct ratio" method. The committee also urges the establishment of a policy whereby stations subject to seasonal conductivity changes can achieve relaxed limits upon submission of "seasonal proofs". Additionally, the committee requests that the Commission refrain from altering monitoring point limits based on partial proofs-of-performance if "substantial conformance" of radiation patterns is demonstrated and the antenna parameters are either essentially unchanged or, if changed, adequately justified.

In response to your first suggestion, I am pleased to announce that we have, on an experimental basis, adopted the policy of assigning monitoring point limits using the direct ratio method. Under the direct ratio method, monitoring point limits are obtained by multiplying the measured field strength at a monitoring point by the ratio of the authorized maximum radiation divided by the unattenuated radiation established in the proof-of-performance. This method simply restricts unattenuated radiation to within its maximum authorized value whereas the traditional method in many cases restricted radiation much more severely. Theoretically, objectionable interference is not caused if antenna radiation is maintained below its maximum authorized value. Assuming, therefore, that changes in monitoring point field strength correspond directly to changes in antenna radiation, monitoring point limits determined by the direct ratio method should be adequate to avoid in-

terference. However, since the assumption of a linear relationship between monitor point readings and antenna radiation becomes somewhat questionable with excessive changes, we do not intend to assign limits higher than 200% above proof values. In addition, because operation with monitoring point field strength in excess of the direct ratio limit could result in objectionable interference, we will continue to deny requests to exceed those limits.

Your second suggestion addresses a problem encountered in many areas of the country where complete proofs-of-performance are done during the summer months when ground conductivity is significantly lower than during the winter months. Often monitoring point limits resulting from such summertime proofs are not sufficient to accommodate higher readings encountered during winter. In such a case increased limits are obtained by collecting supplemental wintertime data in the form of a partial proof of performance consisting of at least 10 measurements on each radial established in the complete proof (see Section 73.154(a) of the Rules). You suggest that the Commission accept "seasonal proofs" for this purpose in lieu of partial proofs. A seasonal proof would consist of "at least 20 field strength measurements, both non-directional and directional, on each of the radials specified in the construction permit and at least one radial in the major lobe".

In responding to this suggestion, it is helpful to understand the approach used by Commission engineers in analyzing complete proofs-of-performance. These generally consist of 20 or 30 measurements per radial (see Section 73.186(a)(1)) and serve as the reference for all subsequent partial proofs. As you know, the fundamental problem is distinguishing between the effects of conductivity and antenna radiation. In making this distinction, we consider it imperative to establish, as conclusively as possible, the size and shape of the non-directional radiation pattern. The non-directional radiating system is simpler (fewer variables) than the directional system and its RMS (size) can be more accurately determined since each measured radial is of more or less equal significance, particularly if the radials are evenly spaced. With a directional pattern, many of the minor-lobe and null radials do not contribute significantly toward defining the RMS, leaving the remaining main lobe radials with a disproportionate influence on the determination of the pattern size. For these same reasons, the Commission relies entirely on non-directional measurement data in determining the extent of seasonal changes in conductivity.

Because of the crucial role played by the non-directional pattern resulting from a complete proof-of-performance, extreme care is used in analyzing the measurement data. Experienced engineers who have been carefully trained are used in the work. All known external factors such as terrain features, re-radiating structures, pipe lines, etc., are taken into account. Each radial is repeatedly weighed against the others with constant attention to the resulting pattern shape and RMS and the analysis is not considered complete until the importance of each element of data is understood from the perspective of the whole. Of course, the more extensive and "well behaved" the measurement data, the more precise and confident the engineer can be with his/her analysis. Once the non-directional pattern is established, analysis of the directional data can usually be done mathematically, rather than graphically, using either arithmetic or logarithmic averages. Any subsequent non-directional partial proofs which are submitted to the Commission for the purpose of documenting suspected conductivity changes are mathematically analyzed, point for point along each radial, against the complete proof non-directional data (See Section 73.186(a)(5)). If the possibilities of distortion and chanted RMS can be eliminated from the partial proof non-directional pattern, then the extent of conductivity change along each radial can be determined and applied to the directional partial proof data revealing whether, in fact, observed change in directional field strengths resulted from changes in the radiation pattern or simply from conductivity changes.

The notion of a seasonal proof, to the extent that some of the proof radials would be eliminated, strikes at the very heart of our approach which is an accurate determination of the non-directional radiation pattern. Although, under the committee's suggestion, the minimum number of measurements on some radials would be raised from 10 to 20, we do not feel the value gained from additional data on these radials would be sufficient to offset the complete loss of data on the remaining radials. This is also the case for directional patterns where changes in radiation in some directions can affect radiation in other directions and assumptions of pattern symmetry are generally unreliable. The Commission encourages supplemental measurements in addition to the minimum of 10 per radial required by the

Rules; this should not be accomplished, however, at the expense of fewer measurements on other radials.

Your last suggestion concerns the Commission's assignment of monitoring point limits in response to partial proofs-of-performance conducted following antenna repairs, refurbishment, construction or readjustment. Often such proofs result in a reduction in limits below those previously assigned because measurements were taken during periods of low conductivity or because antenna radiation in some directions was reduced. The committee suggests we not lower limits in such cases if the pattern remains in substantial conformance and the antenna parameters (phases and current ratios) are either essentially unchanged or, if changed, adequately justified. We believe this suggestion has merit and have, also on an experimental basis, ceased the practice of lowering limits based on partial proofs except when such limits would exceed measured values by more than 200%.

We feel that the current mandatory use of type-approved antenna monitors by directional stations and the widespread use of approved sample systems permit these changes in policy at this time without endangering in any way the technical integrity of our AM broadcasting system. Nonetheless, because of the significance of these changes, we intend to proceed on an experimental basis for at least a year, gaining the benefit of practical experience, before permanently adopting them. In addition, cases clearly falling beyond the scope of these policies will continue to be handled on a case-by-case basis.

We are hopeful that the changes we have initiated in response to your suggestions will provide many stations with operating tolerances sufficient to accommodate variations which under our old policy, would have required a proof-of-performance and the filing of an application with the Commission. Again, I would like to express my sincere appreciation for the work done by your committee in bringing forth these suggestions".

Sincerely,
Chief, Broadcast Bureau

FCC POLICY STATEMENT ENTITLED "ENVIRONMENTAL PROCESSING RULES FOR BROADCASTERS" DATED NOVEMBER 14, 1985

Effective January 1, 1986, the Commission's environmental rules will be amended to provide the evaluation of human exposure to radio frequency (RF) radiation. The following information addresses several aspects of that matter which have been of particular concern in the broadcasting industry.

In the broadcast services, the Commission will routinely consider the effect of a broadcast station on the environment at the time when a party applies for a construction permit (for new or modified facilities), and when a licensee files for renewal.

With regard to applications for new facilities or operations, the Commission will be determining the potential impact, if any, of a station on its surroundings. This will normally be done in conjunction with the staff's review of the technical aspects of a proposal. Consideration of an RF radiation issue at this point in the Commission's authorization process will afford an opportunity for modification before construction has begun.

With regard to renewal applications, the Commission and licensee will be evaluating the consequences of any change in a station's surroundings, usually the construction of nearby businesses and residences. (Part 1, Subpart I of the Commission's rules sets forth the administrative procedures implementing the National Environmental Policy Act, a list of those actions which may affect the environment, and a description of those actions which are categorically excluded.)

With regard to applications for construction permits filed prior to January 1, 1986, but not acted upon by the Commission until after that date, the FCC may require an environmental assessment of RF radiation either on its own motion, or in response to an objection filed by a third party based on a proper technical showing. Environmental assessments of RF radiation will not otherwise routinely be required for those applications.

Although an applicant's affirmative responsibility to include the potential effects of RF

radiation in the application's environmental evaluation does not become effective until January 1, 1986, any applicant who files prior to that date and who has reason to believe that its requested operation would exceed the American National Standards Institute's guidelines is encouraged to bring the facts to the Commission's attention so that the application can be given appropriate environmental review.

Every such applicant will definitely have the affirmative responsibility to report on RF radiation in its renewal application, and with any modification application filed after January 1, 1986. An applicant's diligence and foresight in raising and addressing the RF radiation hazard issue at an early stage in the authorization process may save substantial application processing time and modification expense in the future. The potential effect of RF radiation on the environment was not routinely considered as part of the Commission's processing of the last cycle of broadcast license renewal applications. Accordingly, all licensees must be alert for existing RF radiation problems when renewal first comes due after January 1, 1986, even if the surroundings have remained unchanged over a long period.

2.9

Radio Wave Propagation

Marty Barringer
Staff Engineer
Frederick G. Griffin, P.C
Lynchburg, Virginia

Radio wave propagation is the study of the transfer of energy at radio frequencies from one point, a transmitter, to another, a receiver. Radio waves are part of the broad electromagnetic spectrum that extends from the very low frequencies which are produced by electric power facilities up to the extremely high frequencies of cosmic rays. Between these two extremes are bands of frequencies that are found in every day uses: audio frequencies used in systems for the reproduction of audible sounds, radio frequencies, infrared, light, ultraviolet, and X-rays.

Electromagnetic waves travel at the velocity of light waves, which for a vacuum is 3×10^8 m/sec. The velocity of any wave is dependent upon the medium in which it is traveling, but for simplicity is usually considered with respect to a vacuum. The frequency of a wave is defined in terms of the number of cycles per second or Hertz (Hz) and is related to the wavelength λ in meters by the expression $\lambda = c/f$ where c is the velocity of light. Fig. 1 shows the ranges of various bands of frequencies within the electromagnetic spectrum in terms of frequency and wavelength.

Radio frequencies are generally confined to that portion of the electromagnetic spectrum that is between the audio frequency portion and the infrared portion. At present, the practical limits of radio frequencies lie roughly between 10 kHz and

NOTE: Superscript numbers refer to references at the end of the chapter.

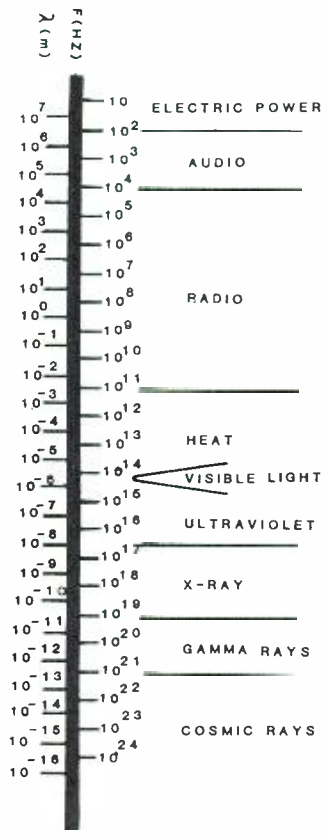


Fig. 1. Electromagnetic spectrum.

100 GHz.[1] Within the radio frequency spectrum are bands of frequencies that have been allocated to the broadcast service. The following discussions and methods will apply particularly to these bands of the radio frequency spectrum.

The AM broadcast frequency allotments are contained in what is referred to as medium frequencies (MF), 300 kHz to 3 MHz. The FM broadcast frequencies and a portion of the TV broadcast frequencies band are contained in the VHF band which extends from 30 MHz to 300 MHz. The remaining TV broadcast allocations are contained in the UHF band of 300 MHz to 3 GHz. Allocations for broadcast auxiliary services such as remote pickup, studio-transmitter links, intercity relays, MDS, and ITFS are interspersed within the MF, VHF, UHF and SHF (Super High Frequency) bands. Table 1 illustrates that portion of the spectrum assigned to the broadcast service. The allocations for auxiliary services may change from time to time as the needs of various services for radio frequencies change and as technology for equipment improves, so Table 1 is included as an illustration of the wide band of frequencies allocated to the broadcast services. For a discussion of the origin of the frequency allocations for broadcasting and broadcast auxiliary services the reader should refer to Chapter 1.5 of the Handbook, "Frequency Allocations for Broadcasting and the Broadcast Auxiliary Services," by Michael Rau. In order to keep abreast of new frequency allocations the most current FCC Rules and Regulations should be consulted.

TABLE 1. Broadcast Frequency Allocations.

MF 300 kHz—3 MHz	
AM:	525 kHz—1605 kHz
VHF 30 MHz—300 MHz	
FM:	88 MHz—108 MHz
TV:	54 MHz—72 MHz Channels 2-4
	76 MHz—88 MHz Channels 5-6
	174 MHz—216 MHz Channels 7-13
UHF 300 MHz—3 GHz	
TV:	470 MHz—806 MHz Channels 14-69
AM-FM SATL:	947 MHz—952 MHz
MDS:	2150 MHz—2162 MHz
ITFS:	2500 MHz—2686 MHz
Auxiliary Services:	2000 MHz—3000 MHz
SHF 3 GHz—30 GHz	
Auxiliary Services:	6.425 GHz—7.125 GHz
CARS:	12.700 GHz—13.250 GHz
TV STL:	17.700 GHz—19.700 GHz

QUANTIFYING PROPAGATION

The energy that is emitted from a transmitter may take many different paths before it is received. The path that the radio wave will take depends on many factors, some of which include: frequency, antenna type and height, atmospheric conditions, and terrain. Radio waves that propagate along the surface of the earth are commonly referred to as ground waves. All radio waves have some ground wave component; however because the earth is a lossy medium, it severely attenuates the radio wave. This attenuation increases with frequency, and so this mode of propagation is useful for only frequencies below 30 MHz. To achieve significant distances the atmosphere is preferred over ground waves as a transmission medium. The atmosphere is comprised of several different layers, as depicted in Fig. 2. The *troposphere* is the layer that extends from the earth's surface up to about 16 km. This layer is the chief mode of propagation for frequencies above about 30 MHz, and propagation through this layer is dependent upon weather conditions. The next layer is the *stratosphere* which extends to about 40 km above the earth. But has no drastic effect on the propagation of radio waves. The *ionosphere* extends upwards of 400 km above the surface of the earth. This region is a charged environment where the air is sufficiently ionized, mainly by the sun's ultraviolet radiation, to reflect or absorb radio waves below about 30 MHz. The ionosphere is constantly changing and is usually considered as consisting of the following sublayers.[2]

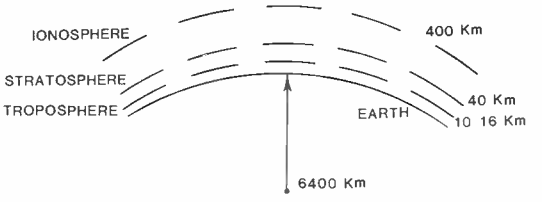


Fig. 2. Atmosphere layers.

- **D layer**—This layer exists at heights from about 50 km to 90 km and is present only during daylight hours. The electron density is directly related to the elevation of the sun. This layer absorbs medium and high frequency radio waves.

- **E layer**—This layer exists at a height of about 110 km and is important in the nighttime propagation of medium frequency radio waves. The ionization of this layer is closely related to the elevation of the sun. At certain times irregular cloud-like areas of high ionization may occur. These areas are known as sporadic E and occasionally prevent frequencies that normally penetrate the E layer from reaching higher layers. [The sporadic E layer is prevalent during the summer and winter months. The sporadic E layer formed during the summer is the longest, lasting from

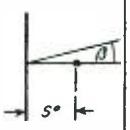
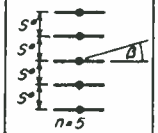
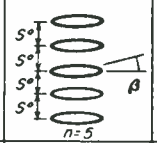
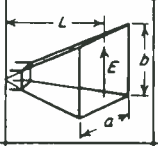
TYPE	CONFIGURATION	PATTERN	POWER GAIN OVER ISOTROPIC	EFFECTIVE AREA
ELECTRIC DOUBLET		$\cos\theta$	1.5	$1.5\frac{\lambda^2}{4\pi}$
MAGNETIC DOUBLET OR LOOP		$\sin\theta$	1.5	$1.5\frac{\lambda^2}{4\pi}$
HALF WAVE DIPOLE		$\frac{\cos(\frac{\pi}{2}\sin\theta)}{\cos\theta}$	1.64	$1.64\frac{\lambda^2}{4\pi}$
HALF WAVE DIPOLE AND SCREEN		$2\sin(S^\circ\cdot\cos\beta)$	6.5	$1.64\,\lambda^2/\pi$
TURNSTILE ARRAY		$\frac{\sin(n\frac{S^\circ}{2}\sin\beta)}{n\sin(\frac{S^\circ}{2}\sin\beta)}$	n OR $2L/\lambda$	$n\lambda^2/4\pi$ OR $L\lambda/2\pi$
LOOP ARRAY		$\frac{\cos\beta\sin(n\frac{S^\circ}{2}\sin\beta)}{n\sin(\frac{S^\circ}{2}\sin\beta)}$	n OR $2L/\lambda$	$n\lambda^2/4\pi$ OR $L\lambda/2\pi$
OPTIMUM HORN $L \geq a^2/\lambda$		HALF POWER WIDTH $70\lambda/a$ DEGREES (H PLANE) $51\lambda/b$ DEGREES (E PLANE)	$10\,ab/\lambda^2$	$0.81\,ab$
PARABOLA		HALF POWER WIDTH $70\lambda/d$ DEGREES	$2\pi d^2/\lambda^2$	$d^2/2$

Fig. 3. Patterns, gains, and areas of typical antennas.

May to August, and the winter layer lasts about half as long beginning in December. During the mid-summer months when the electron density is at its greatest levels, TV signals in the lower VHF band can be transmitted over distances of hundreds or thousands of kilometers.[3]]

• **F1 layer**—This layer exists at heights of about 175 to 200 km and is present only during the day. Waves that penetrate the E layer (3 to 30 MHz) will be reflected by the F2 layer. The F1 layer introduces additional absorption of these waves.

• **F2 layer**—This layer exists at the upper boundaries of the atmosphere, 250 to 400 km, and is present at all times though the height and electron density will vary from day to night, with the seasons, and over sunspot cycles. During the night the F1 layer merges with the F2 layer at about 300 km. This, in addition to the reduction of the D and E layers, causes nighttime field intensities and noise to be generally higher than during the day.

FREE SPACE PROPAGATION

In beginning the study of the means of how radio waves propagate and how the field strengths may be calculated it is necessary to adopt a sim-

ple standard of reference. It is customary to consider as a standard the theoretically calculated loss for waves propagated in free space between two idealized antenna. The simplest case is the radiation emitted from an isotropic source: an ideal antenna which radiates energy with uniform intensity in all directions. An analogy to an isotropic antenna is a point source of light, such as a candle. The intensity of the energy varies proportionally to the inverse of the distance squared from the source, the "inverse square law." The power flux per unit area $P_a(W/m^2)$ at a distance *d(m),* from a loss-free isotropic antenna radiating a power $P_t(W)$, is given by:

$$P_a = P_t/4\pi d^2 \quad [1]$$

where $4\pi d^2$ is the surface area of a sphere at a distance d(m) from the source. The power available from a loss free antenna P_r is the product of the power flux per unit area P_a and the effective aperture area of the receiving antenna A_e. This area is related to the gain of the antenna by the expression:

$$A_e = G\lambda^2/4\pi \quad [2]$$

Aperture areas and gains for specific antennas are given in Fig. 3. For a loss-free isotropic antenna $G = 1$ the basic free space transmission loss is defined as:

$$L_{bf} = P_t/P_r = (4\pi d/\lambda)^{||} \quad [3]$$

where d and λ are in the same units. This equation can be rewritten in its more common form by solving for the common logarithm of both sides (10 *log* (P_t/P_r)):

$$L_{bf} = 32.44 + 20\ log\ F + 20\ log\ d\ [dB] \quad [4]$$

where F is the frequency in megahertz (MHz) and d is the distance between antennas in kilometers. In the above equation it should be remembered that ideal loss-free isotropic antennas are considered. In real world systems, antenna gain is a significant factor. The equation that incorporates antenna gains is known as the transmission loss and is defined as:

$$L = L_{bf} - (G_t + G_r + L_d)\ [dB] \quad [5]$$

where G_t and G_r are the free space antenna gains with respect to isotropic for the transmitting and receiving antenna respectively. The term L_d is the aperture-to-medium coupling loss or polarization coupling between the antennas. The term L_d will have a value of 0 dB when the transmitting and receiving antennas have the same polarization.

In considering the potential service area coverage for a broadcast station, it is usually more desirable to express measurements in terms of field strength rather than transmission loss as previously presented. The root-mean-square (RMS) field strength, E in volts per meter, at a point where the power density of a plane wave is P_a in watts per square meter is given by:

$$E = (120\pi P_a)^{1/2} \quad [6]$$

where the term 120π is the impedance of free space. The power available from a loss free isotropic antenna is determined from equations [1], [3], and [6] above:

$$E = (480\pi^2 P_r/\lambda^2)^{1/2} \quad [7]$$

or in logarithmic terms:

$$E = 107.2 + 10\ log\ P_r + 20\ log\ F\ [dBu] \quad [8]$$

The electric field produced by a transmitter radiating a power $P_t(W)$ at a distance *d(m)* in free space can be derived from [1] and [6] and is given by:

$$E = (30P_t/d^2)^{1/2} \quad [9]$$

A more useful form of the free space field can be expressed in logarithmic terms above 1 microvolt per meter (dBu) when d is in kilometers, P_t is expressed in decibels above 1 kW (dBK), and a transmitting antenna has a gain G_t in decibels above isotropic:

$$E = 105 + P_t + G_t - 20\ log\ d\ [dBu] \quad [10]$$

Using the same units the field strength $E(dBu)$ for non-free space environments can be related to the basic transmission loss by:

$$L_b = 137 + 20\ log\ F + P_t + G_t - E\ [dB] \quad [11]$$

These equations form the basis of propagation. They do not, consider such real world factors as the presence of the earth, atmosphere, or obstructions. To describe an actual radio system, additional losses will need to be added to the free space equations derived above.

Propagation over Earth's Surface

When the transmitting and receiving antennas are placed over ground, the propagation of radio waves is modified from the free space models presented above. Radio waves that strike the earth are partially absorbed and partially reflected. Waves that are reflected by the earth experience changes in the phase of the wave which affects

the distribution of available energy. The extent to which the waves are reflected or absorbed is dependent upon frequency and the ground constants: conductivity (σ) and permittivity (ε_r) the product of materials relative capacitance and the electric constant of free space.

Propagation Over Plane Earth

The geometry of the idealized situation of propagation between two antennas placed above a plane earth is shown in Fig. 4. This geometry is valid for antennas that are sufficiently close so that the curvature of the earth is not a factor, yet removed from each other enough so that the energy may be described as a plane wave, and ray theory can be applied. The resultant received electric field can be represented as the sum of the direct and reflected rays:

$$E = E_d\,[1r|R|e^{j(\Phi_\Delta + \Phi_r)}] \qquad [12]$$

This equation is valid for small angles of θ. The term E_d is the free space electric field that is produced at a distance d(m), and is known as the direct ray. The terms |R| and Φ_r are the magnitude of the complex reflection coefficient and its phase. This term is dependent upon the nature of the surface, i.e. conductivity (σ) and permittivity (ε_r), the angle between the surface and incident wave, the wavelength of the radio wave, the polarization of the wave, and the curvature of the earth. The magnitude of the reflection coefficient varies between -1 and 1. Several sources have derived the equations for the reflection coefficient and plotted the effects of changing variables, and the reader is referred to these for further study.[3,4] The term Φ_Δ is the phase delay due to the longer path that must be taken by the reflected wave, and has the form of:

$$\Phi_\Delta = 4\pi h_1 h_2/\lambda d \qquad [13]$$

It is usual to assume the ground approximates a large flat surface. In such a case a sufficiently accurate expression is given by Martin Hall in

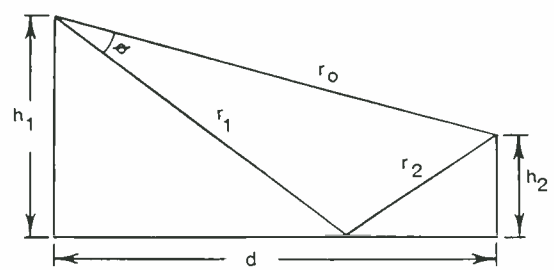


Fig. 4. Path rays for plane earth.

Effects of the Troposphere on Radio Communications.

$$E = 2E_d^{\sin(2\pi h_1 h_2/\lambda d)} \qquad [14]$$

Some cases of special merit that can be derived from equation [14] are:

Case I

$$h_1 h_2 = d\lambda/2 \qquad E = 0$$

When the product of the transmitting and receiving antenna heights equal half the product of the path distance and wavelength the received electric field strength will be completely cancelled.

Case II

$$h_1 h_2 = d\lambda/4 \qquad E = 2E_d$$

When the product of the transmitting and receiving antenna heights equal a quarter of the product of the path distance and wavelength the received electric field strength will be double that which could be achieved from a free space field.

Case III

$$h_1 h_2 = d\lambda/12 \qquad E = E_d$$

When the product of the transmitting and receiving antenna heights equal a twelfth of the product of the path distance and wavelength the received electric field strength will equal the free space field strength.

The above cases assume an ideal plane earth model. In a real world environment undulations in the path between the transmitting and receiving antenna will cause scattering and shadowing of the radio waves. Thus, the above cases will only be approximated in a real world environment. The variation of signal strength due to multipath effects can be minimized in point-to-point applications through the use of antennas with narrow beam widths.

When considering the case of VHF antennas that are close to the ground the effective antenna heights, $h_t(m)$ and $h_r(m)$, will need to be substituted for h_1 and h_2 respectively for [14]. The new antenna heights h_t and h_r allow for the effects caused by the relative permittivity and conductivity of the ground. The effective antenna heights are related to the physical antenna heights above ground level by the work by Martin Hall cited previously.

$$h_t = (h_1^2 + h_o^2)^{1/2} \qquad [15.1]$$
$$h_r = (h_2^2 + h_o^2)^{1/2} \qquad [15.2]$$

the term $h_o(m)$ is dependent upon the type of polarization being considered:

Vertical Polarization

$$h_o = (\lambda/2\pi)[(\varepsilon_r + 1)^2 + (60\lambda\sigma^2)]^{1/4} \qquad [16.1]$$

Horizontal Polarization

$$h_o = (\lambda/2\pi)[(\varepsilon_r - 1)^2 + (60\lambda\sigma^2)]^{-1/4} \quad [16.2]$$

Table 2 lists values for conductivity and permittivity for various soil conditions. As an example, assume that an antenna is placed 3 meters (9.8 feet) above dry, sandy, flat coastal land ($\sigma = 2\times10^{-3}$ S/m, $\varepsilon_r = 10$) and operated at a frequency of 100 MHz ($\lambda = 3$ m). Then, h_o in [16.1] and [16.2] will be 1.59 m and 0.16 m respectively. The effective height of the antenna will then be increased to 3.4 m (11.1 feet) for vertical polarization and will remain unchanged at 3 m (9.8 feet) for horizontal polarization. As the frequency increases above VHF, the wavelength becomes increasingly small and the distinction between true antenna height and effective height is immaterial.

TABLE 2. Ground Conductivity and Dielectric Constants.

Terrain	Conductivity σ (S/m)	Dielectric Constant ε_r (esu)
Sea Water	5	80
Fresh Water	8×10^{-3}	80
Dry Sandy, flat coastal land	8×10^{-3}	10
Marsh, forested flat land	8×10^{-3}	12
Rich agricultural land, low hills	1×10^{-2}	15
Pasture land, medium hills and forest	5×10^{-3}	13
Rocky land, steep hills	2×10^{-3}	10
Mountainous	1×10^{-3}	5
Residential Area	2×10^{-3}	5
Industrial Area	1×10^{-4}	3

MEDIUM FREQUENCY PROPAGATION

Medium frequency (MF) waves lie in the frequency range of 300 kHz to 3 MHz and are characterized by their long wavelengths, 1000 meters to 100 meters. The AM Broadcast band of frequencies is within this range, and the transmitting antenna is frequently located right at the surface of the earth. The typical receiving antenna is also very close to the earth's surface with respect to a wavelength. In this case the direct and ground *reflected* waves are cancelled and transmission is by means of the *ground* wave (also known as the surface wave) as well as by the sky wave.

Ground Waves

These waves are characterized by the fact that the wave is guided along the earth's surface, similar to a transmission line. The field is attenuated in this propagation mode by losses in the ground. Therefore the composition of the soil, ε_r and σ, have a direct bearing on the attenuation of the wave and subsequently the distances for reliable communications. The attenuation is also dependent upon the frequency and polarization. Thus the attenuation factor is a measure of the amount of attenuation present and can be determined for a ground wave using the chart of Fig. 5. The term p is the numerical distance and b is the phase constant. The term x related the conductivity of the soil to the frequency of the radio wave expressed in megahertz. Values for these terms can be calculated from the following equations:[4]

$$p = (\pi d/\lambda x)\cos b \quad [17.1]$$
$$b = tan^{-1}[(\varepsilon_r + 1)/x] \quad [17.2]$$
$$x = 18\times10^3\sigma/F \quad [17.3]$$

To determine the electric field strength, the attenuation factor must be added to equation [11]:

$$E = E_d\,[1 + Re^{j(\Phi_\Delta + \Phi_r)} + (1-R)Ae^{j(\Phi_\Delta + \Phi_r)}] \quad [18]$$

It is interesting to note that the same earth which acts as a conductor at very low frequencies will act as a small loss dielectric at very high frequencies. Note also that the losses for horizontally polarized waves are greater than for vertically polarized waves. Thus, for all practical purposes, vertically polarized waves should be (and normally are) considered for medium frequencies. For more detailed and accurate representations of the effects of ground wave the works of Norton and Jordan should be consulted.[5,4]

Sky Waves

The ground wave provides the major path for medium frequency propagation. Ground waves attenuate rapidly with distance and reliable communications are limited to only a few hundred kilometers. Medium frequency waves are propagated via the ionosphere, are known as sky waves, and can provide sufficient signal strength at distances up to a few thousand kilometers.

The *ionosphere* is a constantly changing environment that begins approximately 65 km (40 miles) above the earth and extends to about 400 km (250 miles). This region of the atmosphere is composed of three major sub-layers D, E, and F. These layers are not present at all times. The D layer, present only during the day, absorbs medium frequency waves. The E layer, above the D layer, reflects medium frequency waves. Thus, during the day, most medium frequency waves are absorbed by the D layer, but at night the D layer is not present allowing the medium fre-

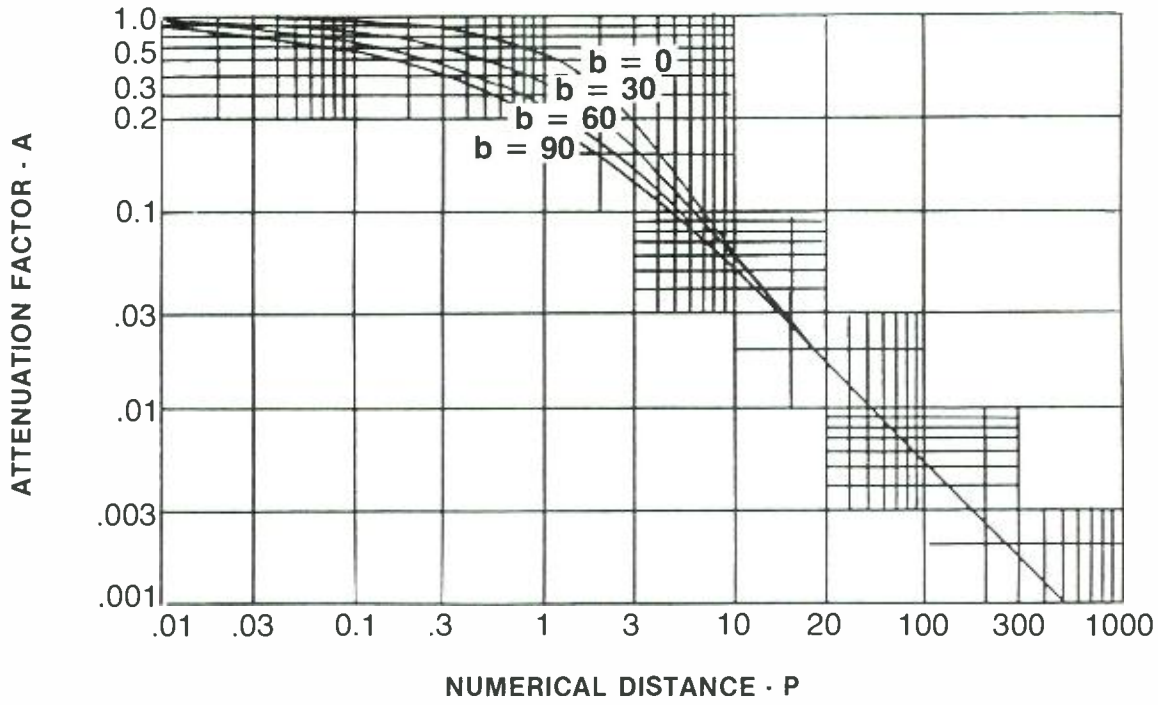


Fig. 5. Attenuation factor of ground waves.

quency waves to be reflected by the E layer permitting long distance transmission.

Interference Between Ground Waves and Sky Waves

Interference can occur from co-channel stations located many kilometers from the desired station, and because of the sky wave sufficient signal strength may be received to interfere with the local station. This effect has been minimized by the FCC by limiting two factors in the operation of some AM stations: the operating power and time of operation. The directional antenna is a selective limitation on operating power. That is, the antenna system is designed and located so as to radiate power toward the population area(s) while reducing radiation in the direction of other stations on the same or adjacent frequencies. For more information see Chapter 2.4 "AM Broadcast Antenna Systems," in this *Handbook*.

Multipath interference occurs when the waves from the same transmitting antenna reach a receiver from different paths in such a manner as to cancel or severely limit each other. The geometry of this is similar to that shown in Fig. 4. The direct ray will be from the ground wave and the reflected sky wave will be from the ionosphere. This effect occurs at those distances where both the ground wave and sky wave will interact. At distances relatively close to the transmitter the ionosphere will not reflect waves back to the earth, so the ground wave is dominant. At distances beyond a few hundred kilometers the sky wave will dominate and the ground wave will be too weak to interfere. Multipath interference can also occur where the sky wave follows two different paths.

Effects of Solar Activity

Interference to medium frequency waves can also be caused by solar activity such as sunspots and flares caused by a reduction or increased emission of radiation from the sun. This in turn causes changes in the ionospheric layers that may result in unusual sky wave patterns called "skip" which can cause inter-station interference. (The effects of such activities as solar storms and high solar flare activity, will have the strongest influence on propagation of the AM band during the first five to ten days after the start of a solar storm. This has the effect of reducing sky wave field strengths. The effect has been observed to increase with increasing frequency at higher frequencies.)[12]

PROPAGATION ABOVE 30 MHz

Smooth Earth Conditions

At frequencies above about 30 MHz the principal propagation mode is the troposphere. The ground surface wave is attenuated too severely

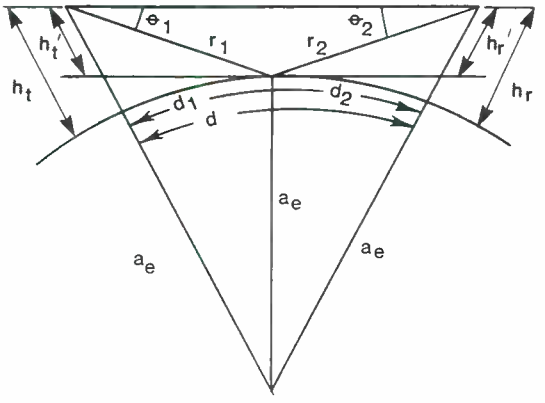


Fig. 6. Reflection from smooth earth on line-of-sight path.

to be of any practical long distance use and, though mildly attenuated, the sky wave is usually passed through the ionosphere to space.

For waves that propagate close to the earth's surface the curvature of the earth will introduce additional effects that must be included in the plane earth model that was considered earlier, Fig. 6 shows the geometry of a smooth earth model. First, the reflection coefficient R of the reflected wave has different characteristics than that of a plane surface. Since the wave is reflected against a curved earth the energy diverges more than that predicted by the inverse square law and the reflection coefficient R, in equation [12], must be multiplied by the divergence factor D, given by[3]

$$D = [1 + 2d_1d_2/2a_e\ (h_t' + h_r')]^{1/2} \qquad [19]$$

It should be noted that for smooth earth conditions, the heights h_t', and h_r', for the transmitting and receiving antennas above the plane tangent to the earth at the point of reflection, are less than the antenna heights h_t and h_r, above the surface of the earth.

Under normal propagation conditions the refractive index of the atmosphere decreases with height, so that radio waves near the surface of the earth travel more slowly than at higher altitudes. This variation in velocity as a function of height results in a bending of the radio waves. This may be represented as a modified earth radius or more commonly known as the effective earth radius a_e, which allows the radio waves to be represented as straight lines. The ratio of the effective earth radius to true earth radius is commonly known as the *k factor*. Values of k can vary between about 0.6 to 5.0 depending on the climate of the area between the transmitter and receiver being considered. For temperate climates, the average value of k is 1.33 and most works refer to this as the 4/3's earth model when used in calculation.[2] Additional values of k for the United States can be obtained from the map in section 4.2, page 63 of this *Handbook*.

Beyond Line-of-Sight Conditions

In order to predict when conditions exist to be termed beyond line-of-sight, the distance from the respective transmitter and receiver to the radio horizon must be calculated. The radio horizon is the distance the horizon appears from an antenna, as defined by a plane from the antenna to the tangent of the earth's surface and is depicted in Fig. 7. The equation for the radio horizon in terms of $d_{lt}(km)$ and $h_t(m)$ and the k factor is of the form:

$$d_{lt} = 3.57(h_tk)^{1/2} \qquad [20]$$

When the sum of the distances to the radio horizon for the transmitter and receiver is less than the total distance of the path being considered then a beyond line-of-sight condition exists. The amount of attenuation can be determined by "diffraction." This effect makes it possible for radio waves to travel beyond line-of-sight although an additional loss term must be added to the free space loss equations. The geometry of beyond line-of-sight propagation is shown in Fig. 8.

The exact calculation of the field strength at any point beyond the line-of-sight for a smooth earth is rather complex and the presentation of such a method is beyond the intent of this text. However, nomograms have been developed that apply to a large number of cases. For the reader interested in the prediction of the losses to be expected for smooth earth diffraction the National Bureau of Standards publication may be consulted.[8]

Fig. 9 is a nomogram that can be used to determine the loss for beyond line-of-sight that must

Fig. 7. Distance to radio horizon.

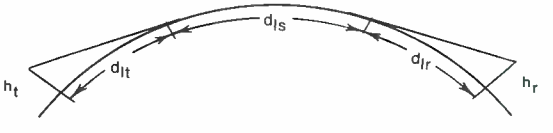


Fig. 8. Beyond line of sight.

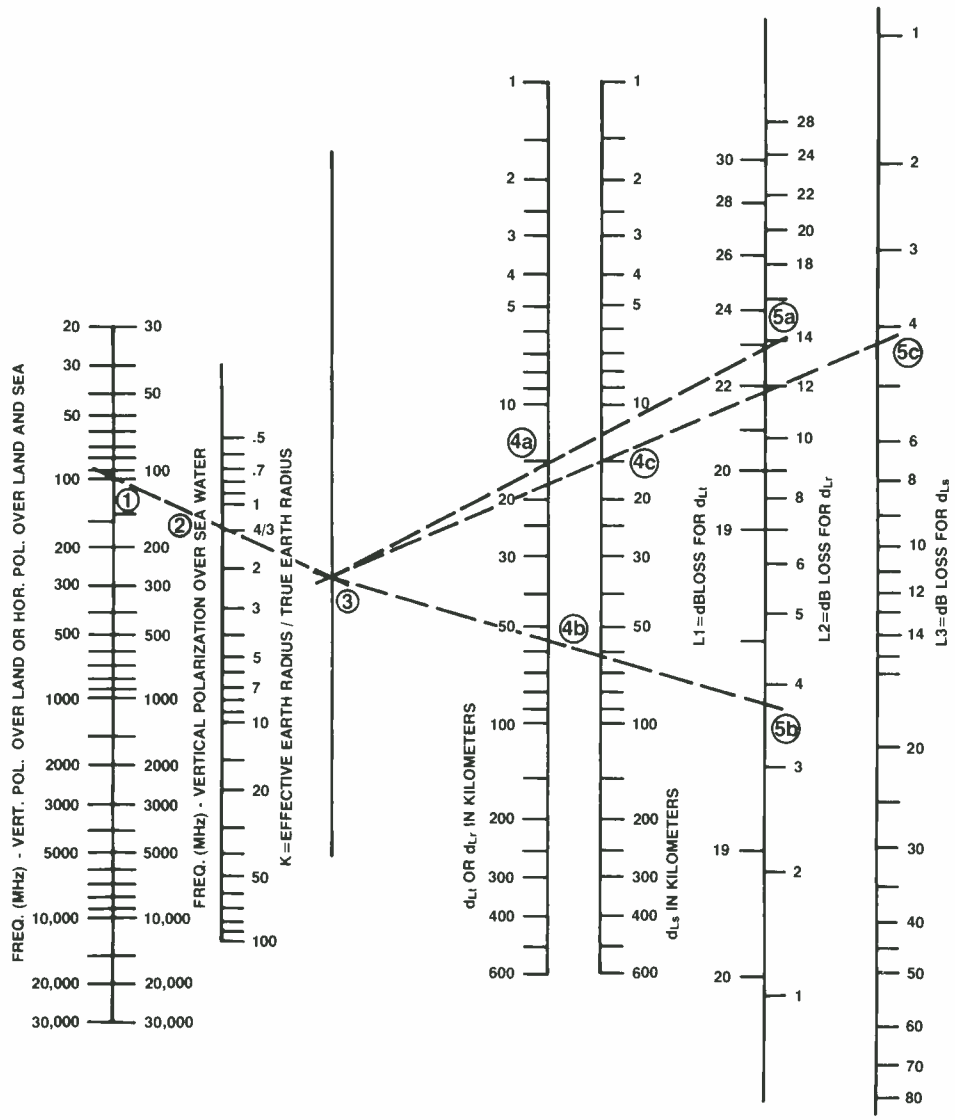


Fig. 9. Diffraction loss over smooth earth.

be added to the free space loss. In order to use the nomogram, the distance d_{lt} must be less than d_{lr}. The total loss L is the sum of the three losses $L1$, $L2$, and $L3$. By way of example assume a system that has the following parameters: h_{lt} = 14 m (45.9 feet); h_{lr} = 178 m (583.8 feet); F = 100 MHz; k = 4/3; total path length of 85 km and the wave is vertically polarized over land. The distances are calculated to be: d_{lt} = 15 km (9.3 miles), d_{lr} = 55 km (34.2 miles) and d_{ls} = 15 km (9.3 miles). The total loss relative to free space is thus $L = L1 + L2 + L3$ = 18.5 + 12.0 + 4.3 = 34.8 dB.[6]

Effects of Obstacles on Propagation

So far only a perfectly smooth sphere has been assumed for earth. The only effect of an atmosphere was accounted for in the *k factor*. These conditions allowed for a relatively simple calculation of the expected field strengths and transmission losses at various points within the line-of-sight and regions beyond the line-of-sight. However, the real world is much less than ideal and the presence of hills, buildings, vegetation as well as the atmosphere have a bearing on the computation of field strengths. The higher the frequency the more the effect buildings and terrain will have on the propagation of the wave between transmitter and receiver. Because these obstacles have a complex effect on the propagation of radio waves, it is extremely difficult to predict the field strength or transmission losses at discrete points close to these obstacles. However, the path under consideration may be quantized by use of elevation profiles: and, through

the use of some simplifying assumptions, predictions of the field strength which are more accurate than smooth earth calculations can be performed

Hills

Hills are the single most common form of obstruction that will appear in the path of a radio wave. The distance from the antenna and height of the hill can be determined by constructing a path profile and plotting the terrain features on special graph paper that includes the effect of refraction. The most common charts are defined for a factor of k of 4/3. A typical path is shown in Fig. 10. Terrain elevations necessary to construct a path profile can be obtained from topographical maps of the area, or from computer databases. To obtain the best accuracy, topographical maps the smallest scale available should be used, such as 1:24,000. These maps can be obtained from the United States Geological Survey in Arlington, Virginia 22202 or from any of its branch dealerships. Computer models exist which use a terrain data base that can map the terrain along a propagation path and are available from many sources.

In order to determine when a hill is sufficiently removed from a path to allow free space conditions to exist the Fresnel zone equation can be used. This equation was initially developed to explain the diffraction of light around knife edged obstacles and has since been applied to radio theory. This equation describes a radio path as an ellipsoid with the transmitting and receiving antenna located at the focal points of the ellipse. As Fig. 11 depicts, the curves for various reflection coefficients intersect at 0 dB from free space at a value equivalent to six-tenths of the first Fresnel zone. Thus free space conditions exist when obstacles are outside the $0.6F_1$ zone radius. This distance can be calculated by:

$$h = 0.6F_1 = 328.6(d_1d_2/Fd)^{1/2} \quad [21]$$

where the height of the $0.6F_1$ zone is in meters; d_1 is the distance from one antenna to the obstacle in kilometers; d_2 is the distance from the second antenna to the obstacle in kilometers; d is the total path distance in kilometers; and F is the frequency in megahertz. When determining whether a path clears an obstacle such as a hill, additional height should be added to account for any trees that may be present. A typical value for the tree height is 15 meters.

If the hill lies within the calculated Fresnel zone radius then non-free space conditions exist and additional losses will occur. When the frequency is high enough for the hill to appear as a sharp ridge and the transmitter and receiver are distant from the hill, then the loss may be calculated using diffraction from a knife edge, as shown in Fig. 12. The height of the hill H(m) is measured from the line joining the centers of the two antenna to the top of the ridge. The amount of attenuation or shadow loss with respect to free

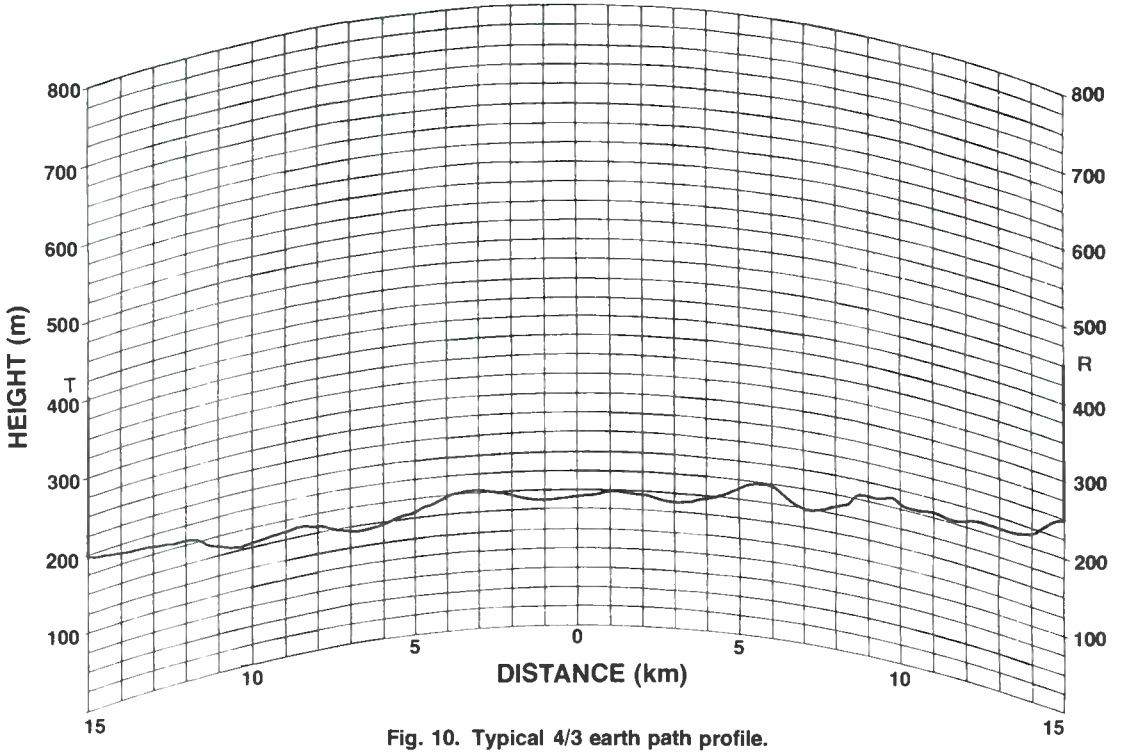


Fig. 10. Typical 4/3 earth path profile.

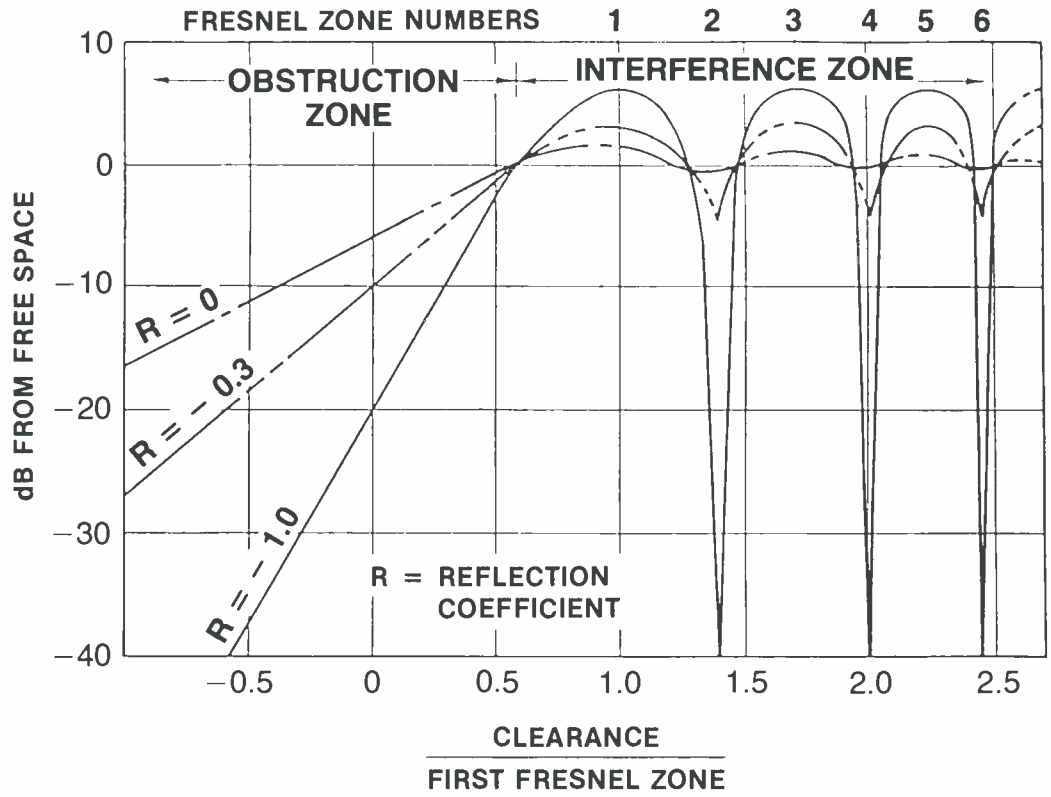


Fig. 11. Effect of path clearance on radio propagation.

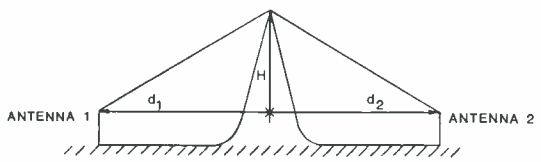


Fig. 12. Ray path for knife edge diffraction.

space may be read from the graph shown in Fig. 13. The value of the v, diffraction parameter, can be calculated, with respect to the distances measured in kilometers and the frequency F(MHz).[3]

$$v = 0.00258H[dF/d_1d_2]^{1/2} \quad [22]$$

When considering paths that are obstructed by hills that appear rounded rather than knife edged, the attenuation can be calculated using diffraction around a cylindrical surface, as depicted in Fig. 14. This condition will be prominent when the elevation of the hill changes drastically within a wavelength. This can be found when investigating paths at the lower end of the VHF spectrum that pass over older mountain ranges, i.e. Appalachian, Blue Ridge, Catskill.

The amount of attenuation can be found from the chart of Fig. 13. The term p from the chart

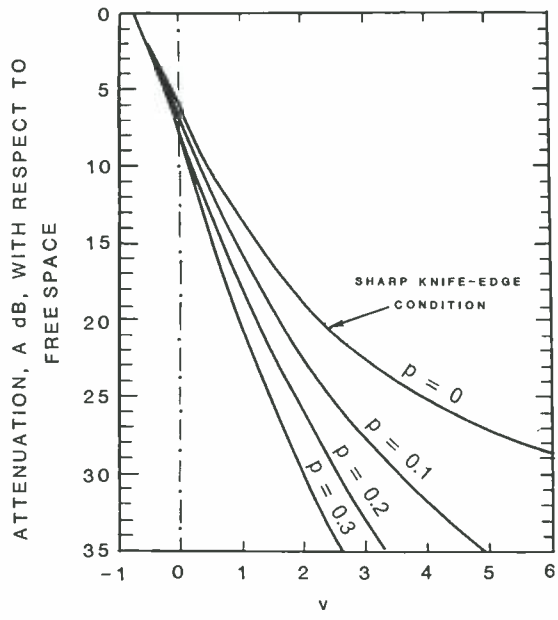


Fig. 13. Attenuation due to various diffraction conditions.

is a dimensionless quantity known as the index of curvature of the cylinder's radius R and is calculated from[3]

$$p = 0.83R^{1/3}\lambda^{1/4}[d/d_1d_2]^{1/2} \quad [23]$$

where all distances are in the same units. For those interested in incorporating the calculation of losses due to diffraction over knife edge and rounded obstacles into digital computers, more exact equations can be found in Rice, et al.[8]

While the method for calculating the loss due to a single obstacle is relatively straight forward, there are times when successive obstacles are present in a radio path as shown in Fig. 15. In order to determine the loss associated with multiple diffraction regions, an approximate method has been developed based on an extension of single edge diffraction. The obstacle which by itself would produce the greatest diffraction loss is determined using the methods discussed above. The summit of this obstacle should be joined to the antenna locations. The additional attenuation caused by the remaining obstacles should be added to the loss of the main obstacle using the heights they are above the lines so drawn, h_a and h_b. It is important to note that even if h_a and h_b are slightly negative, i.e. below the lines, they may still produce a small amount of attenuation due to the Fresnel zone clearance requirements.[3]

Buildings

When planning for radio locations within built-up areas of cities or residential areas, buildings will have an effect on radio propagation. For radio relay stations such as studio-to-transmitter links, it is the normal practice to select sites that will be clear of buildings. However, where this is not feasible and the path geometry is known, i.e. height and location of buildings, then the diffraction methods discussed for hills may be applied. In planning for broadcast systems it is not practical to relate attenuation measurements made in built-up areas to the particular geometry of buildings. Therefore, it is more conventional to treat the losses in a statistical manner dividing the general classifications of building types into loss groups, so that a loss can be derived for a particular type of building, i.e. multistory structures made of concrete and steel versus single story residential buildings made of wood.

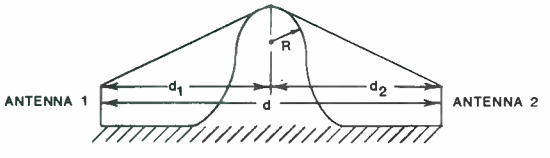


Fig. 14. Diffraction due to cylinder.

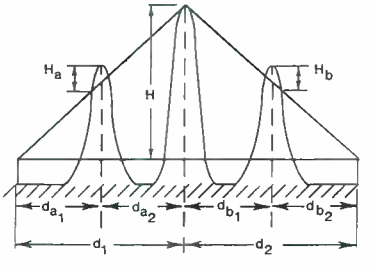


Fig. 15. Multiple knife edge diffraction.

Within built-up areas there is much more back scatter than in open country. Additionally, due to the fact that buildings are more transparent to radio waves than the earth, there tends to be less shadow loss caused by buildings. However, the angles of diffraction due to buildings are usually much greater than in open country for natural terrain and thus the loss resulting from the presence of buildings tends to increase. Measurements indicate that at 100 MHz the median field strengths are 4 to 6 dB below that expected for a plane earth and up to 10 dB for 200 MHz. These measurements were made in areas comprising of some large buildings and open areas, but were mainly residential areas. Some recent measurements conducted in the 850 MHz band indicate values of 20 to 34 dB below that expected for free space for path distances of from 1 km to 25 km.[9]

Vegetation

Among the many factors that have an effect on the determination of the losses present in a propagation path, effects of vegetation are sometimes the most overlooked. Depending on the type of terrain in consideration, i.e. open or forest, the effect of vegetation can add several dB loss to the system. The amount of attenuation present is dependent upon the frequency and polarization of the wave, see Fig. 16. For example, the attenuation for a horizontally polarized wave for frequencies below about 1000 MHz is much less than that for a vertically polarized wave. At around 1000 MHz trees that are thick enough to block the field of vision can be modeled as an obstruction and the attenuation over or around these obstructions can be predicted from knife edge diffraction methods.

The effect of vegetation on a radio path varies seasonally in the case of deciduous trees. During the winter months the losses due to shadowing and absorption are less than those during the spring and summer. It is interesting to note that the greatest losses will occur during the spring since new growth has more sap and moisture content which increases the absorption losses. When the antenna is raised above trees and other vegetation, the prediction of field strengths depend upon the estimation of the height of the antenna above areas of reflection and the reflection coefficients.

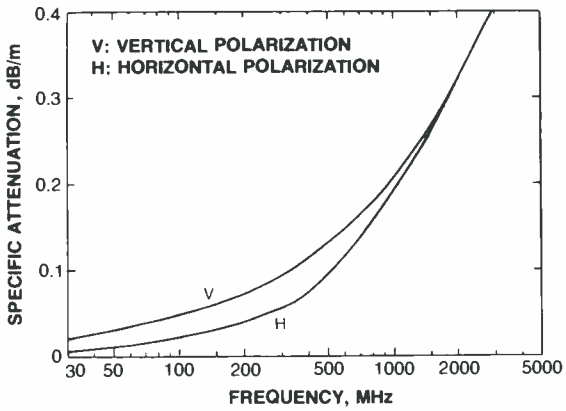


Fig. 16. Attenuation through woodland.

Atmospheric Refraction

The refractive index of air is approximately one. It is dependent upon the dielectric constant, and can vary depending on the pressure and temperature of the air and on the amount of water vapor present. Therefore, the refractive index of the atmosphere can change with weather conditions and with the height above the earth. The velocity of radio waves is dependent on the refractive index of the atmosphere. As a general rule the velocity of a radio wave is slower at the earth's surface than at higher altitudes. So, a horizontally polarized wave will be refracted back towards the earth, though unusual atmospheric conditions may change this. Because there are numerous constantly changing variables involved in the prediction of field strengths due to atmospheric conditions some simplifying assumptions are generally needed to obtain a solution under known meteorological conditions.

The refractive index *(n)* of the atmosphere has a value near unity (typically 1.00035). Changes of only a few parts per million of the refractive index can have dramatic effects on radio waves, therefore it is usually more convenient to refer to the refractive index in terms of the refractivity n:

$$N = (n-1)\times 10^6 \qquad [24]$$

and the typical value would then be $n = 350$.

Ducting

Under meteorological conditions where the refractive index decreases rapidly with height over a large horizontal distance, radio waves can become trapped and experience low loss propagation over long distances. This phenomena is known as ducting. Although ducting is frequent at some locations and under certain meteorological conditions, due to its randomness and the inability to predict range, it is not a reliable mode for communications. However, due to the strong fields ducting can cause beyond the horizon, co-channel interference can result. In addition, line-of-sight paths may be affected by severe fading caused by ducting.

In order for atmospheric ducts to occur two conditions must exist. First, the refractive index gradient must be equal to or more negative than -157 N/km. The refractive index gradient is a measure of the change of the refractivity across a vertical height h, dN/dh. When this condition is present, the radio waves will remain close to the earth's surface beyond the normal horizon. Secondly, the refractive index gradient must be maintained over a height of many wavelengths. The duct may be thought of as similar to a transmission line waveguide. Unlike metallic waveguides, natural ducts do not have sharp boundaries, although there is a wavelength cut-off above which waves will not propagate. Since the duct does not have sharp boundaries, the thickness (t) will not be rigid. The cut-off wavelength λ therefore, will not be rigid, but an estimate can be obtained from.[3]

$$\lambda = 2.5\text{X}10^{-3}\left(\frac{dN}{t} - 0.157\right)^{1/2} t^{1/3} \qquad [25]$$

where the wavelength and thickness are in meters. The term dN is the refractive index change across the duct. As an example, a duct near the ground that is 25 meters thick and has a refractive index change of 10 N, i.e. -400 N/km, (-10/0.025 km) will have a cut-off wavelength of 0.15 m (2 GHz). However, a duct with the same refractive index gradient will have to about 87 meters thick to propagate a wavelength of 1 meter (300 MHz).

A duct spreads the energy within it in the horizontal direction, but is constrained in the vertical direction as the distance from the transmitter is increased. Thus, in principle, it is possible for the field strength within a duct to be greater than the free space field at the same distance. However, a duct will 'leak', or allow energy to escape at the boundary, adding to the transmission losses so that field strengths are seldom greater than free space values.[3]

Radio waves that leave the transmitting antenna at an angle greater than a certain vertical angle, the critical angle, will not become trapped in a duct. These radio waves will propagate through the duct, though they will experience some bending due to the change in the index of refraction at the duct's boundaries. There are typically two types of ducts: ground based and elevated. A ground based duct, as its name implies, forms close to the earth's surface. Energy is propagated in this duct by being refracted back to the earth, then reflected off the earth, then refracted again, see Fig. 17A. An elevated duct forms above the earth's surface and is generally very short lived.

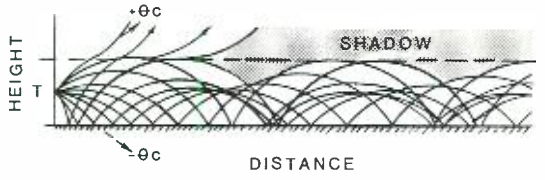


Fig. 17A. Ray propagation in a ground based duct.

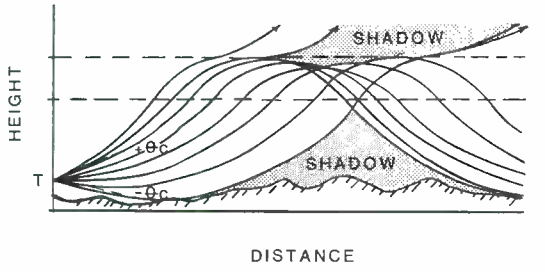


Fig. 17B. Ray propagation in an elevated duct.

Energy in this duct is refracted back and forth between boundaries without coming in contact with the earth, see Fig. 17B.

Shadow regions are formed along a duct where, due to the nature of the duct, radio waves are not present. Receiving antennas placed in such a region will experience a loss of signal. Fig. 17A and B shows these regions can not only form above the earth's surface, as in a ground based duct, but can also form along the earth's surface in the case of an elevated duct. Therefore, a shadow region that can result in loss of communications can form at a receiver that is located relatively close to the transmitter.

Rain Attenuation and Absorption

The use of radio systems using frequencies above 1 GHz adds another loss that must be accounted for when planning the system. Inadequately engineered systems, such as relay and STL links, may experience outages during periods of heavy rainfall. The amount of attenuation due to rain is dependent upon three factors: 1) the rate the rain is falling, 2) the frequency of the wave, and 3) the length of the rain cell through which the wave must propagate. For adequate planning purposes, if the path length is only several kilometers, the length of a rain cell may be approximated by the total path distance. The average rainfall rate varies from one section of the country to another section, however typical rainfall amounts are shown in Table 3. The specific attenuation γ_r is given by *Transmission Loss Predictions for Tropospheric Communications Circuits*, by Rice, Longley, Norton and Barsis.

$$\gamma_r = KR_r^{\alpha} \; [dB/km] \qquad [26]$$

TABLE 3. Rainfall Amounts.

Characteristics	Rate
Drizzle	0.25 mm/hr
Light Rain	1.00 mm/hr
Moderate Rain	4.00 mm/hr
Heavy Rain	16.00 mm/hr
Very Heavy Rain	100.00 mm/hr

where R_r is the rainfall rate in millimeters per hour, and the terms K and α are found from material cited previously.

$$k = [3(F-2)^2 - 2(F-2)] \times 10^{-4} \qquad [27.1]$$

$$\alpha = [1.14 - 0.07(F-2)^{1/3}]\,[1 + 0.085(F-3.5)e^{(-0.0066F^2)}] \qquad [27.2]$$

where F is the frequency in GHz. These equations give a good approximation to attenuation curves published by the CCIR for frequencies below 50 GHz.[13] As an example assume F = 12 GHz and a rainfall rate (R_r) of 16 mm/hr. The terms K and α will them be: K = 0.0280 and $\alpha = 1.2655$, yielding a specific attenuation (γ_r) of 0.9353 dB/km.

In addition to rain, radio wave absorption can also occur from water vapor and oxygen that is present in the air. The attenuation is less than that for rain and usually can be neglected below 20 GHz. However, at higher frequencies, attenuation due to absorption losses can become significant.[8]

COVERAGE AREAS

Engineering a radio or television broadcast station using the methods presented previously is far too cumbersome to be of any practical use in determining the service area of the station. While radio waves actually behave in the manner described in the previous sections, it is too complicated to calculate the signal at every point surrounding a station. Therefore other quantitative methods are needed to quickly and reliably determine field strengths. Considerable work has been conducted in this area and is still being carried out.

The received field strengths are subject to several natural and man-made phenomena described earlier which can cause the field strengths to vary over periods of time and from one location to another. These changes can be long term such as seasonal changes, i.e. weather, temperature, and foliage, or short term changes such as weather disturbances, i.e. storms and fronts, and vehicles passing in front of the receiver. These

variations have an effect on radio systems that is difficult to account for when determining service areas. Thus, it is appropriate to describe the field strength by statistical means: the percentage of locations that will receive a particular field strength for some percentage of time. By describing field variations in this manner it is possible to arrive quickly at a satisfactory determination of the service area of a station. However, the general terrain in the area still must be considered. In preparing propagation curves, this is accomplished by incorporating a terrain roughness factor Δh. The terrain roughness factor is a generalization of the local terrain and is defined as the difference in elevation between the levels exceeded for 10 and 90 percent of the terrain along a path. The average value of h for the United States is 50 meters.[10] In using the propagation curves found in the FCC Rules and Regulations for FM and television stations the local terrain is accounted for by determining the height of the antenna above average terrain along a radial.[11]

To simplify field strength prediction, curves have been developed to determine the service area of a station. These curves are generally developed using measured values taken from different geographical areas over certain periods of time. The median values are incorporated into a family of curves that describe the field strengths for various antenna heights, frequencies, and distances. A detailed discussion of how to perform field strength measurements may be found in Chapter 2.7, "FM and TV Field Strength Measurements" and Chapter 2.8, "AM Field Strength Measurements and Directional Antenna Proof" of this *Handbook*. The FCC curves for FM and television broadcast stations were derived in this manner. The curves used by the FCC for FM and TV describe the field strengths for service at 50 percent of the locations for 50 percent of the time. These curves are referred to as F(50,50) and are based on an effective power of 1 kW radiated from a half wave dipole in free space. The F(50,10) curves used by the FCC describe the field strength for 50 percent of the locations for 10 percent of the time. These curves can be used to estimate the service provided by FM and television stations.

Through the use of a computer, field strength estimates can be made quickly permitting designers to try more options and see the effect on the service area. The designer can change transmitter locations, power levels and tower heights to optimize the station. Computer methods rely on terrain databases and user supplied technical information of the station, i.e. frequency, power, location, and height, to derive the service contours.

REFERENCES

1. *IEEE Standard Directory of Electrical and Electronic Terms*, ANSI/IEEE Std 100-1977, Wiley-Interscience.
2. Reference Data For Radio Engineers, 6th ed., Howard W. Sams & Co., 1982.
3. Hall, Martin. *Effects of the Troposphere on Radio Communications*, Peter Peregrinus Ltd. New York, 1979.
4. Jordan, Edward C. *Electromagnetic Waves and Radiating Systems*, (Englewood Cliffs: Prentice-Hall, Inc., 1950), pp. 608-688.
5. Norton, K.A. "Ground Wave Intensity Over a Finitely Conducting Spherical Earth," *Proceedings of the IRE*, December, 1941, p. 623.
6. Bullington, K. "Radio Propagation Variation at VHF and UHF," *Proceedings of the IRE*, January 1950, p. 27.
7. "Wave Propagation," *The ARRL Antenna Book*, 14th ed., 1982, American Radio Relay League pp. 1-19.
8. Rice, Longley, Norton, and Barsis. "Transmission Loss Predictions for Tropospheric Communication Circuits," *National Bureau of Standards Technical Note 101* (Rev.)
9. Okumura, "Field Strength and its Variability in VHF and UHF Land-Mobile Radio Service," *Review of the Electrical Communication Laboratory Volume 16,* (Tokyo) 1968, pp. 825-873.
10. Damelin, Daniel, Fine, and Waldo. "Development of VHF and UHF Propagation Curves for TV and FM Broadcasting," *FCC Report No. R-6602.*
11. Federal Communications Commission, Rules and Regulations, Section 73. See most recent edition.
12. Wang, John C.H. "A Skywave Propagation Study in Preparation for the 1605-1705 kHz Broadcasting Conference," *IEEE Transactions on Broadcasting*, vol. BC-31, March 1985, pp. 10-17.
13. "Attenuation and Scattering by Rain and Other Atmospheric Particles," *CCIR Report 721*, Vol. V.

2.10

Radio and TV RF Systems

William DeCormier
Donald Manion
Staff Engineers
Dielectric Communications
Raymond, Maine

INTRODUCTION

In this chapter, several methods of connecting the output of the transmitter(s) to the external transmission line system, utilizing either coaxial transmission line or waveguide, will be presented. Various components ranging from the simple patch panels, that have been in existence for quite some time, to the recently developed "switchless" combiner-routing systems will be discussed as to their operation and implementation into the transmitter system. Filters and filter networks, such as diplexers and multistage multiplexers, will also be covered.

SWITCHING

Every transmitter installation requires some type of switching in the transmission line system. The amount of switching utilized will depend on the individual needs of the station. It can be as simple as a 3-port patch panel to connect the output of the transmitter to the station load, or as complex as a multiple transmitter-antenna installation.

Patch Panels

Patch panels provide a convenient method of rerouting the interconnecting transmission lines between various inputs and outputs in the transmitter plant. Since they are manual devices and cannot be changed very rapidly, their use is limited to maintenance type functions or as a secondary source of switching.

Coaxial Patch Panels

Coaxial patch panels can be configured in any number of ports, however the more common are 3,4, and 7-ports. They consist of the appropriate number of quick disconnect connectors mounted on a panel, and interconnecting transmission lines, usually in the form of "U-links". The connectors are spaced such that the "U-link" may be utilized to interconnect any two adjacent connectors. For example: the connectors of a 3-port patch panel would form an equilateral triangle (all sides equal and all angles are 60 degrees).

Interlock switches are utilized to prevent transmitter power from being applied until the "U-links" are in the proper positions and properly seated. Power handling capabilities of the patch panels are essentially the same as the mating transmission line.

Waveguide Patch Panels

Waveguide patch panels are utilized much the same way as their coaxial counterparts. However, since waveguide is larger, and most transmitter installations use rectangular waveguide inside the transmitter building, the patch panels aren't quite as versatile. Generally, the waveguide patch panel is only available as a 3-port unit.

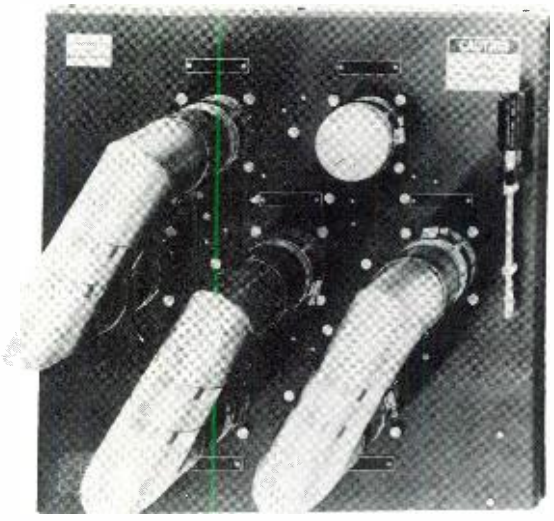


Fig. 1. 7-port coaxial patch panel.

Fig. 2. 3-port "E" plane waveguide patch panel.

Since the waveguide is rectangular, the ports need to be oriented in a straight line in either the broad wall or narrow wall plane. Fig. 2 illustrates a 3-port E plane patch panel.

Manual Coaxial Switches

Manual coaxial switches are generally available in either single pole double throw (spst) or 4-port transfer type configurations. They have two distinct advantages over the manual patch panels, which are ease of operation and speed of switching.

Most manual coaxial switches have either a lever or knob that is turned to change positions of the switch, which can be accomplished in a few seconds as compared to minutes for the manual patch panel. Like the patch panels, the manual coaxial switch is equipped with interlock switches for turning off the transmitters during switching.

Fig. 3. Coaxial rotary switch.

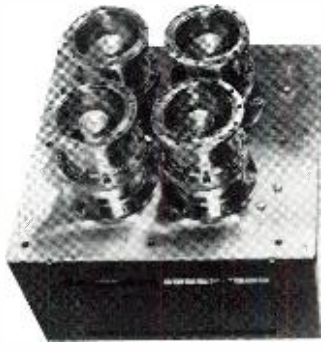


Fig. 4. High power coaxial switch.

Power ratings of the coaxial switches are approximately 80% of the equivalent coaxial transmission line. Since they are more complicated to build, they cost more than a patch panel. In order to get the same functions of a 7-port patch panel, several switches will be required as they are only available in 3-port spot and 4-port transfer configurations.

Motorized Coaxial Switches

Generally, the motorized coaxial switches will be very similar to the manual type switches. To reduce production costs, a lot of the parts will be the same.

Usually, the RF portion of the switch will be the same for either the manual or the motorized switch. The manual drive is replaced with a motor drive assembly. The motor drive system requires some type of control system to start and stop the motor in the switching sequence.

Most motorized switches will offer a choice of motor voltages, with 115 vac being the more common, and various control circuit voltages. A small control relay is provided to isolate the switch from the control circuits of the transmitter system. Generally, both sides of the control relays are

available in the electrical connector. Therefore, the user must supply a source to energize the control relay.

Rotary type motorized coaxial switches are available in 1 5/8", 3 1/8", 4 1/16", and 6 1/8". These switches will switch positions in approximately 2 seconds. Their frequency range is good up through the high band TV frequencies. Some of the larger switches are limited in their use at the UHF range because of possible moding problems. The power ratings of most of the types of switches is limited to approximately 80% of the comparable transmission line.

For use at higher power levels and higher frequencies, another type of switch was developed. This is a motorized "U-link" type of switch. Its power ratings are essentially the same as the comparable transmission line and its problems at the higher frequencies have been greatly reduced. Sizes of 3 1/8", 4 1/16", 6 1/8", 8 3/16", and 9 3/16" are available. Because of the mass of the moving parts of the larger switches, the switching time is increased to approximately 10 seconds or less. A switch of this style is shown in Fig. 4.

Open Wire Switches

Open wire switches can be utilized in lower frequency applications, such as the AM and short wave bands. These switches often resemble high power relays or contactors. The major differences would be the type of dielectric material and the proximity of the contacts. An open wire RF contactor is shown in Fig. 5. The configuration shown is a 30 ampere unit, that would handle 10 kW. It is a double pole-double throw type ZZ relay, which allows several configurations including a transfer type switch. Various types and sizes are available for use from a few watts to several hundred kilowatts.

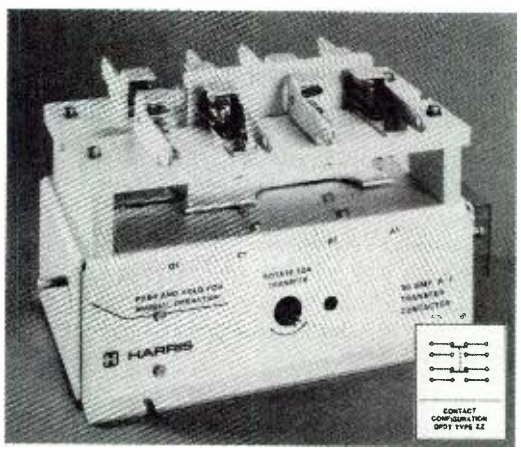


Fig. 5. RF contactor for AM & short wave applications. (Courtesy Harris Corp.)

Waveguide Switches

Waveguide switches are available in 3, 4, and 5-port versions, both manual and motorized. The RF sections of the manual and motorized switches are usually the same. Manual units will have a knob or handle to change the positions of the switch. Motorized units have the manual drive replaced with a motor drive assembly. Some type of motor control circuits will also be required.

The 4-port transfer switch shown in Fig. 6, is an E-plane type of switch. Both E-plane and H-plane units are available. The 4-port units usually take the form of crossed waveguide, with the ports 90 degrees apart. Within the switch is a metal back plate that has fingerstock around the four sides, which contact the waveguide case. The back plate is positioned at a 45 degree angle to the ports of the switch. Thus, two ports of the switch will be connected together in the form of an elbow. In one position, the top port will be connected to the right hand port, while the bottom port is connected to the left hand port. In the other position the opposite is true.

The control circuits of the waveguide switch are very similar to the ones utilized in the coaxial switches. Various motor and control voltages are available. The waveguide switch will be equipped with some type of interlock switches to turn off the transmitters during the switching process.

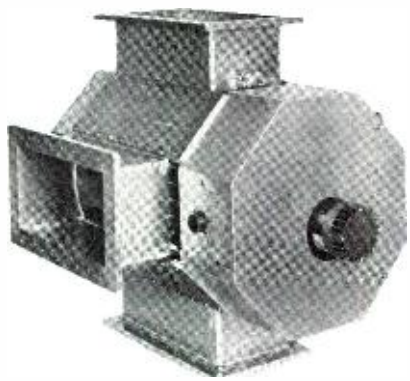


Fig. 6. 4-port motorized waveguide switch.

FILTERS

Filters are used in broadcasting to limit the undesirable emissions of transmitters. More specifically it is necessary to limit the harmonic content of transmitters to prevent interference at higher frequencies with other services. In addition it is also necessary to limit the intrusion of other RF signals into the final stage of transmitters as a result of antenna coupling.

The FCC addresses these requirements in Volume III, subpart B, section 73.317, paragraph 14 for the FM broadcaster by stating that "Any emissions appearing on a frequency removed from the carrier by more than 600 kHz shall be attenuated by 43 dB + 10 log (power) dB below the level of the unmodulated carrier or 80 dB, whichever is the lesser attenuation." If a broadcaster is operating above 5 kW the 80 dB requirement applies. For comparison, a broadcaster operating at 100 watts would be required to meet a 63 dB requirement under these rules.

The TV requirement is addressed in Volume III subpart D section 73.687 paragraph i,1. It, in part, states "...all emissions removed in frequency in excess of 3 MHz above or below the respective channel edge shall be attenuated no less than 60 dB." It goes on to say that this requirement should be considered temporary and that the state of the art might be the more appropriate limit and broadcasters are encouraged to seek this limit in order to meet future rulemaking requirements.

Harmonic Filters

Harmonic filters are commonly used on the output of all transmitters used for broadcast applications. They can be built in coax or waveguide. The decision to use one form over the other is a matter of convenience (i.e. size), performance and cost.

The coax form is used in the lower portions of the broadcast spectrum namely VHF, FM and portions of UHF bands. For low band VHF and FM where the maximum ERP is limited to 100 kW, coaxial harmonic filters are used since the common EIA line sizes from 3-1/8 to 6-1/8 inch coax can handle the power levels without degradation due to higher order modes. Waveguide would have to be in excess of 60 inches wide to operate in the fundamental mode at these frequencies.

Harmonic filters will pass the fundamental frequency with efficiencies of about 98% or—.1 dB insertion loss. They will reject the second through the fifth harmonic (i.e. frequencies 2 times through 5 times the fundamental) with attenuation of -40 to -50 dB. This limits the passage of these harmonic frequencies to 1/10000 to 1/100000 of the harmonic power level before filtering. By virtue of their function of attenuating harmonics they are of necessity designed to handle a limited segment of the band containing less than an octave. Table 1 lists the typical way in which the band is divided.

The skirt of the attenuation curve must have a slope sufficiently large to pass the highest fundamental frequency and reject the lowest frequency in the 2nd Harmonic. A filter with nine to eleven stages will normally provide 40 to 50 dB rejection at the low end of the 2nd harmonic.

Table 1

Channel	Fundamental	2nd Harmonic	Typical Construction
2-3	54- 66 MHz	108-132 MHz	Coax
4-6	66- 88 MHz	132-176 MHz	Coax
FM	88-108 MHz	176-216 MHz	Coax
7-13	174-216 MHz	348-432 MHz	Coax
14-43	470-650 MHz	940-1300 MHz	Coax
44-52	650-698 MHz	1300-1396 MHz	Coax or Waveguide
52-69	698-806 MHz	1396-1612 MHz	Waveguide

The waveguide form of the harmonic filter is usually utilized at frequencies on the high end of the UHF band. This is necessary for a combination of reasons. Larger coax sizes will support the generation of higher order modes near the high end of the frequency spectrum for UHF TV. Higher order modes will be sustained at a frequency where the:

$$\text{Wavelength} = \pi\,(a+b)$$

where a and b are the radii of inner and outer. Larger coax sizes are also needed to handle the power levels authorized in the UHF band. 8-3/16—75 ohm line will support higher order modes at frequencies just above channel 56 and 9-3/16—75 ohm at frequencies just above channel 40. But the construction of a coax filter is a cascade of larger and smaller diameter inner conductors. The larger inners essentially cause the moding to occur at larger wavelengths or lower frequencies. This phenomenon lowers the effective frequency at which coax filters can be used.

The waveguide filter must therefore be used for channels above 40 when transmission line power levels exceed the rating of 6-1/8 coax. One example of the solution in waveguide is commonly called a waffle iron filter because the broad walls of the waveguide appear as the top and bottom plate in a waffle iron. A waffle iron harmonic filter in WR 1150 waveguide can be utilized for all those channels between 40 and 69.

Usually harmonic filters of appropriate type are supplied with the transmitter since the transmitters cannot meet FCC rules with regard to harmonic content without a harmonic filter. The broadcaster will seldom find the need to acquire a harmonic filter unless he has experienced a severe transmission line failure or acquired a used transmitter.

Band Pass and Band Stop Filters

Band pass filters are used sometimes in combination with band stop filters to control another

class of spurious emission problems. The transmitter with its harmonic filter is capable in the absence of other RF signals of producing transmissions which are free of any spurious emissions. Potential problems arise however when two or more broadcast channels are located very close to one another physically.

Assume, for the sake of illustration, that Channel A consists of an entire system (i.e. transmitter, transmission line and antenna). Assume, also, that Channel B is similarly constructed and that both antennae are on the same tower. This is a common scenario in today's broadcast site. Each antenna in addition to transmitting its primary signal is also capable of receiving. Therefore, Channel A is capable of receiving some of Channel B's signal. The magnitude of this received signal is dependent on the gain and bandwidth of Antenna A at the frequency of Channel B as well as the distance between the two antennas. Several spurious signals can be generated in Transmitter A and transmitted on the air as a result of the presence of RF from Channel B. The transmitter will usually, because of its limited bandwidth, provide several dB turn-around loss for this spur. The most troublesome spur will occur at a frequency which is

$$F = 2A\text{-}B$$

A comparable problem could occur in transmitter B where

$$F = 2B\text{-}A$$

The magnitude of the spur will be equal to the power level of the coupled signal minus the turn-around loss. So, if Channel B is present in Channel A's transmission line at a level of -40 dB down from Channel A's power level and transmitter A provides -10 dB turn-around loss, then a spur will likely exist at *(F = 2A-B)* with an amplitude of -50 dB from Channel A's amplitude. In order to bring this situation into compliance with FCC rules at FM, for example, a filter would have to be installed in Channel A's transmission line which would pass Channel A with a minimum insertion loss (usually—.15 dB) and provide -30 dB rejection at Channel B. This would lower the spur level to -80 dB below Channel A's transmission line level.

The broadcaster must first determine if such a problem exists. This can be done by inserting a dual directional coupler in Channel A's transmission line. Then connect a spectrum analyzer through a suitable attenuator and monitor the system to determine the presence of any undesirable RF signal. Check the reflected power coupler to detect incoming signals and the forward coupler for any resulting spurious emissions. If spurs are detected in the forward coupler at levels higher than the -80 dB level the reverse measurements can be used to determine the offending source.

The decision to use band pass versus band stop filters should be based on the nature and extent of the problem. Each has virtues and limitations which make them suitable for certain problems.

The typical response curves for several combinations are presented in Fig. 7 through 10. The band stop as depicted in Fig. 7 is characterized by rapidly rising skirts which make these filters particularly suited to rejecting frequencies that are extremely close to the desired frequency (i.e. frequencies displaced by as little as .8%). However, due to their sharp response they are more prone to drifting with temperature than the band pass configuration if not properly designed. It must be emphasized that they can be built so that drifting does not affect their desired performance. But, manufacturers must design to minimize this tendency. Band stop cavities are commonly used in the FM band. They are also used in VHF or UHF diplexers but not to protect one TV channel from another since their band stop widths are generally too narrow to reject an entire TV channel.

The band pass response is depicted in Fig. 8 and 9. The skirts of these filters rise much more slowly than the reject curves. They rise at 6 dB per octave per stage. Again using the FM band for comparison at 100 MHz with a usable bandwidth of .3%, the reject will rise to -30 dB when displaced from the pass band by approximately 3% for a 2 stage, and by 1.5% for a 3 stage filter. This suggests that more stages will be needed in band pass to obtain the same attenuation as a band stop cavity. The band pass, however, has some advantages; since the pass band is broad it is not affected by drifting due to temperature changes. The reject curves are also symmetrically located about the pass band. The formula for determining the location of the spur

$$F = 2A\text{-}B$$

will always place the spur at exactly the same distance, frequency wise from the pass but on the opposite side of the pass band. So the band pass is attenuating the incoming RF on one side and the resulting spur on the other side of the pass band. It also has the advantage of attenuating all frequencies sufficiently removed from the pass band. This is especially useful when multiple interferences are detected.

The combinations of band pass and band stop are depicted in Fig. 9 and 10. These can be produced with mirror images or with the reject ap-

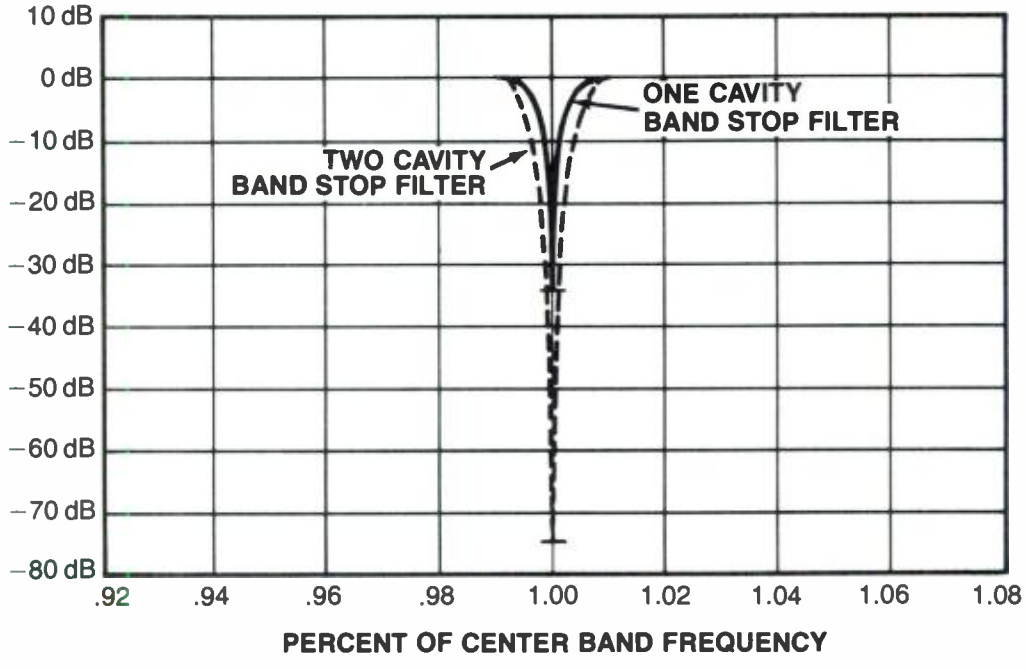


Fig. 7. Band stop filter frequency response characteristics for one and two cavity filters.

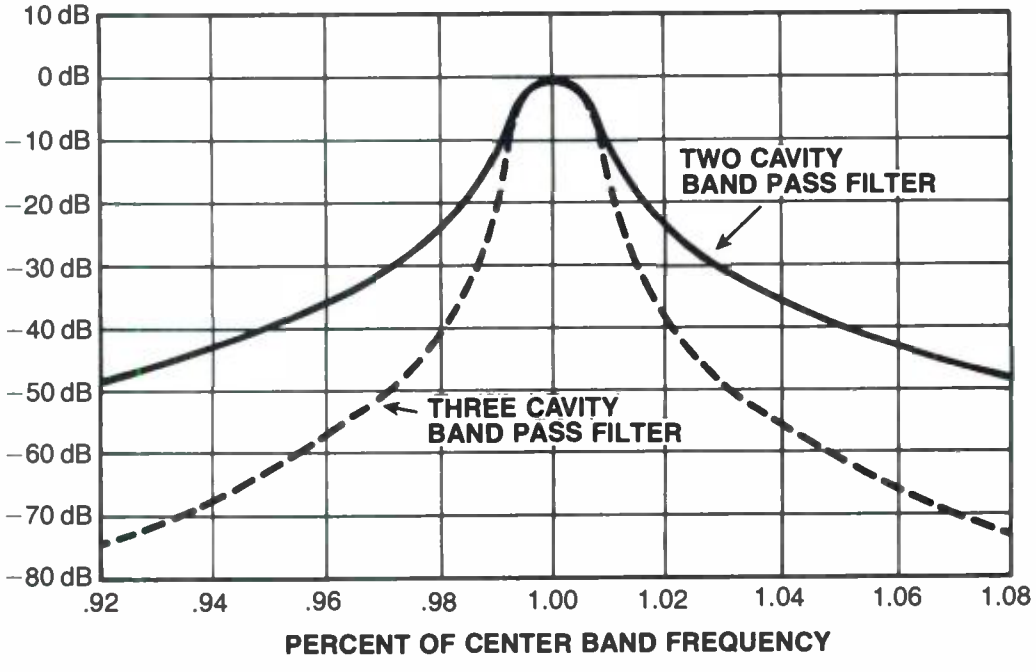


Fig. 8. Band pass filter frequency response characteristics for two and three cavity filters.

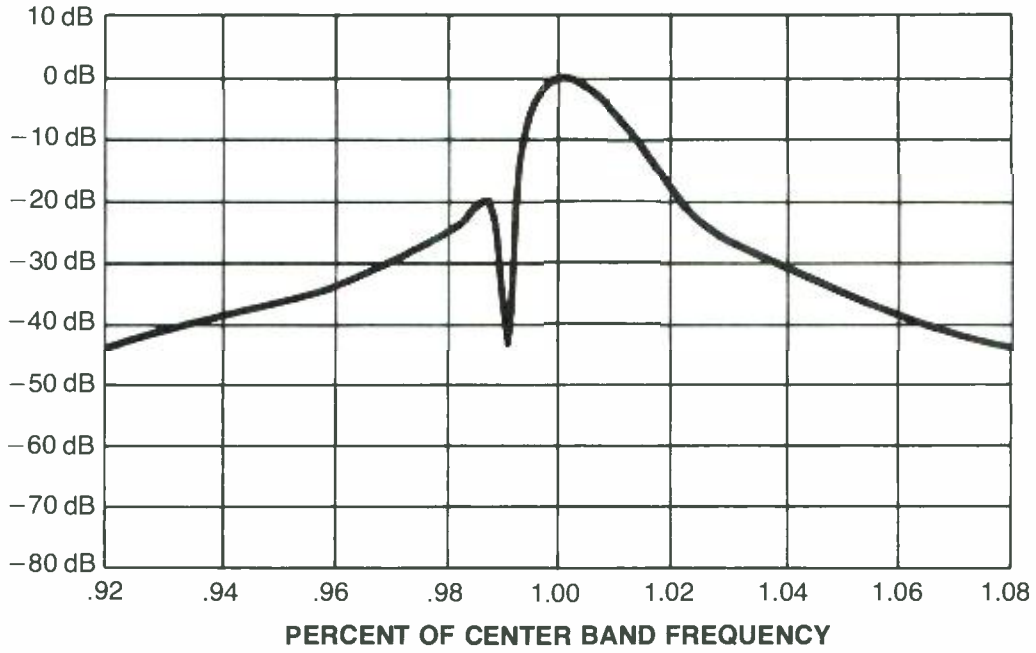


Fig. 9. Two cavity band pass-one cavity band stop filter.

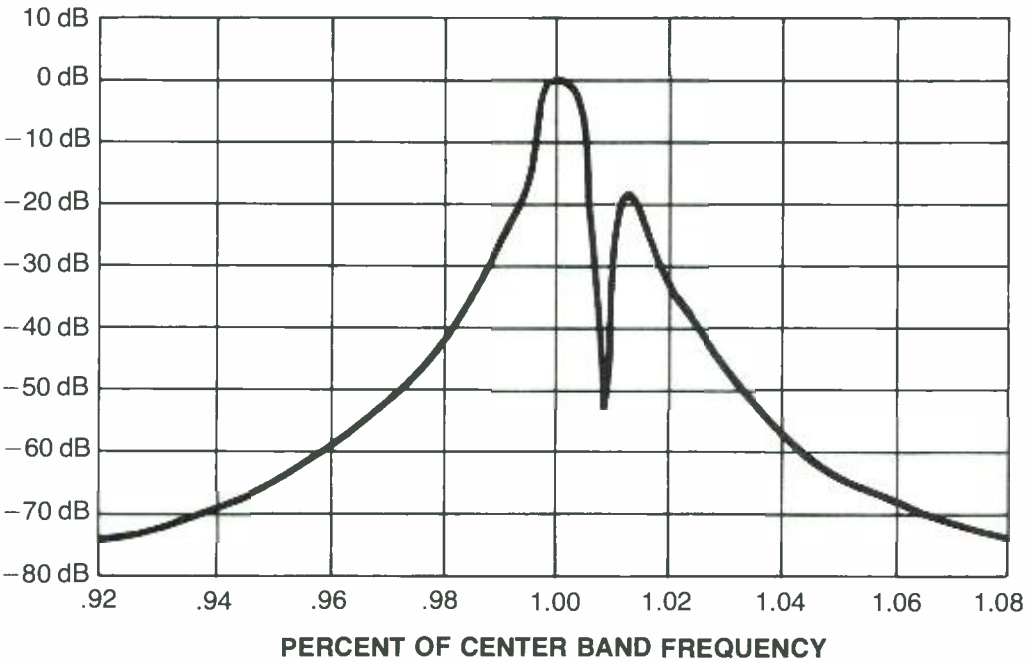


Fig. 10. Three cavity band pass-one cavity band stop filter.

pearing on both sides. These are useful when interference is caused by a combination of one frequency closely spaced and multiples further removed.

All of these responses in the VHF and FM bands are generated by coaxial cavities approximately 3/8 of a wavelength long and 12 to 24 inches in diameter (See Fig. 11). In the UHF band they can be produced by coaxial cavities or waveguide cavities. They also serve as building blocks for the diplexing and multiplexing systems discussed in the next section.

Once a decision is made to use band pass, band stop or a combination of both for a particular application, it is important to specify a few additional parameters to insure that the filter does not introduce degradation to the audio or visual content of the broadcast signal.

For example, if a filter is used to prevent Channel B from entering the transmitter of Channel A. The filter will pass Channel A and reject Channel B. But the reject curve of Channel B must not infringe upon the bandwidth of Channel A. Therefore, an insertion loss variation must be specified across the operating bandwidth and perhaps beyond. At FM, where these filters are commonly used, insertion loss variation can be kept within

0 to − .1 dB, +/- 75 kHz
0 to − .3 dB, +/-150 kHz
0 to − 1.0 dB, +/-200 kHz

when either the notch is sufficiently removed or the band pass is broad enough. The edge of the reject skirt in either configuration is also characterized by a large deviation in group delay. Group delay is defined as a change in phase divided by a change in frequency.

Fig. 11. Dielectric 1 CAV band stop for FM application.

$$Group\ delay = \frac{change\ in\ phase}{change\ in\ frequency}$$

Since the maximum excursion in the group delay occurs at the 3 dB point for filters with Butterworth or Chebyshev amplitude response, it is difficult to determine whether the group delay or the lack of bandwidth causes deterioration in cross talk and separation of stereo signals.

A paper delivered at the 1983 NAB Engineering Conference by Spencer Smith and Robert Weirather cites actual measured data of an FM multiplexer with group delay of +/- 100 ns for +/- 200 kHz resulting in stereo separation greater than 50 dB and crosstalk equal to 50 dB. The issues of bandwidth and group delay which they address are equally important for simple filter systems as discussed here. Some broadcasters are, however, requiring +/- 25 ns for +/- 150 kHz. This latter specification approaches the state of the art limits when two FM channels are separated by only 800 kHz. Since group delay can exceed either of the above specifications at frequencies well inside the 3 dB points of a band pass filter if improperly tuned, the specification of group delay is desirable to assure proper audio performance.

Diplexers and Multiplexers

Diplexers and multiplexers are devices which allow broadcasters to combine two or more frequencies into a common transmission line while providing the necessary isolation between transmitters. The isolation is needed to prevent either transmitter from generating spurious emissions. Fig. 12, 13 and 14 provide schematic examples of three configurations which can provide in varying degree the necessary response.

Fig. 12 will be called a Tee Diplexer. In the Tee Diplexer each input leg contains either a band pass or a band stop filter. For the band pass, each of these filters is characterized by a good VSWR and low insertion loss within the pass band. The slope of the reject curve away from center band is completely dependent on the number of cavities in each leg. Therefore, F1 and F2 must be separated sufficiently frequency wise to allow the reject skirt to reach a suitable rejection to obtain isolation. All of the isolation other than the 3 dB split of the tee must be provided by the filter cavities. Fig. 8 is an example of the rejection to be expected with deviations from center band. In general F1 and F2 must be widely separated for band pass legs and each operating band must be narrow for band stop legs. In addition, this configuration has limitations when multiple frequencies must be combined.

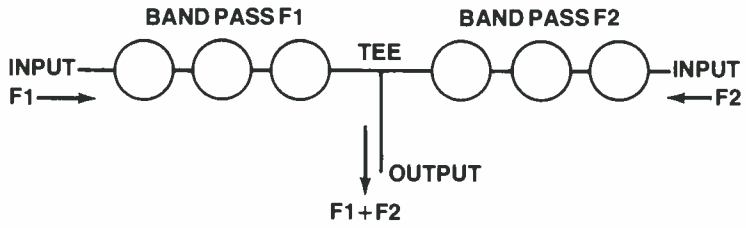


Fig. 12. Tee diplexer.

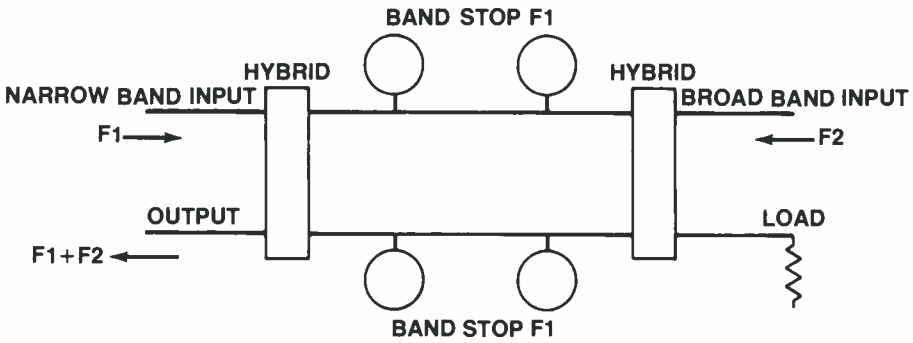


Fig. 13. Band stop.

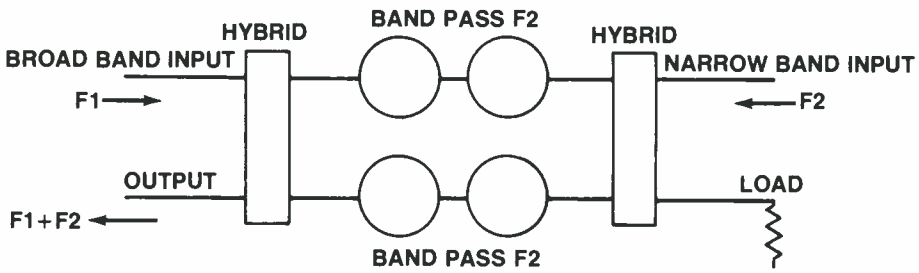


Fig. 14. Band pass

Fig. 13 and 14 respectively are band stop and band pass versions of a diplexing configuration in common usage today at VHF, UHF and FM frequencies. In both configurations 3 dB hybrids are used on both ends of the system and there will be an equal number of cavities in each leg between the hybrids. With the exception of the load on the isolated port and possible differences in line size, each system is electrically symmetrical about lines running through the center both vertically and horizontally. These systems have similar response in both coax and waveguide configurations.

In either band pass or band stop systems the hybrid on each end, when fed with an RF signal in one port, will split the power equally between two outputs with 90 degrees phase difference between the outputs. In addition, the fourth or isolated port will only pass the signal reduced by 35 dB. A matrix analysis of the magnitudes and phase of a signal such as F2 entering from the upper right port of these figures will show that it will pass through the parallel lines unattenuated by the cavities tuned to reject F1 and due to phase characteristic of hybrid will recombine in the lower left side port or output of system. It must be noted, however, that due to the isolation characteristics of the left hybrid, the entry port for F1 is isolated from F2 by 35 dB (F2 to F1). This isolation is strictly due to the presence of the hybrids and works similarly for F1 to F2 since the signal from F1 passing through the cavities

aside from being attenuated by the cavities would recombine into the load port with 35 dB isolation to the F2 port due to the hybrid.

The 35 dB mentioned is a nominal figure and with the one side being a narrow band input, some additional isolation can usually be gleaned from the hybrid possibly 40 to 45 dB. The input frequency at F2 can be any frequency within the bandwidth of the hybrid and unattenuated by the cavities so it is generally called the broad band input in Fig. 13 and the narrow band input in Fig. 14. Without the presence of the cavities, the signal input at F1 would recombine into the load, so the cavities are used to create a short circuit at F1, which reflects the power back to the left side and due to phase considerations combines into the output port of the system. Because the cavities in Fig. 13 stop only F1, it is a narrow band input. In Fig. 14 the cavities will stop any frequency sufficiently removed from F2 so the F1 input is the broad band input.

The differences in the response of the two systems stem from the differences in the response of the cavities. As in the filters discussed earlier, the band stop cavities rise quickly to a high attenuation rate but the width of the attenuation band is narrow. The response of band stop cavities is used extensively in TV Diplexers (See Fig. 15 and 16) where the narrow band port accepts the audio which is reflected usually by a single notch (band stop) cavity back to the output port of the diplexer. In the UHF portion of the band where the visual transmitter is actually capable of amplifying the audio if diplexed low level, special motor driven devices are used in waveguide to de-tune the notch so that the entire content of the TV channel can be amplified by the visual transmitter, fed into the broad band port and recombined into the output without being attenuated by the notches. This is an emergency configuration when an audio transmitter fails. In the FM band two cavities in each leg will generally provide adequate bandwidth to reject the entire content of an FM channel fed into the narrow band port. For this FM application the isolation of Fig. 13 is 70 dB nominal for F1 to F2 and 40 dB nominal F2 to F1. This is adequate for a diplexer but additional cavities can be added to the narrow band input which will reject all frequencies input at F2 and thereby increase the isolation from F2 to F1 to 65 to 70 dB when modules are connected in cascade to create a multiplexer.

The band pass configuration of Fig. 14 does not find extensive use in TV since it would require several cavities in each leg to obtain the sharp skirts necessary to pass visual and reject audio components. It, however, has been used in FM diplexers as well as multiplexers. With four cavities in each leg this configuration will provide 70 dB isolation F1 to F2 for frequencies separated by as little as .8 MHz and 40 dB isolation F2 to F1; the latter not being dependent on frequency separation but only on isolation of the hybrid. These isolation figures are adequate for diplexers. When multiple modules are connected in cascade the output of one module fed into the broad band input of the next, the resulting multiplexer has greater isolation F2 to F1. This occurs because F1 is in fact introduced to the network through its own narrow band port in the previous module in the chain. So that the isolation F2 to F1 is the combination of the 40 dB previously mentioned plus the additional isolation provided by the reject skirt of the band pass cavities in the module used to introduce F1 into the system. This analysis assumes 1 module for each frequency in the system leaving a spare broad band input which through proper patching can be used as an emergency port in the event of a failure of one of the modules.

If redundancy with the spare port is not deemed necessary, the first port in the series can be sup-

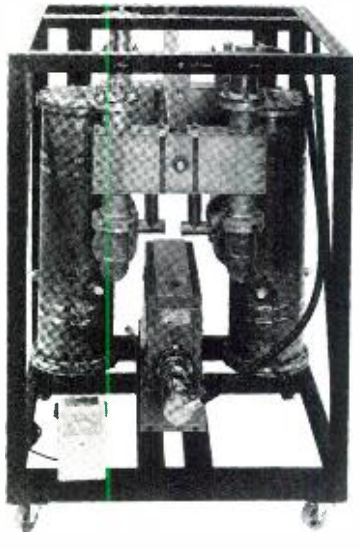


Fig. 15. High band VHF diplexer.

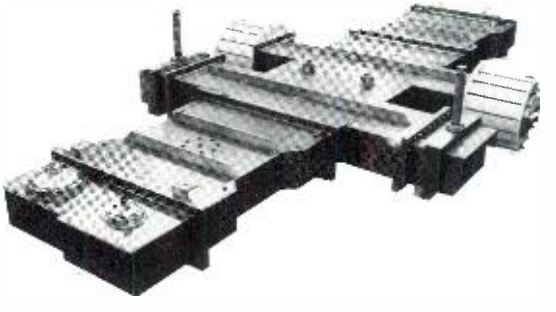


Fig. 16. UHF diplexer.

plemented with additional input cavities to provide the necessary isolation for proper system performance. This reduces the number of modules to one less than the number of frequencies.

TRANSMITTER SYSTEMS

In the following section, several methods of connecting one or more transmitters to the antenna system will be discussed. It would be impossible to cover all the possible combinations that could be conceived, therefore, only some of the basic configurations will be discussed. They can be modified or expanded to suit the individual station requirements. Most of the broadcast manufacturers will be happy to assist in designing custom systems.

When designing an RF output system with motorized coaxial switches, it is essential to make sure that the transmitter is not producing RF power when the switch contacts open. Most coaxial switches are constructed so that the interlock switches function before the RF contacts open. However, this timing will vary between different types of switches. Also, the time it takes a transmitter to stop producing RF after the interlock signal is applied will vary. Therefore, it is a good idea to check this timing. It may be necessary to turn off the transmitter a short time before commanding the coaxial switch to change positions. If the transmitter is still producing RF power, when the RF contacts open, the RF contacts of the coax switch will be burned.

Single and Alternate Main Transmitter Systems

Fig. 17 illustrates a single TV transmitter system utilizing a 7-port patch panel. The patch panel would allow the visual, aural or the diplexer output to be terminated in station load. If the transmitter has multiplex capability (amplifying both the visual and aural signals in the visual amplifier), the visual amplifier could be connected directly to the antenna, bypassing the diplexer.

An alternate main transmitter with a coaxial switch is shown in Fig. 18. A single ended transmitter like an AM or FM unit, would connect as shown. A TV transmitter would require two switches. Fig. 19 shows wiring for the interlocking of the transmitters. Notice that the station load interlocks will transfer to the transmitter that connects to the station load. Also, during switching, both transmitters will be interlocked off.

Parallel Transmitters

Parallel transmitters are two complete transmitters that are combined on the output to double the available output power. In addition to the increase in output power the parallel transmitter has additional advantages, such as redundancy and reduction of ghosting in TV applications.

When the parallel transmitter is operating normally, and one of the transmitters fail, the output power will drop to quarter power. If switching is provided in the output system, the output power can be increased to half power by bypassing the

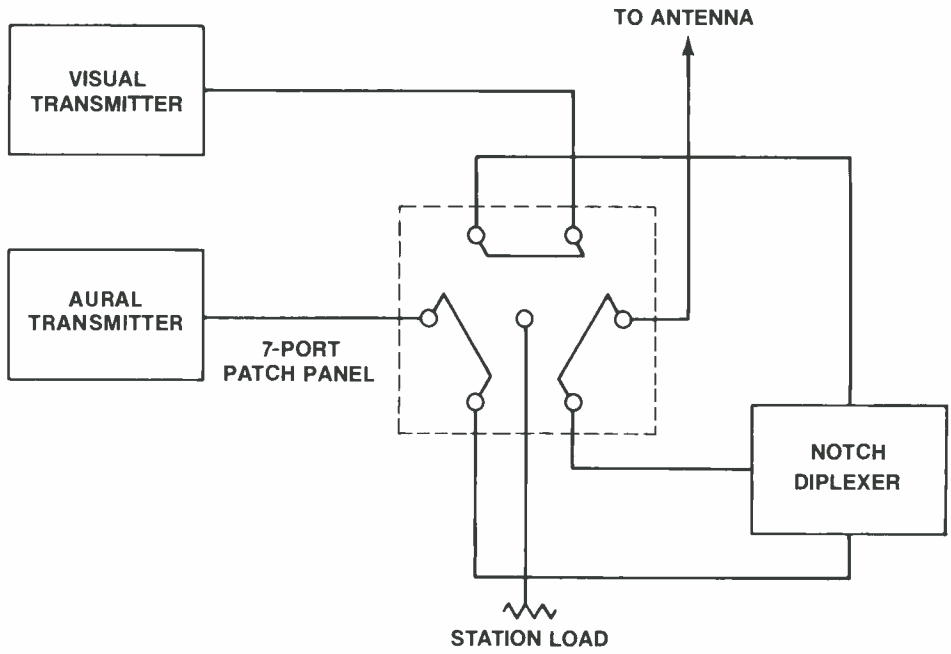


Fig. 17. RF flow diagram TV transmitter with 7-port patch panel.

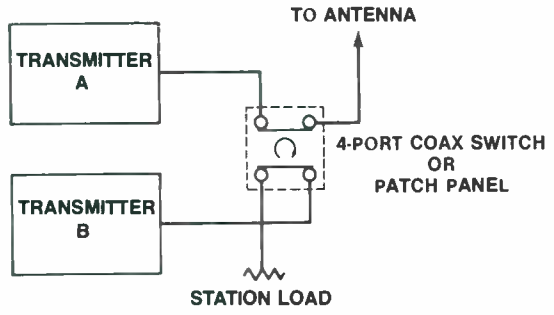


Fig. 18. RF flow diagram alternate main transmitter.

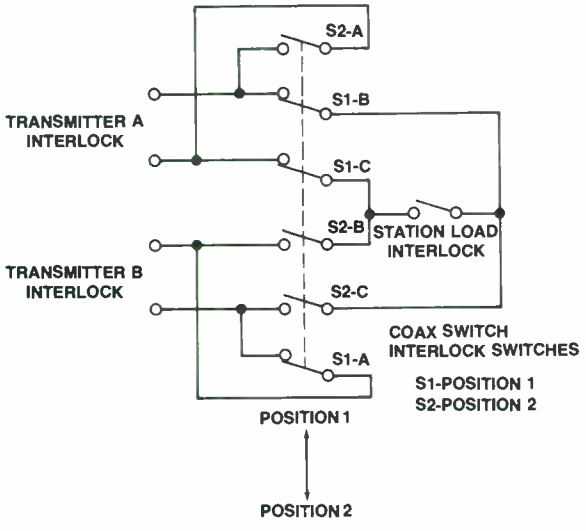


Fig. 19. Schematic alternate-main transmitter interlocks.

output combiner. The switching can take place at any convenient time.

In its simplest form, a parallel transmitter consists of an exciter-modulator, input power divider, two amplifier sections, output combiner, and reject load as shown in Fig. 20. In order to properly combine the input signals to the output combiner, they must be of the proper phase and amplitude. These relationships vary with the various types of combiners.

AM and Short Wave Parallel Transmitters

Parallel transmitters in the AM and short wave broadcast bands are not as common as in the higher frequency bands. They are generally used only to double the output power available.

Combiners used at these lower frequencies are usually a bridge type of circuit. The bridge circuit is usually made up of four π circuits with a characteristic impedance of 70.7 ohms and are constructed with lumped elements (capacitors and inductors). The bridge circuit is shown in Fig. 21A. The phase shifts produced by each leg can either be a positive or negative 90 degrees depending on the elements used. If the shunt elements are capacitors, a negative phase shift will be produced. Using shunt inductors will produce a positive phase shift.

If the two transmitters are fed to the two inputs in-phase, the two signals will be in-phase at the antenna output, Thus they will combine. The two input signals will be 180 degrees out-of-phase at the reject load output, therefore, there will be no power dissipated in the load. When one of the transmitters stop producing power, the power from the remaining transmitter will be split equally to the reject load and the antenna.

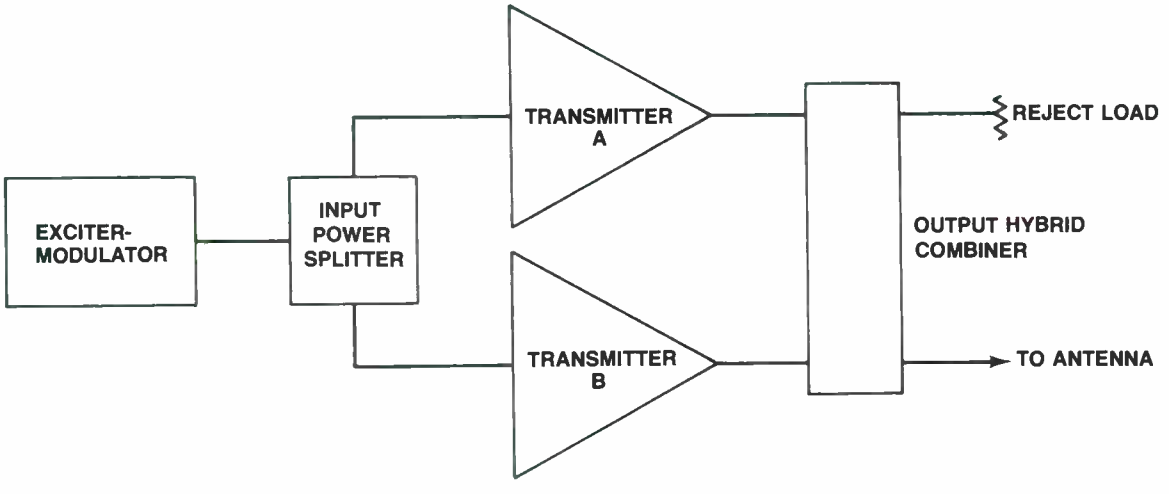


Fig. 20. Basic parallel transmitter.

By making three of the legs of the bridge a positive phase shift, the number of circuit components can be reduced. This simplified circuit is shown in Fig. 21B. The two parallel capacitors across the antenna output and transmitter 1 input can be combined so that only one capacitor is required at each point. The capacitor and inductor that are in parallel across the reject load and transmitter 2 input, will have equal reactance and thus cancel, so neither are required. The bridge combiner can be built with only three capacitors and three inductors, thereby reducing the costs of the unit. As an added advantage the high current carrying devices are the series elements, of which three are inductors.

Ferrite core transformers have been used in lower power applications. One parallel transmitter using such a device is shown in Fig. 22. This unit is used to combine two 5 kilowatt transmitters.

The combiner can be thought of as a center tapped autoformer that operates at these RF frequencies. If equal amplitude signals that are in-phase are applied to the ferrite combiner, with a common ground, the center tap will contain the sum of the two signals. Since the two signals are in-phase, there will be no voltage differential across the reject load resistor.

If each input is 200 watts for example, there will be 100 volts, at 2 amperes across the 50 ohm input of the ferrite transformer. When the two signals are added, there will be a total of 4 amperes. Since the center tap of the transformer has an impedance of 25 ohms, the 4 amperes will produce 400 watts of power. A "L" network is used to match the 25 ohm center tap of the transformer back to the 50 ohm output.

When only one transmitter is operating, the power it produces will be split equally between the antenna and the reject load. The operating transmitter will produce 200 watts, or 100 volts at 2 amperes as in the example above. Therefore, there will be only 2 amperes at the center tap of the transformer, which will produce 100 watts of power. Since the other transmitter is not operating, there will be 100 volts across the 100 ohm reject load, which will be the remaining 100 watts produced by the operating transmitter.

VHF Parallel Transmitters (Coaxial)

In VHF parallel transmitters' the output combiner is usually a 3 dB 90 degree hybrid. In order to properly combine the two transmitter signals, the hybrid requires the signals be equal amplitude and phased in quadrature (90 degrees). If we assume that the amplifier sections of the transmitters are identically tuned and the electrical path lengths and gain are the same, then the input power divider must provide two signals that are equal amplitude and phased in quadrature. A

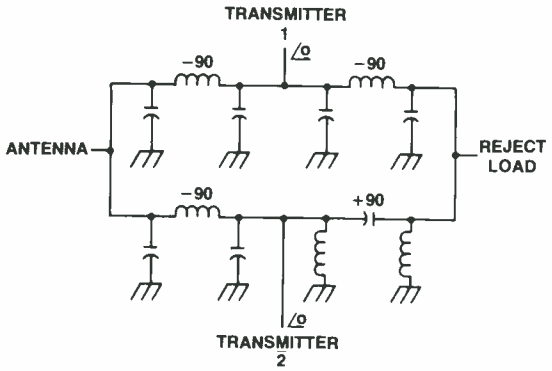


Fig. 21A. Bridge combiner - π networks.

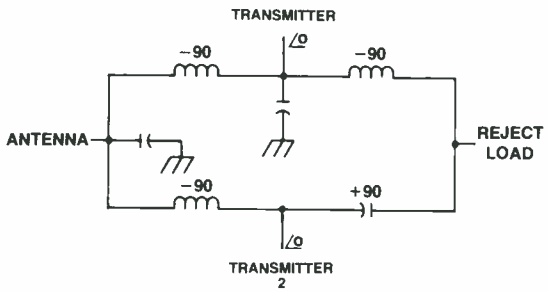


Fig. 21B. Bridge combiner simplified.

3 dB hybrid will provide this type of power division. Other types of power dividers could be used. An "in-phase" power divider with a 90 degree delay in one output would work just as well.

Fig. 23 shows the relative phase relationship to the output power of the parallel transmitter system. With no phase error, input signals to the output hybrid in quadrature, 100% of the available transmitter power will be delivered to the antenna. If there is a 90 degree phase error, both signals in-phase, the power will be divided equally between the antenna and the reject load. All the available transmitter power will be dissipated in the reject load if the phase error is 180 degrees. A phase error of 20 degrees will only result in an output power reduction of approximately 3%. This would indicate that the phasing is not critical for output power considerations.

The relative amplitude relationship to the output power is shown in Fig. 24. The graph assumes that one of the transmitters is operating at full power and output power of the second transmitter is varied from 0 to full power. If only one transmitter is operating the output power will be only 25% of the normal combined output power. With only one input signal, the output hybrid acts as a power divider, applying half the power to the antenna and the other half to the reject load. The power being fed to the antenna is 25% of

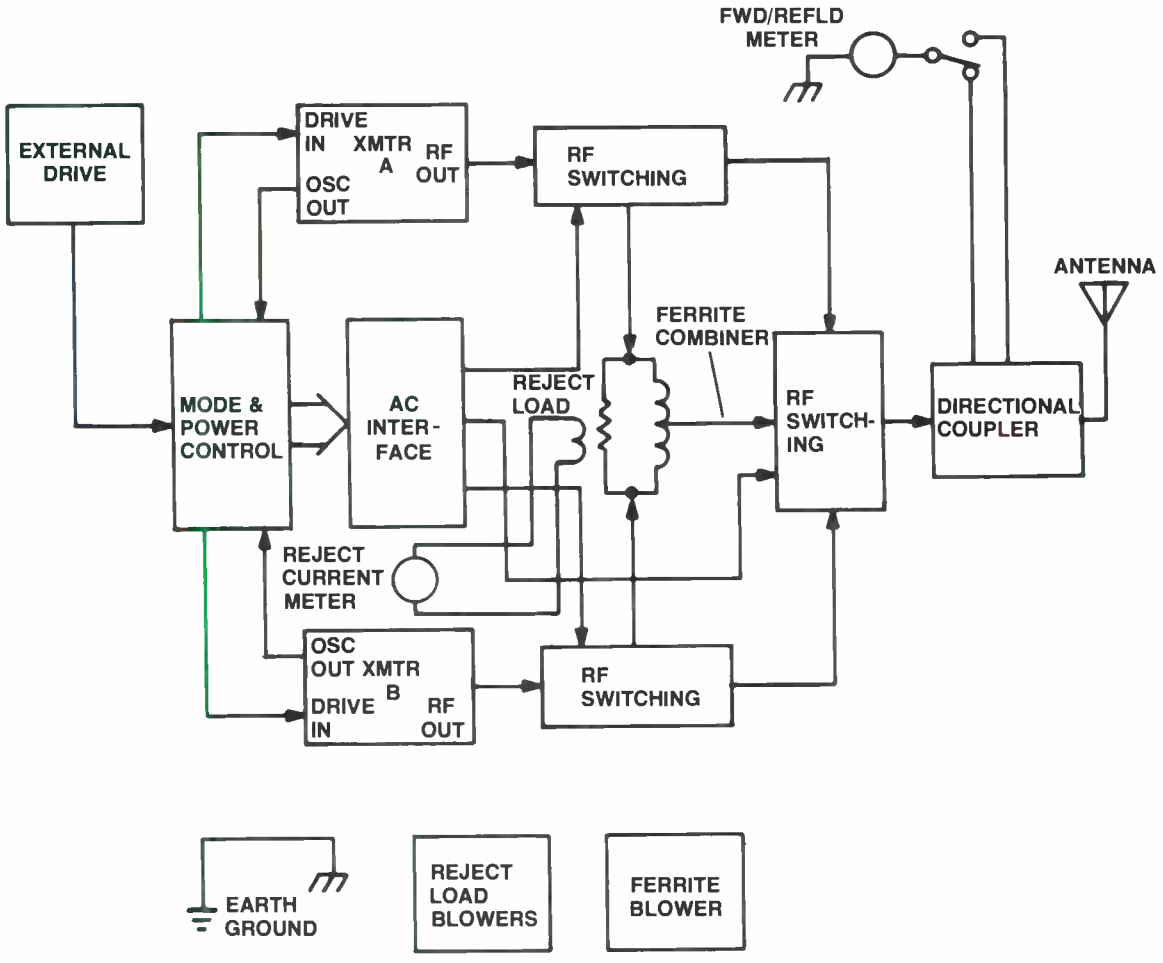


Fig. 22. Simplified block diagram, combiner and RF switching. (Courtesy Harris Corp.)

the normal combined transmitter power. If one of the transmitters is operated at half its normal output power, while the other transmitter is operated at full power, the combined output power will be approximately 73% of the normal combined power. Since the two transmitters are only generating 75% of the normal combined power, only about 2% of the power is being dissipated in the reject load. Therefore, there is not a great amount of power being wasted in the reject load. The maximum power that the reject load should be required to dissipate is half of one transmitter's power.

Thus far only the basic parallel transmitter system has been discussed. It was assumed earlier that the amplifier sections of the transmitters were identically tuned, having the same electrical path lengths and gain. From a practical view point this could be done, but with difficulty. Therefore, most parallel transmitter systems will provide a means of controlling the phase and gain of the transmitters that are independent of the tuning. It usually is an attenuator for gain and a phase shifter for the phase. Some transmitters may use a gain control within the amplifier section for the gain control and one of the input matching controls of the power amplifier for phasing. This practice is probably more common in FM than TV since the bandwidth is smaller.

One of the major advantages of a parallel transmitter is the reduction of ghosts or reflections from the antenna. Ghosts are reflections from the antenna that are re-reflected from the transmitter and radiated from the antenna. The distance between the original image and the ghost on a TV receiver can be used to determine the approximate location of the reflection in the antenna system. Since the horizontal frequency of the TV is 15734 Hz. The full horizontal line would be equal to 63.6 microseconds. The length of the visible portion of the horizontal line is 53.1 microseconds, therefore, the time between image and the ghost can be measured. This time, when compared to the speed of light, will yield the

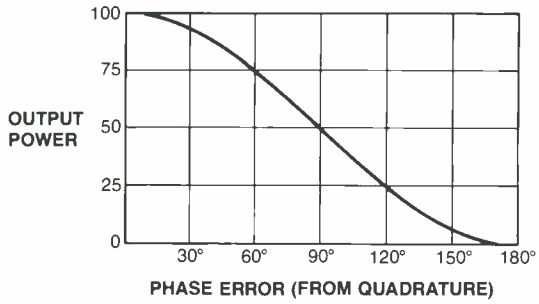


Fig. 23. Relative phase error verses output power.

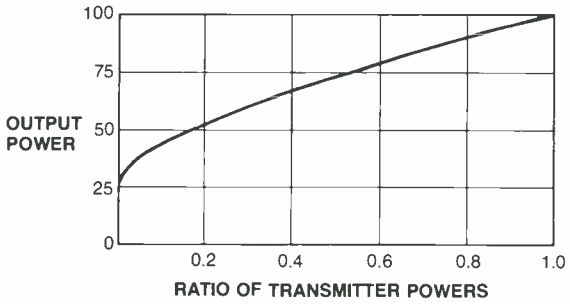


Fig. 24. Relative amplitude error verses output power.

distance the reflected signal had to travel to produce the ghost. It must be kept in mind that the signal had to travel from the point of origination down the transmission line to the transmitter and back up the transmission line to the antenna to be radiated. The velocity of propagation of the transmission line must also be taken into account.

The use of the 3 dB hybrid in the parallel transmitter will reduce the reflected signals that produce the ghosts. When the reflected energy from the antenna is applied to the output of the 3 dB hybrid, it is split into two signals at the two transmitter inputs. These signals will be phased 90 degrees apart and will continue until they are re-reflected by the output circuitry of the transmitters. The signals will be applied to the inputs of the 3 dB hybrid, however, their phases are such that instead of combining in the antenna output, they will combine in the reject load of the parallel transmitter. For optimum ghost reduction the electrical path lengths between the hybrid and transmitter inputs must be the same. The use of slugs or other tuning devices can upset the phase balance or electrical length of the system. One method to measure the performance of a system for ghost reduction, is to measure the reverse VSWR of the system. This is accomplished by placing open or short circuits on the transmission lines that would connect to the transmitter outputs and measuring the VSWR looking in the output of the combining system. Thus the path of the ghost signal is being measured. Ideally, this path should be as good as the forward VSWR of the system, however, from a practical standpoint a VSWR of 1.1:1 or better will reduce the ghosting. It should be noted that the equal electrical line lengths are needed for quadrature type combining networks. For systems using in-phase type combining networks there needs to be a 90 degree delay in the proper input. To offset this delay, a 90 degree delay can be inserted in the input circuitry of the opposite transmitter.

Fig. 25 shows a complete output switcher for a parallel television transmitter. For single ended transmitters such as FM, only half the system would be required. This figure shows the output switching around the output hybrid combiner. There are normally four modes of operation:

1. A&B Combined to the Antenna
2. A&B Combined to the Station Load
3. A to the Antenna and B to the Station Load
4. B to the Antenna and A to the Station Load

The RF flow diagram is shown in the A&B to the antenna mode. By rotating S3 and S6 the system is changed to the A&B to the station load mode. If S1, S2, S4, and S5 are changed, transmitter A will be connected to the antenna while transmitter B will be connected to the station load. If S3 and S6 are rotated, the transmitters will switch transmitter A to the station load while transmitter B is connected to the antenna.

Since a parallel transmitter is two complete transmitters, there should be two exciter-modulators. Some manufacturers may offer the second exciter-modulator as an option. By adding a switch on the input of the input power divider, either exciter-modulator could be selected. This would provide redundancy, should the active exciter-modulator fail. Since the power levels of the exciter-modulator is usually fairly low, the switching could be done under power which would allow the switching to be automatic. By using relatively fast switches, the transfer could be done with only a small carrier interruption.

Automatic switching of the output switching system is not usually done. Stations would rather choose when the carrier break occurs, since it will be noticeable to the audience. In lower power installations, the carrier break will be 2 seconds or less. With higher power switches the break could be up to 10 seconds.

Again referring to Fig. 25, the combined output of the visual hybrid must pass through S2 and S3. Therefore, these switches must be sized to carry the combined power. Some systems will add another coaxial switch (S7) on the output of

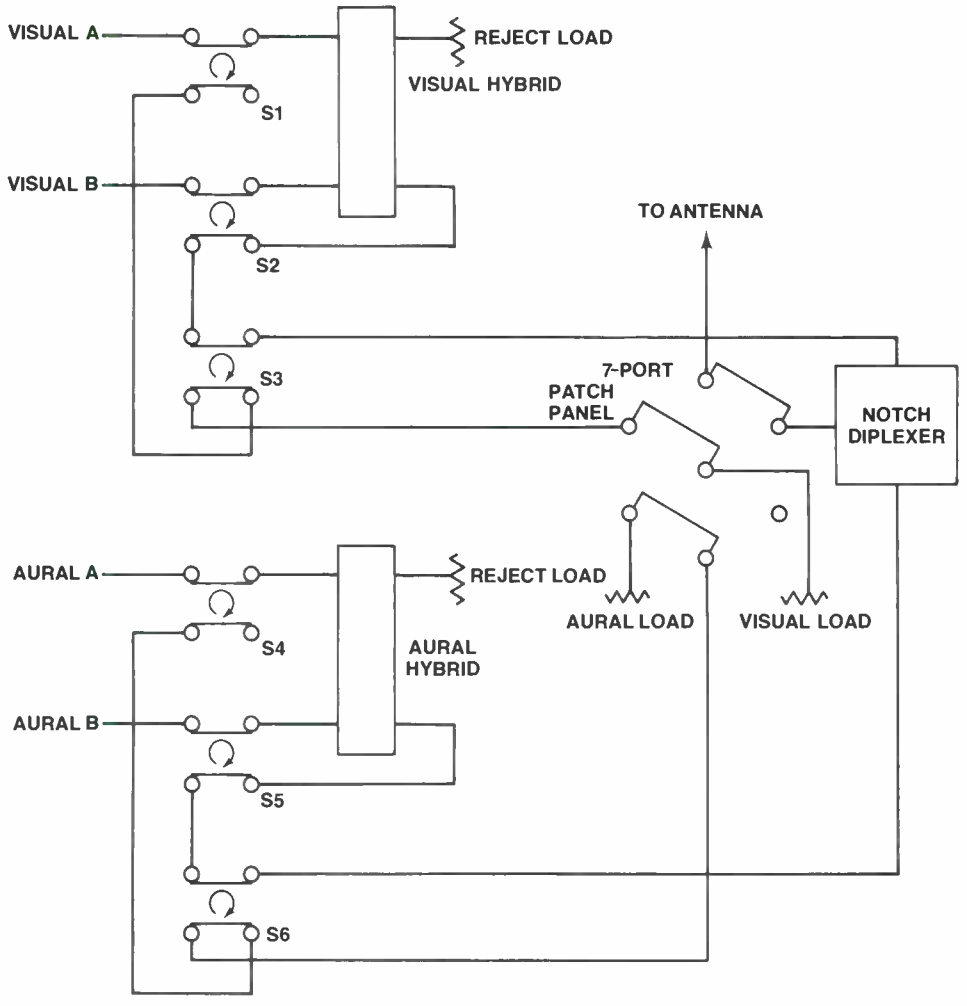


Fig. 25. RF flow diagram output switcher.

the visual hybrid as shown in Fig. 26. This higher power switch will allow the other three switches to be a smaller size, since the combined power will only be applied to S7. It will also be necessary to add another station load for the combined signal at S7. Generally, this will reduce both the package size and the cost of the parallel transmitter system. A television system requires a diplexer of some type in order to combine the aural and visual signals. The output switching system usually contains a patch panel which allows the output of the diplexer to be routed to either the antenna or the station load. The output switching system must also contain the necessary monitoring points for combined power and reject power.

VHF "Switchless" System (Coaxial)

The "switchless" phase shifter system for VHF frequencies is probably the most recent development in RF switching systems. At the time of writing, the writer is not aware of these systems operating in the field. The "switchless" system is designed to combine the outputs of two transmitters operating in parallel. It is intended to replace the switch type output switchers previously used.

As with the switch type output switchers, it is desired to have four basic modes of operation which are:

1. A&B Combined to the Antenna
2. A&B Combined to the Station Load
3. A to the Antenna and B to the Station Load
4. B to the Antenna and A to the Station Load

There are several methods to accomplish the mode changes performed by the "switchless" system. The basic system is shown in Fig. 29, and consists of two 90 degree hybrids, a reject load, and some type of phase shifting device. It is the method used to do the phase shifting that makes the systems different. Therefore, the basic system will be presented and then the different methods

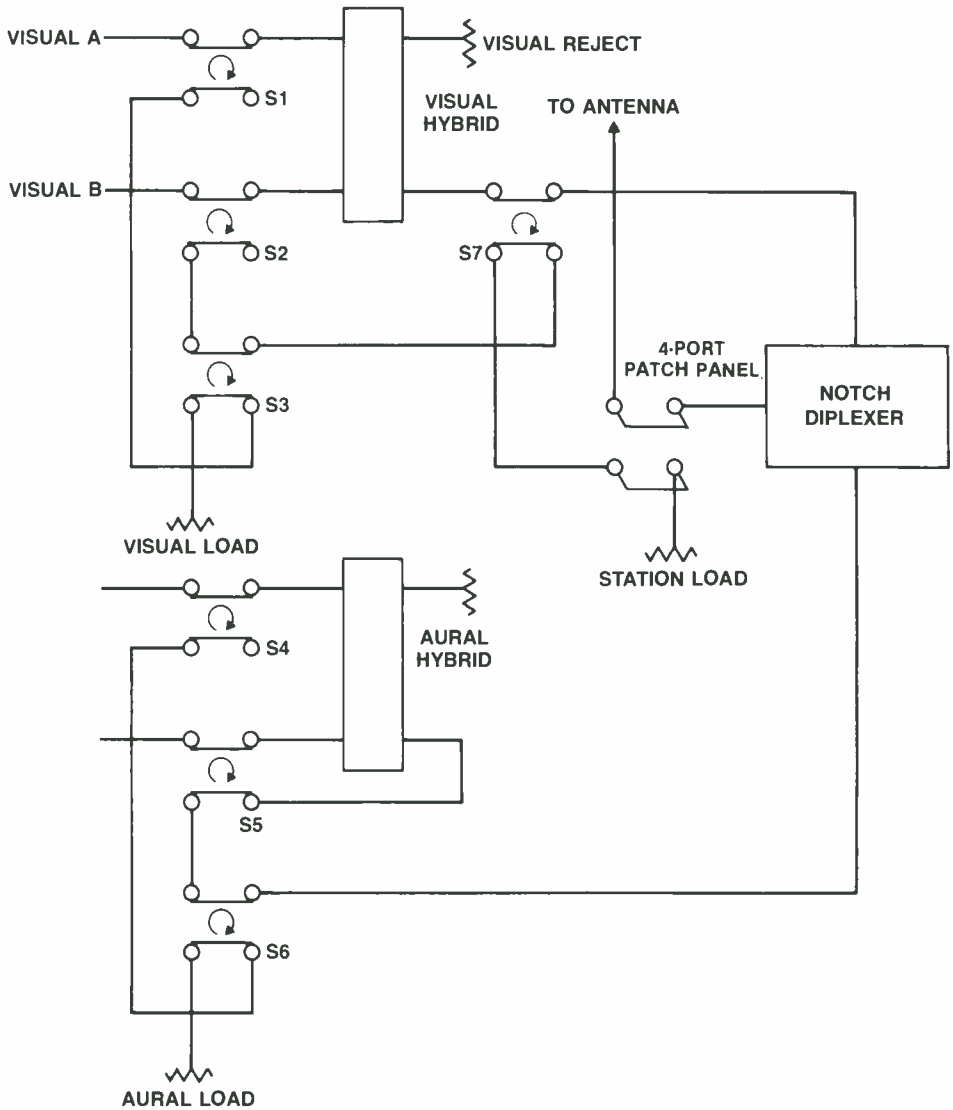


Fig. 26. RF flow diagram high power output switcher.

of accomplishing the phase shifting will be discussed.

Since the "switchless" system contains two hybrids, it is necessary to understand how the hybrid operates. The 90 degree hybrid can be utilized as either a power divider or a power combiner. In the "switchless" system both are used.

When used as a power combiner, the hybrid will combine two signals that are equal amplitude and phased in quadrature. Again referring to Fig. 29, if two equal amplitude signals are applied to points E and F, with the signal at F lagging in phase by 90 degrees, the signals will be combined into the antenna. Conversely, if the signal at point E is lagging by 90 degrees, the signals will be combined into the load.

If a signal is applied to the A input of the hybrid, being used as a power divider, it will be split into two signals of equal amplitude that are phased 90 degrees apart. The signal appearing at point C will be in-phase with the input signal (point A), while the signal at point D will lag the input signal by 90 degrees. The converse is true for a signal being fed into the B input. The signal at point D will be in-phase, while the signal at point C will lag 90 degrees. If two signals that are in-phase are applied to inputs A and B, then each of the outputs (points C and D) will have two signals, one in-phase with the inputs and one lagging by 90 degrees.

If the "switchless" system is set in the A&B to the antenna mode, phase shifter #2 must have 90 degrees more phase shift than phase shifter #1. The two signals at point F will lag the two signals at point E. In this situation, the signals will combine in the antenna output.

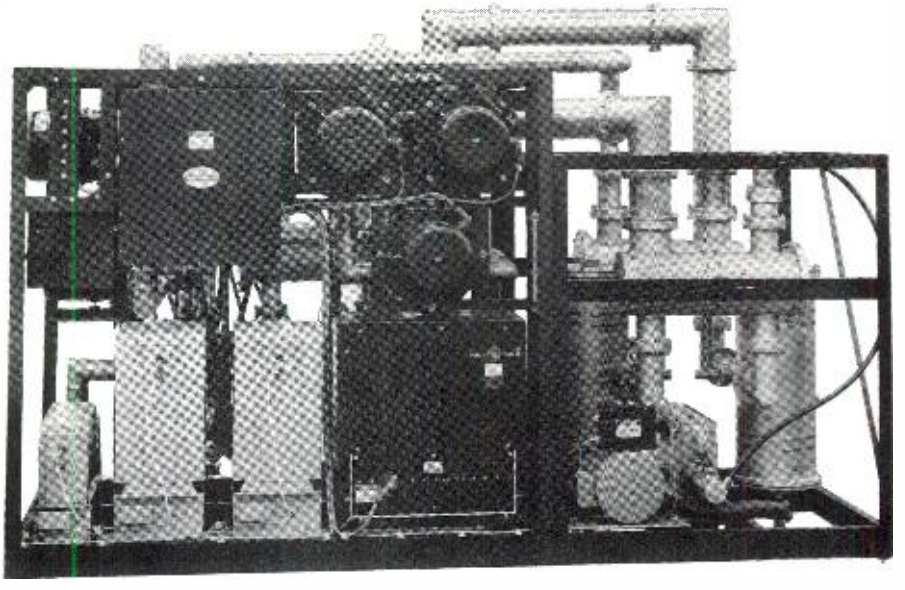


Fig. 27. VHF output switcher parallel TV transmitters front view.

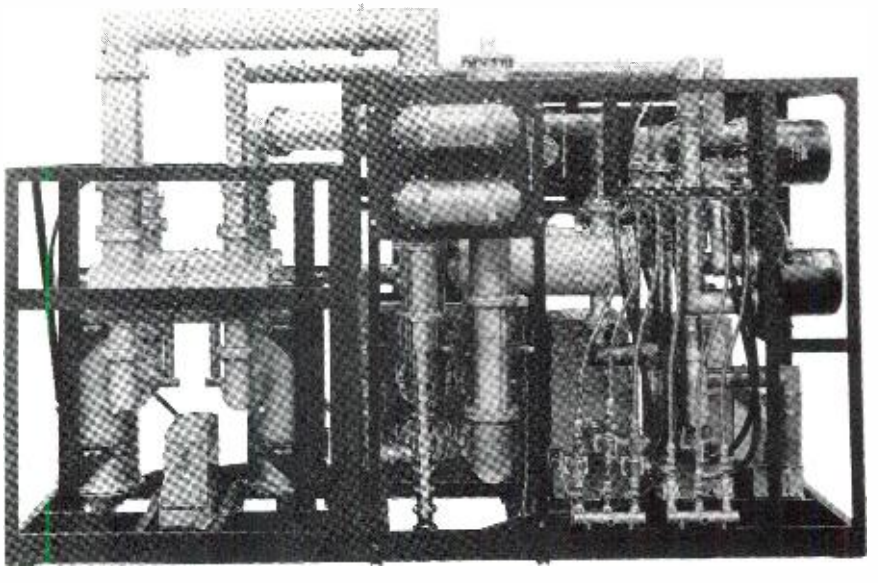
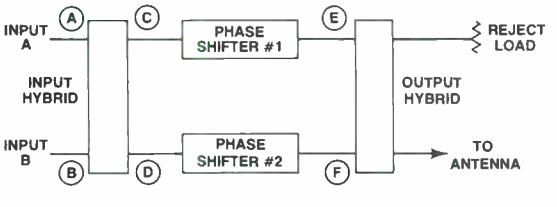


Fig. 28. VHF output switcher parallel TV transmitter rear view.



MODE	PHASE SHIFTER #1	PHASE SHIFTER #2
A+B ANTENNA	0	90
A-ANTENNA B-LOAD	90	90
B-ANTENNA A-LOAD	0	180

NOTES:
1. INPUTS A + B ARE IN-PHASE
2. PHASE SHIFTER #2 WILL USUALLY CONTAIN A FIXED 90° SECTION AND A VARIABLE 90° SECTION

Fig. 29. Basic switchless combining system.

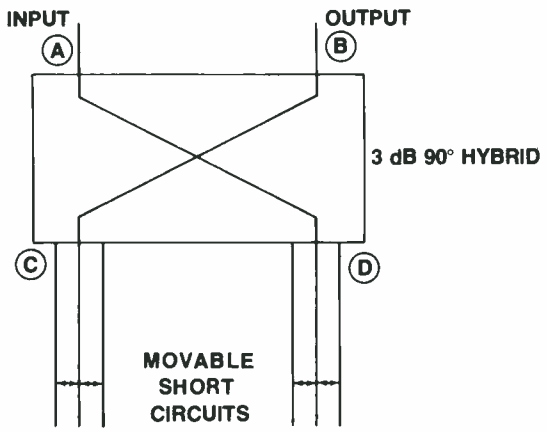


Fig. 30. Variable phase shifter.

If either of the phase shifters are set for an additional 90 degrees of phase shift, the system will be in one of the single transmitter modes of operation. If phase shifter #1 is changed, then transmitter A will be routed to the antenna, while transmitter B will be terminated in the station load. Should phase shifter #2 be changed, transmitter B will be routed to the antenna, while transmitter A is terminated in the station load.

There are three methods of getting the combined transmitters routed to the station load.

1. A coaxial switch or patch panel could be used on the antenna output to route this output to a separate station load.
2. The combined transmitters could be routed to the reject load by moving the additional 90 degree phase shift in phase shifter #2 to the #1 phase shifter.
3. The transmitter outputs could also be combined into the reject load by changing the input phases to the "switchless" system. By adding 180 degrees delay to the A input the combined transmitter will be routed to the reject load.

The later two methods will require that the power rating of the reject load be increased to the combined power level instead of that of a single transmitter. They also require the antenna to function as the reject load for any power that is not absorbed in the reject load.

There are several methods of changing the phase of the RF signals in the "switchless" system.

1. Probably the most familiar method of changing the phase at higher power levels is the line stretcher. It is a piece of transmission line, whose length can be changed. For convenience, it often takes the form of a "U-link", or trombone, so that the connectors can be mounted and the "U-link" moved to change the length.
2. Another method is to use a 90 degree hybrid with movable short circuits on two of the arms. This device is shown in Fig. 30. If a signal is applied to the input (Point A), the hybrid will divide it into two equal signals that are phased 90 degrees apart. The signal at Point D will lag by 90 degrees. The short circuits attached to Points C and D will reflect the two signals back to the hybrid. The phase of the two signals will be delayed by twice the electrical length of the short circuits. If the two short circuits are the same length, the relative phases of the two signals will still be 90 degrees. Since the signal at Point D is lagging by 90 degrees, the two signals will combine into the output (Point D). By changing the length of the short circuits, the delay or phase shift through the circuit will change. If the short circuits are moved 90 degrees, the phase shift through the circuit will be 180 degrees. The signal must travel from the hybrid to the short circuit and then return to the hybrid, twice the distance of the short circuit. The two short circuits must be moved together in order to make the hybrid combine the reflected signals properly.
3. There are several methods of making a short circuit needed in the above circuit, which are shown in Fig. 31. It could be the traditional short (i.e. a piece of metal contacting the inner and outer conductors of the transmission line, employing finger stock, allowing it to be moved). A "deep short" could be used which moved the ringer contacts one quarter wave length away from the short. This greatly reduces the amount of current that the fingers are required to carry. A "non-contacting" short may be used. It is a pair of cylinders that are a quarter wavelength long and shorted at one end. The sizes of the cylinders are such that they fit between the inner and outer conductors of the transmission line. The shorted cylinders are insulated from the transmission line, thus forming a capacitor. The capacitor is large enough so as to have very little impedance to the operating frequency, therefore, it appears as a short circuit.

   Another method of creating phase shift is to change the short circuit to an open circuit. A short section of the center conductor is removed from a shorted piece of transmission line. The transmission line appears as an open circuit, since there is very little capacitance between the two pieces of cut center conductor. By moving an insulated metal probe across the gap in the cut center conductor, a large amount of capacity is created. This causes the

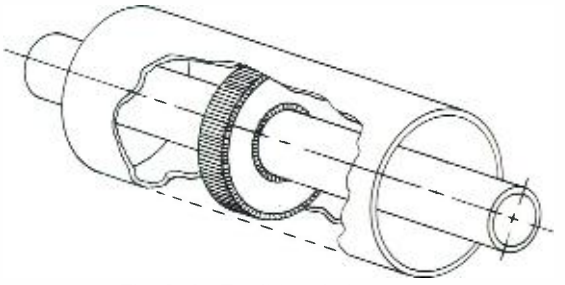


Fig. 31A. Traditional short.

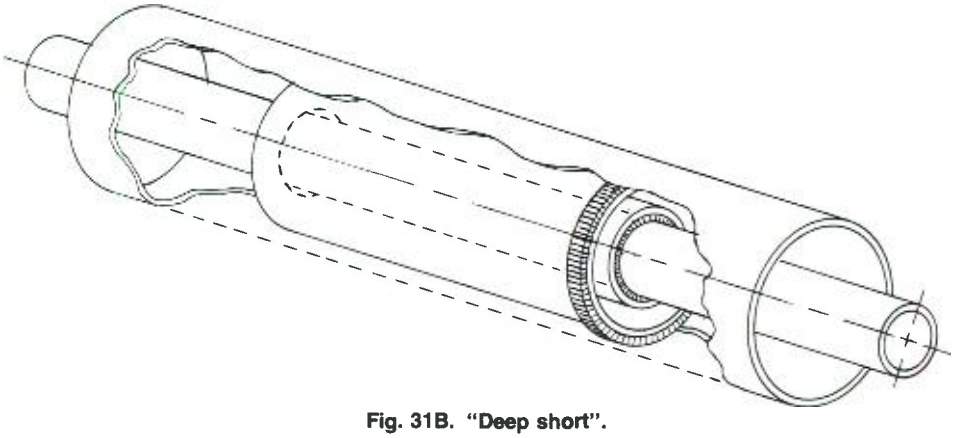


Fig. 31B. "Deep short".

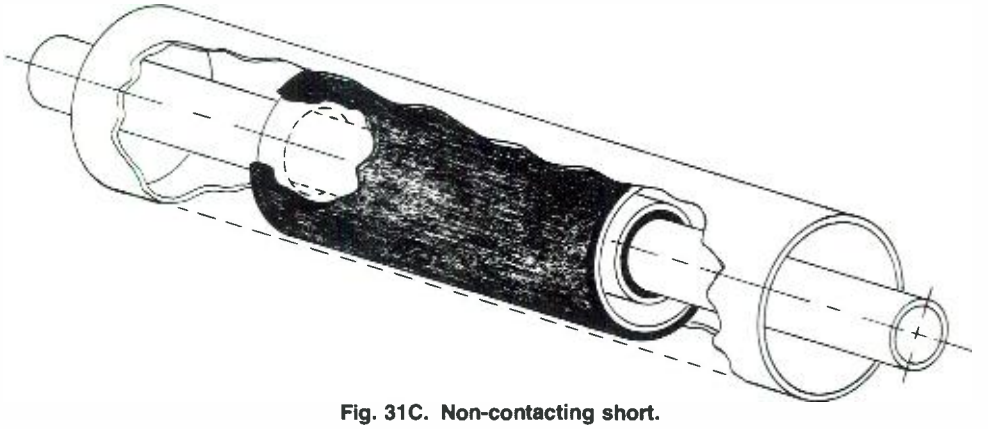


Fig. 31C. Non-contacting short.

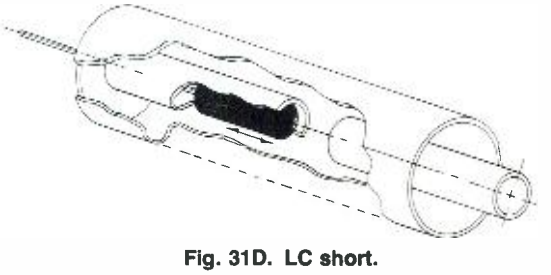


Fig. 31D. LC short.

transmission line to appear as a short circuit, thus changing the phase.

All the above methods will accomplish changing the phase and allow the "switchless" system to operate. Each of the methods have advantages and disadvantages that should be taken into consideration upon purchasing a "switchless" system.

The "switchless" system does not require that the transmitters be turned off during the switching process. Since there is no carrier break, the length of switching is not important. It also allows the switching to be done with no regard to program content. Switching can be done while the commercial is on the air.

The "switchless" system will offer the same ghost reduction as the other types of parallel transmitters. Since the two signals from the transmitters are applied to the "switchless"system in-phase, there needs to be an external phase shift to take advantage of the ghost reduction feature. A 90 degree phase shift has to be added between the output of one of the transmitters and the "switchless" system. This will delay the reflected signal in that path 90 degrees as it passes from the output system to the transmitter, and another 90 degrees as it passes from the transmitter back to the output system. The two reflected signals will now be 180 degrees out-of-phase, thus be combined in the reject load. Since a 90 degree delay was added to one of the transmitter signals it will be necessary to add an equal phase shift to the other transmitter so that the transmitter signals will combine in the antenna output. This delay can be added to the input circuits thus allowing the ghost reduction circuit to operate properly.

There are some differences in the "switchless" system that were not common to the switch type systems. In a switch type system, the transmitters were isolated by the mechanical switch when operating in the single transmitter mode. The "switchless" system does not have that isolation. The isolation is provided only by the two hybrids of the system. Therefore, the 60 dB or better isolation provided by the coaxial switches, is not present in the "switchless" system. It is possible that voltages could be present on the input, even though the transmitter driving that input is turned off. It is necessary to make sure safety devices are utilized to protect individuals. It would be a good idea to delay maintenance on the system until both transmitters could be turned off.

UHF Parallel Transmitters (Waveguide)

UHF Parallel transmitters are a little different than their VHF counterparts. Because of the power rating of the klystron (30 kW to 60 kW), complete parallel transmitters are not as common as in VHF. A 220-240 kW transmitter is the more common parallel UHF transmitter. There are quite a few 110-120 kW transmitters operating, but these aren't complete parallel transmitters, as only the visual klystrons are operating in parallel. The UHF transmitters also have aural multiplex capabilities, which reduce the need for parallel aural amplifiers.

A typical RF flow diagram for a waveguide output switching system is shown in Fig. 35. It contains four waveguide transfer switches, a hybrid combiner, and a reject load. S1 and S2 switch the input of the system around the hybrid for single transmitter operation. S3 determines

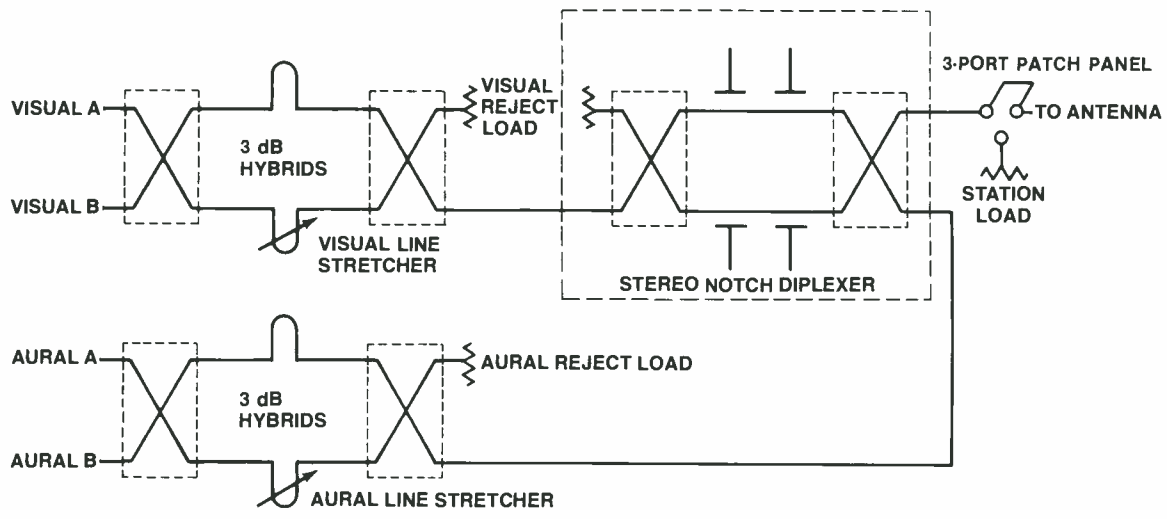


Fig. 32. RF flow diagram VHF "switchless" system with phase shifters.

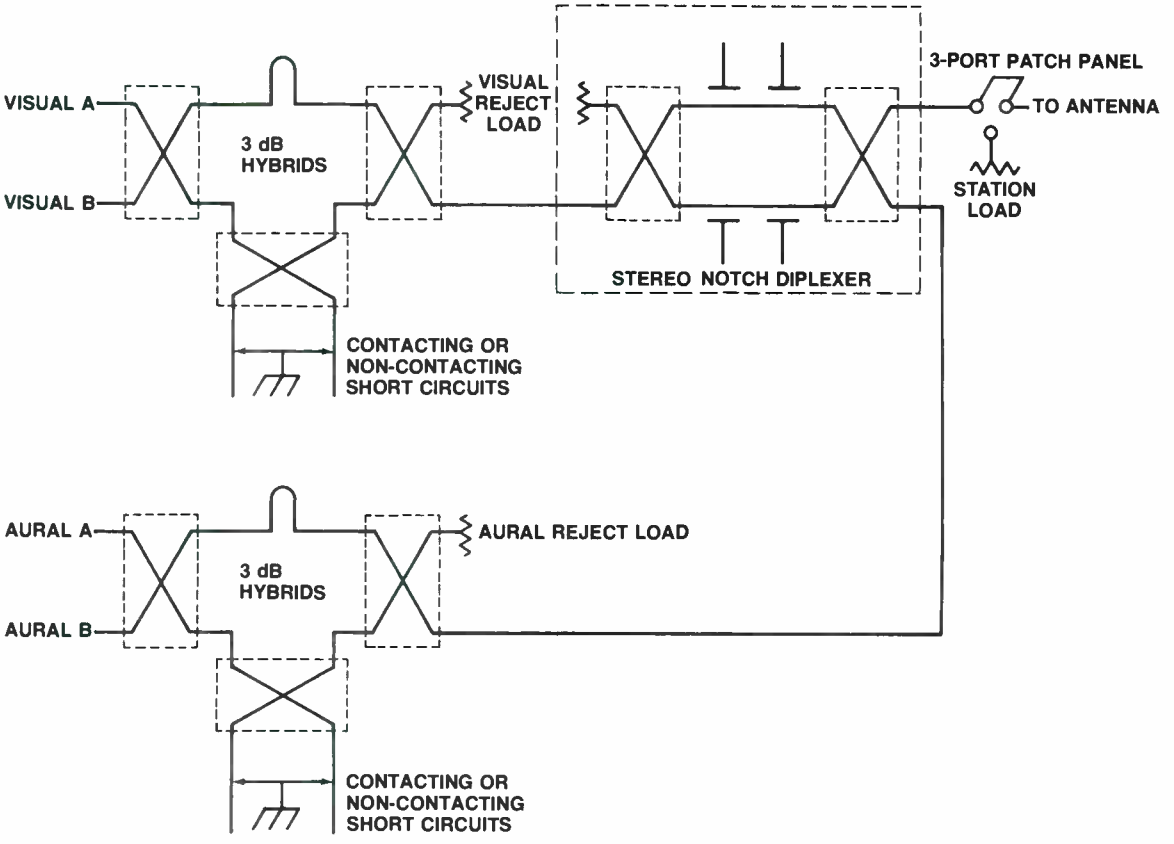
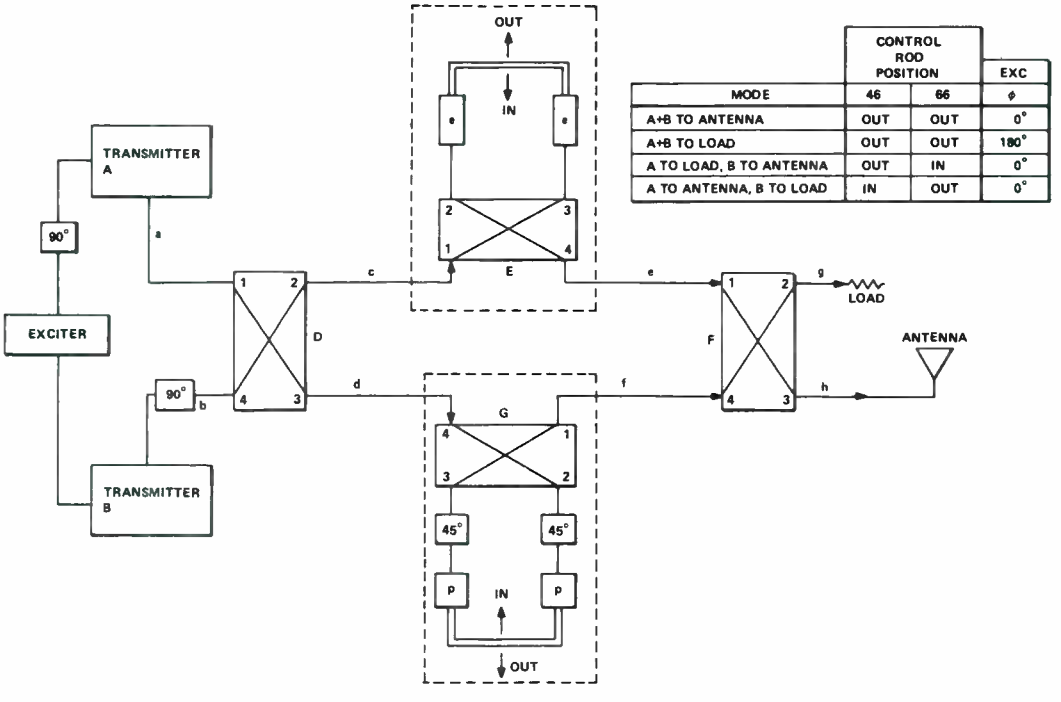


Fig. 33. RF flow diagram VHF "switchless" system with hybrid phase shifters.



MODE	CONTROL ROD POSITION 46	66	EXC ϕ
A+B TO ANTENNA	OUT	OUT	0°
A+B TO LOAD	OUT	OUT	180°
A TO LOAD, B TO ANTENNA	OUT	IN	0°
A TO ANTENNA, B TO LOAD	IN	OUT	0°

Fig. 34. Block diagram RCA OPTO-SX "switchless" system. (Courtesy RCA)

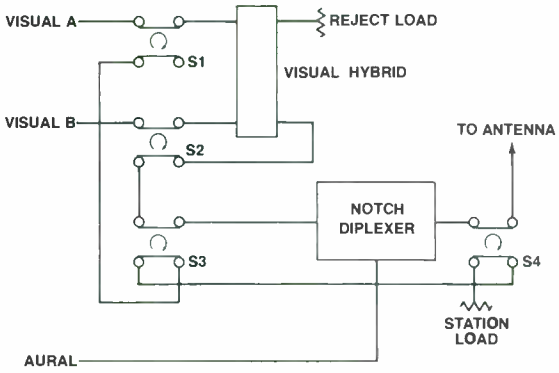


Fig. 35. RF flow diagram output switcher parallel visual amplifiers.

whether the transmitter signals will be routed through the diplexer, while S4 routes the output of the diplexer to the antenna or station load. The aural amplifier is routed directly to the diplexer. This system would have the four basic modes of operation:

1. Visual A & B combined to the antenna
2. Visual A & B combined to the station load
3. Visual A to the antenna and visual B to the station load
4. Visual B to the antenna and visual A to the station load

In addition, each of the modes could be operated either multiplexed or normal.

Recent developments in diplexers have simplified the switching systems. Aural notch detuners allow the multiplexed signals to pass through the notch diplexer, rather than being switched around it. The detuners will raise the aural notch cavities frequency so that it is above the aural carrier. This allows the multiplexed visual carrier to pass through the diplexer, just as the visual signal does normally.

Each RF output switching system is usually unique. Either the RF layout of the system will be slightly different, or the mechanical layout of the system needs to be changed to fit in the transmitter building. Since this is usually the case rather than the exception, most manufacturers are equipped to handle these situations. Fig. 36 shows a system utilizing coaxial patch panels and switches on the input, and a waveguide patch panel on the output of the diplexer.

UHF "Switchless" System (Waveguide)

One of the more recent developments in RF switching systems is the "switchless" phase-shifter systems. It is used to combine the outputs of higher power UHF amplifiers and can be used for either aural or visual service. This system consists of a 3 dB 90 degree hybrid, a dual phase shifter, a reject load, and a magic tee (180 degree hybrid) and is shown in Fig. 37. To better understand how the system operates, it is essential to understand the individual component operation.

The magic tee (180 degree hybrid) works similarly to the 90 degree hybrid. The difference is the amount of phase difference of the device. When it is used as a splitter, the outputs will either be in-phase or 180 degrees out-of-phase, depending which input is being driven. When used as a combiner, the magic tee will combine signals that are in-phase into the main output or into the coupled output if the signals are 180 degrees out-of-phase.

The phase shifters consist of a movable piece of dielectric material inside a section of waveguide. When the dielectric material is against the side wall of the waveguide, the phase shift will be at the minimum. As the dielectric material is moved toward the center of the waveguide, the phase shift of the signal going through the waveguide will increase. By choosing the type and amount of dielectric material, the relative phase shift can be adjusted to produce 90 degrees of phase shift. The amount of phase shift with the dielectric material against the side wall is not important in this instance. The critical point is that the phase shift through the two units are equal. Therefore, assume that there is no phase shift through the unit, when the dielectric material is against the side wall and 90 degrees when it is in the center of the waveguide.

If a signal is applied to the A input of the hybrid, it will be split into two signals of equal amplitude that are phased 90 degrees apart. The signal appearing at point C will be in-phase with the input signal (Point A), while the signal at point D will lag the input signal by 90 degrees. The converse is true for a signal being fed into the B input. The signal at point D will be in-phase, while the signal at point C will lag 90 degrees. If two signals that are in-phase are applied to inputs A and B, then each of a the outputs (points C and D) will have two signals, one in-phase with the inputs and one lagging by 90 degrees.

With the assumption that the phase shifters have no phase shift when set to the minimum position, the signals at the output of the input hybrid (points C and D) would be applied to the input of the magic tee (points E and F). There will be a signal present at both points E and F that are in-phase with the input signal. The signal at point E was produced by amplifier A, while the signal at point F was produced by amplifier B. Since these signals are equal amplitude and in-phase they will combine into the main output of the magic tee. At the same time, the other two signals at point E and F are equal in amplitude and in-phase, therefore, they will combine just

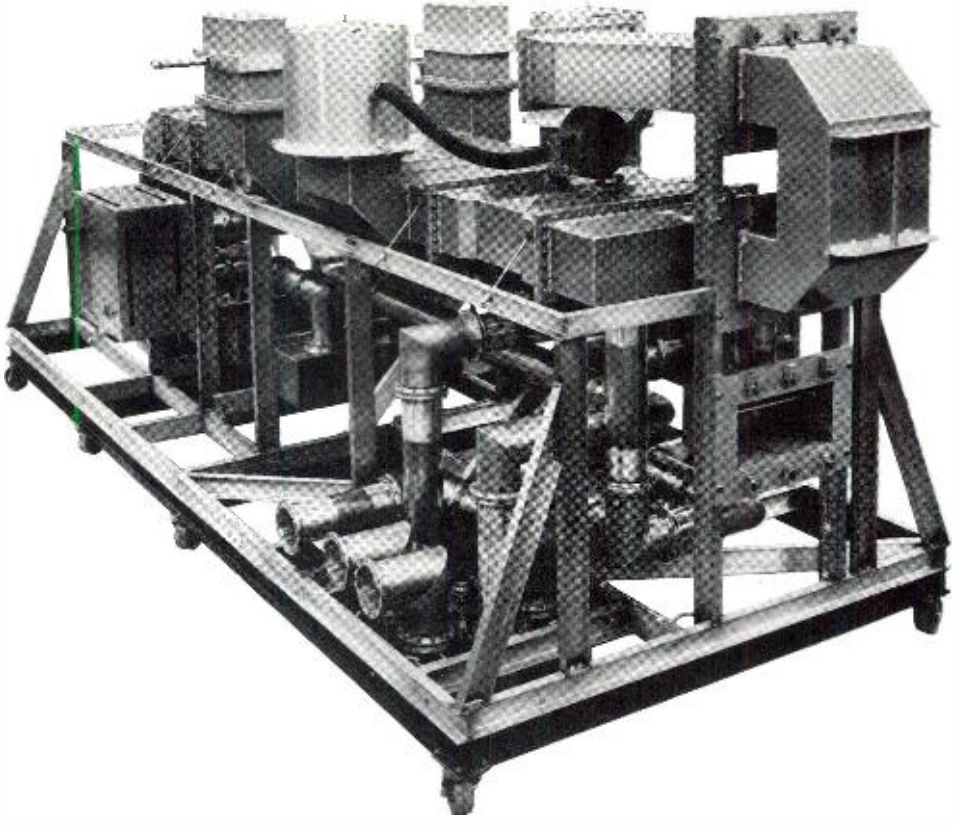


Fig. 36. UHF output switcher 110 kW TV transmitter.

MODE	PHASE SHIFTER #1	PHASE SHIFTER #2
A+B ANTENNA	0°	0°
A-ANTENNA B-LOAD	90°	0°
B-ANTENNA A-LOAD	0°	90°

INPUTS A +B ARE IN-PHASE

Fig. 37A. Phase chart magic tee "switching" system.

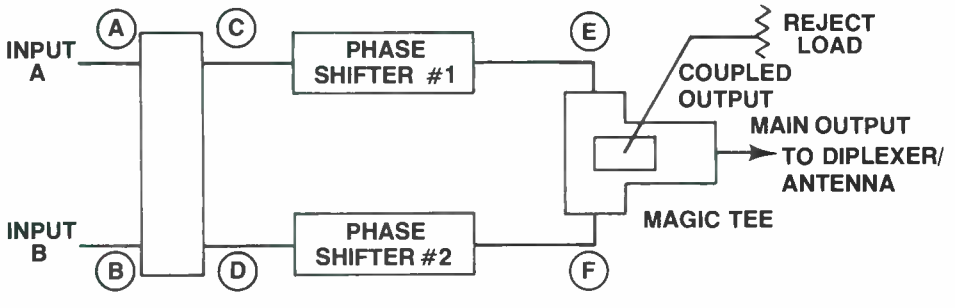


Fig. 37. RF flow diagram magic tee "switching" system.

as the other signals did. Since these signals are not in-phase at the output of the magic tee, the resultant signal will be the vector sum.

By inserting 90 degrees of phase shift in phase shifter #1, a new mode is created. The phases at the output of the hybrid (points C and D) will be the same as before. Since 90 degrees is added between points C and E, the phases at E will now be 90 degrees for signal from input A and 180 degrees for the one from input B. Therefore, on the inputs of the magic tee, the signals from input A are in-phase, while the signals from the B input are 180 degrees out-of-phase. The in-phase signals will add at the main output of the magic tee while the signals that are 180 degrees out-of-phase will add in the coupled output.

If phase shifter #1 is returned to the minimum position and phase shifter #2 is set for 90 degrees of phase shift, the signals from the B input will add in the main output, while the signals from the A input will add in the coupled output. By adding the phase shift in the #2 phase shifter, the signals at point F will be 90 degrees for the one from input B and 180 degrees for the one from input A. Thus the signals from input B will be in-phase at the inputs of the magic tee, while the ones from input A are 180 degrees out-of-phase.

Thus far three modes of operation have been accomplished within the "switchless" system. The fourth mode, both transmitters combined to the station load, can be done two ways. If the phase of the input signals are changed from in-phase to 180 degrees, the combining that takes place, will be applied to the coupled output (reject load) rather than the main output. The second method is to add a switch to the output of the system to allow the output to be connected to the antenna or the station load. The later seems to be the more common method at the present time.

The "switchless" phase shifter can be changed under power, since there are no contacts that are breaking and making. The only part that is moving is the piece of dielectric material in the phase shifter section. Since the full power of one transmitter can be applied to the reject load, it must be capable of handling that power.

In the past, switching systems used switches that changed the RF path by mechanically moving the parts of the switch. A typical switch will have around 60 dB of isolation between the paths of the switch. In the "switchless" system there is no mechanical isolation. The isolation is provided by the isolation of the hybrid and the magic tee within the system. Typically, this isolation will be on the order of 35 to 45 dB, which is sufficient for good performance. However, the operator must be aware that the isolation that he has been used to in a switch type system is not there in the "switchless" system. Therefore, when maintenance is being performed on the system or the transmitters, there may be a small amount of power present from the other transmitter.

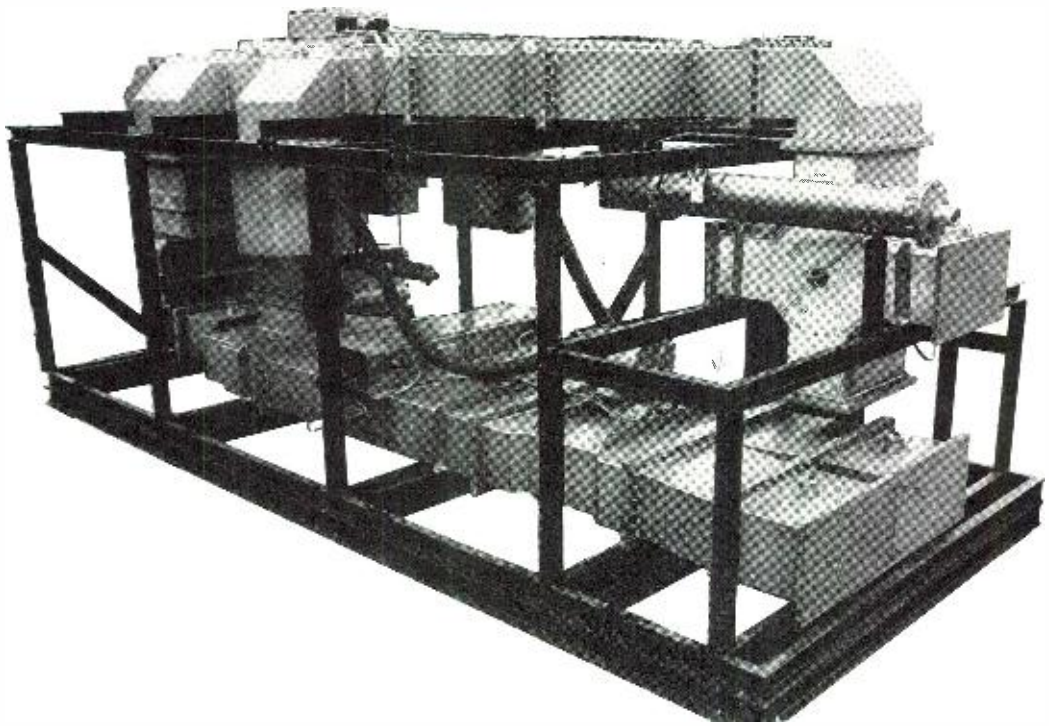


Fig. 38. UHF "Switchless" system with notch diplexer.

Multi-Transmitter Different Frequencies

Coax System

Within the FM band there is a growing demand for multiplexing systems that not only provide the capability of simply combining several stations but also provide a spare broadband port for emergency use should any module in the system fail and/or dual outputs with switching should either half of the antenna fail and extended monitoring capabilities.

The basic functions of a multiplexer module have been discussed as a category of filters earlier in this chapter. Here the peripheral features will be explored in an effort to examine additional benefits of a multiplexer system.

Whether the diplexer modules in the system are made of band pass or band stop cavities the system can be built with N modules or N-1 modules where N is the number of channels to be combined. Building the system with N-1 modules is the most economical way while N modules provide a spare broad band input. The spare input can be used as an emergency input if any of the modules fails for any reason. A switch or patch panel is needed both on the input side and output side of each module. See Fig. 39 and 40 for typical schematics of these systems. (Fig. 41 is a 9-station band stop system). The need for a patch panel on the input side is obvious. The patch panel is also necessary on the output so that the defective module can be by-passed. It would reject the frequency of the bypassed module at any input of the module due to symmetry.

The modules in the multiplexer also provide built-in isolation to any other frequency which might be transmitted from the same tower or another antenna. This is true only at the so called narrow band inputs. So the likelihood of generating inter-modulation products in transmitters tied to multiplexer is reduced in combination with sister stations in the multiplexer and also in combination with other local stations. However, this system does not necessarily preclude the, need for filters in "other" local stations transmitters.

If broadcasters on the system are committed to back up systems, they may also find it advantageous to split the output of the multiplexer into two transmission lines, one each feeding top and bottom half of the antenna. With proper combination of patch panels and a hybrid it is possible in emergency situations to operate at full or reduced power into either half of the antenna assuming lines and antenna have appropriate power capacity.

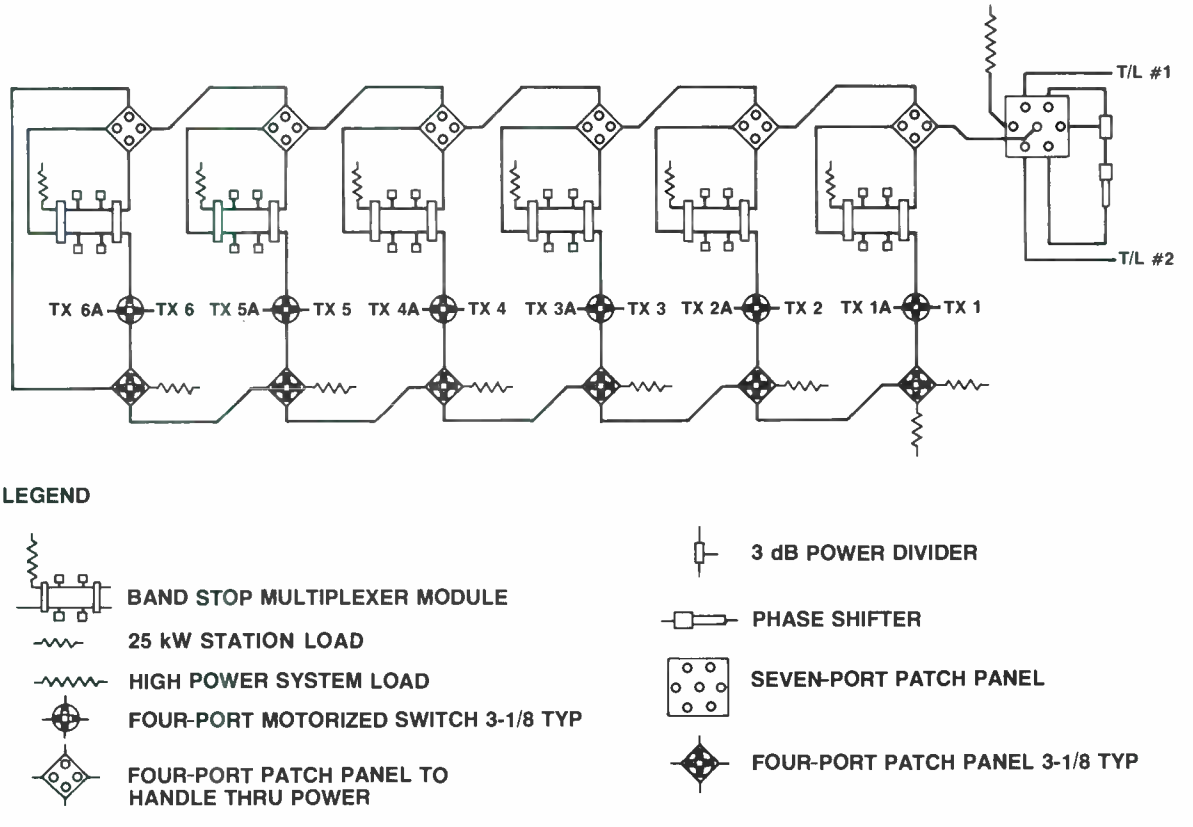


Fig. 39. Schematic of 6 module band stop multiplexer.

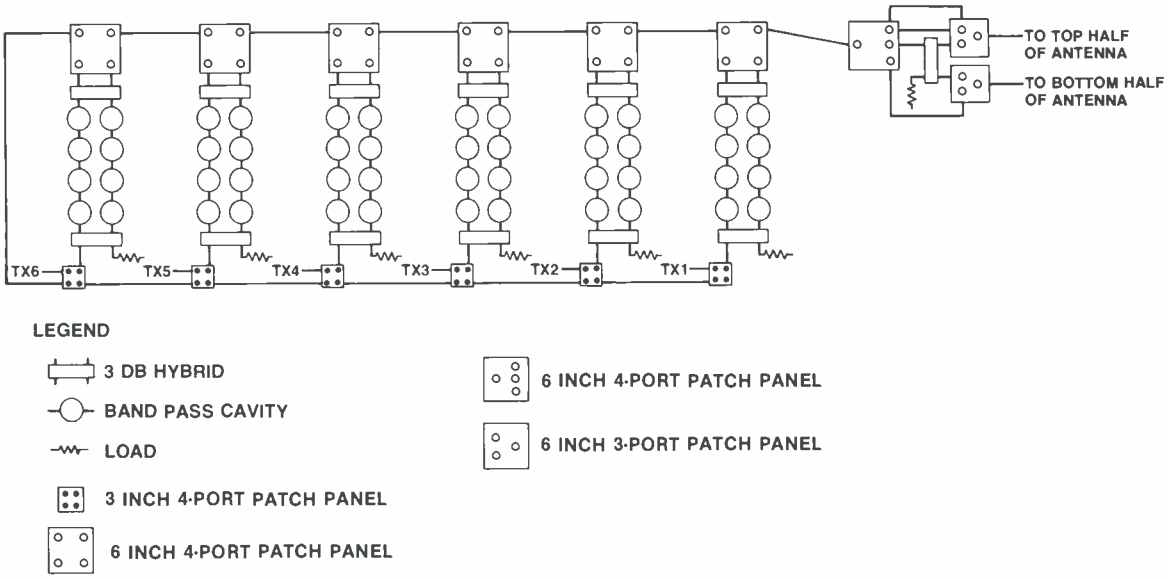


Fig. 40. Schematic of 6 module band pass multiplexer.

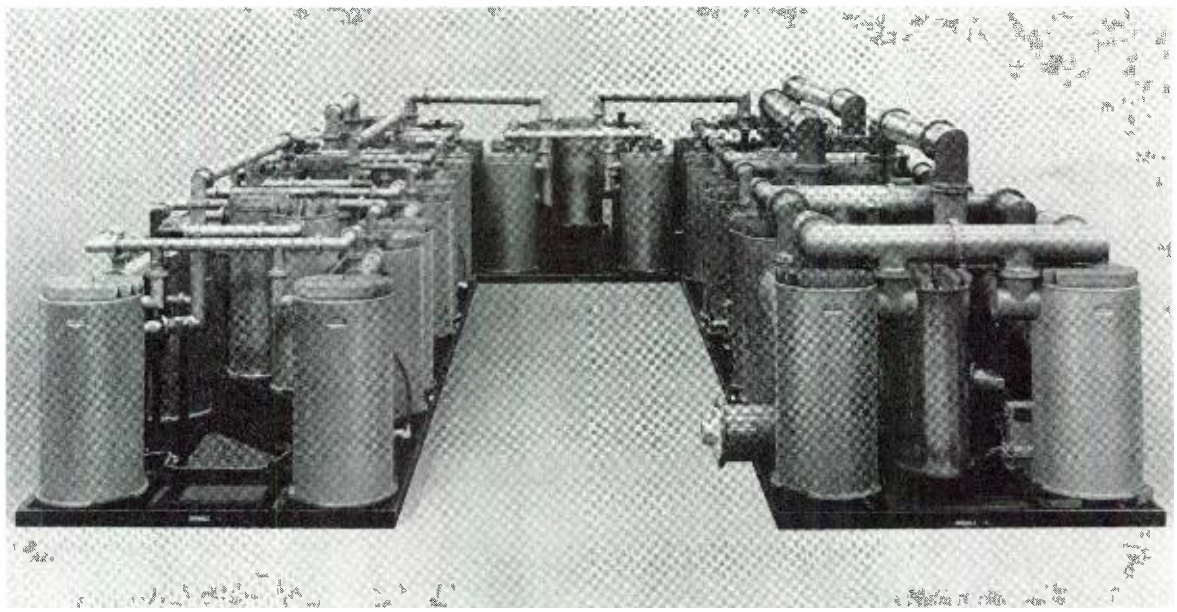


Fig. 41. 9 station band stop multiplexer at Senior Road Tower Group in Houston, Texas. Manufactured by Dielectric Communications.

The dividing of costs for a system among all participants often makes it possible to consider monitoring systems that any one participant might have considered too costly. At a minimum, each station must have individual fail safe power trip to trip the transmitter. Some broadcasters may consider a computer monitor system superimposed on the fail safe. The computer can monitor forward and reflected power. It can monitor status of interlocks and heat sensors. It can be programmed to transmit status hourly, daily or upon an unusual event through a modem to a responsible individual.

All of the features mentioned need to be addressed with the philosophy of the participants in mind. These systems are all custom made using components that have been standardized over years of use in the industry. Extensive discussions with manufacturers or suppliers are necessary to specify sizes, power capacity, VSWR, insertion

loss, band width response, group delay, patch panels, switches, monitoring, interlocks, heat sensors, cooling and layout to meet individual requirements. When seeking bids it is prudent to specify all of the above so that all bidders are quoting the same system. These systems can be built with all the bells and whistles or stripped to a bare minimum.

SECTION 3: TRANSMITTERS

Chapter 1: AM Transmitters
Chapter 2: AM Stereo Systems
Chapter 3: FM Transmitters
Chapter 4: Subcarrier Transmission and Stereophonic Broadcasting
Chapter 5: Television Transmitters
Chapter 6: Multichannel Television Sound
Chapter 7: Transmitter Control Systems
Chapter 8: Frequency and Aural Modulation Monitoring

3.1

AM Transmitters

George W. Woodard, P.E.*
Radio Free Europe/Radio Liberty
Washington, DC

Broadcasting to the general public began with the process known as Amplitude Modulation near the start of the second decade of this century. Then, as now, the system of modulation chosen for transmission was heavily dependent on practical and economic aspects of receiver technology. The evidence is clear that amplitude detection was the only known practical method of signal demodulation when the ideas of radio communication began to be formulated in the late 1800's and early 1900's. It is apparent from some of the earliest technical writings on radio communication that a general mathematical knowledge of angular modulation, i.e.; frequency and phase modulation, did not exist until the mid 1920's.[1] These modes of transmission and the necessary receiver technology were not to be proven practical until long after amplitude modulation had become the standard of the radio communication and broadcast technological art. Amplitude modulation in broadcasting is today more accurately referred to as DSB-FC-AM, an acronym for Double SideBand-Full Carrier-Amplitude Modulation, however, the abbreviation "AM" has been generally accepted to describe the mode of transmission currently used throughout the world in the standard broadcast Amplitude Modulation band of 535 to 1605 kHz in North America, and slightly wider in other parts of the world. From almost the very beginning of broadcast technology, it was known that AM was not a very efficient mode of transmission, either in spectrum usage or in transmission of intelligence. The pioneers in AM broadcast transmitter and receiver engineering technology had a deep sense of responsibility toward developing this "marvelous medium" to enhance the lives of the general public with informative, educational, and entertaining programs. Some of the early communication technology pioneers in the U.S. and abroad had great vision for both the technical and programming aspects of public broadcasting.[2]

As time and technology progressed, engineers could no longer ignore the problems of transmission efficiency. When, in the 1930's, the telephone industry was planning a major switch from DSB-FC-AM in favor of Single SideBand-Suppressed Carrier (SSB-SC) for both its long distance wire and wireless services because of its higher transmission efficiency and channel capacity[3], the broadcast industry was necessarily committed to the continuance of conventional AM because of

*Formerly with Continental Electronics Manufacturing Company.

[1] "Notes on Modulation Theory". John R. Carson, Proc. IRE, Vol. 10, No. 1, June 1925, p. 57.

[2] Inaugural Address of Dr. Lee DeForest upon becoming the President of the I.R.E. Proc. IRE, VOL. 18, No. 7, Jul. 1930, p. 1121.

[3] "Production of Single Side-Band for Trans-Atlantic Radio Telephony". R. A. Heising, Proc. IRE, Vol. 13, No. 3, June 1925, p. 291.

the need for economic public receiver compatibility. Therefore, the broadcast engineers attention naturally turned to improvement of transmission standards such as fidelity, efficiency of transmission, reliability of transmission, and co-channel and adjacent channel interference, etc. Of these, efficiency and reliability of transmission have seen and continue to see the greatest improvement in the views of many transmitter designers and users. Transmission fidelity, always important, reached a plateau in the late 1940's which has not been significantly improved upon even in today's latest transmitter designs; though pre-transmitter program processing equipment and philosophy, which influence perceived reception fidelity, continue to change.

In the early 1980's, stereo transmission on the AM band became a widespread reality on the North American continent. This mode of transmission has become known and is referred to as AM-Stereo. Some AM broadcasters see AM-Stereo as a necessary means to compete with FM-Stereo which continues to gain increased public acceptance for all types of programming. AM-Stereo transmission was approved on a general basis by the FCC in 1981, but unlike FM-Stereo or Color Television, the FCC did not adopt a transmission standard for this potentially revolutionary development in the standard broadcast band. Instead the FCC allowed any commercially developed AM-Stereo transmission system, which will pass FCC type approval requirements regarding mono compatibility and interference, to compete for the broadcasters and consumers favor in order to establish a de-facto standard for AM-Stereo transmission. Some receiver manufacturers have decided to build mass production receivers for only one of the various proposed systems based on their public and private study of the systems merits and market potential. Other receiver manufacturers have decided to build mass production receivers which will automatically and/or manually decode any of the several proposed systems. Which receiver marketing philosophy will prevail and what is in the best long term interest of the listening AM public are yet unknown. Several AM-Stereo systems are presented in the chapter following this one.

AMPLITUDE MODULATION THEORY

Amplitude modulation of a radio signal occurs in at least two basic forms, coded (digital) and linear (analog). The first amplitude modulation processes for long distance communication involved on/off keying of a radio carrier wave. The pattern or "code" of the on/off keying process determined the content of the information being transmitted. Linear or quasi-linear undulations in the amplitude of the carrier wave, however, are normally used to transmit the analog information present in speech and music. The radio carrier wave signal onto which the analog amplitude variations are to be impressed is expressed as

$$e(t) = A \times Ec \times \mathrm{Cos}(\omega ct) \qquad [1]$$

Where:

- $e(t)$ = instantaneous amplitude of carrier wave as a function of time (t)
- A = a factor of amplitude modulation of the carrier wave
- ωc = angular frequency of carrier wave (radians/second)
- Ec = peak amplitude of carrier wave

If A is a constant, the peak amplitude of the carrier wave is therefore constant and no modulation exists. Periodic modulation of the carrier wave exists if the magnitude of A is caused to vary with respect to time as, for instance, a sinusoidal wave, i.e.;

$$A = 1 + (Em/Ec) \times \mathrm{Cos}(\omega mt) \qquad [2]$$

Where:

Em/Ec is the ratio of modulation amplitude to carrier amplitude

therefore;

$$e(t) = Ec \times (1 + (Em/Ec) \times \mathrm{Cos}(\omega mt)) \times \mathrm{Cos}(\omega ct) \qquad [3]$$

this is the well known basic equation for periodic amplitude modulation and when all multiplications and a simple trigonometric identity are performed the result is

$$e(t) = Ec \times \mathrm{Cos}(\omega ct) + (M/2) \times \mathrm{Cos}(\omega ct + \omega mt) + (M/2) \times \mathrm{Cos}(\omega ct - \omega mt) \qquad [4]$$

Where:

M = the amplitude modulation factor Em/Ec

Equation [4] can be represented graphically three familiar ways; in the time domain representation as shown in Fig. 1, in the frequency domain as shown in Fig. 2, and as relative vectors as shown in Fig. 3. The graphical representations shown are for a single tone modulation index (M) of 0.7, i.e.; the peak modulating voltage is 70% of the peak carrier wave voltage ($Em/Ec = 0.7$). Fig. 2 shows the occupied bandwidth of an AM signal with single tone modulation. From this Fig.

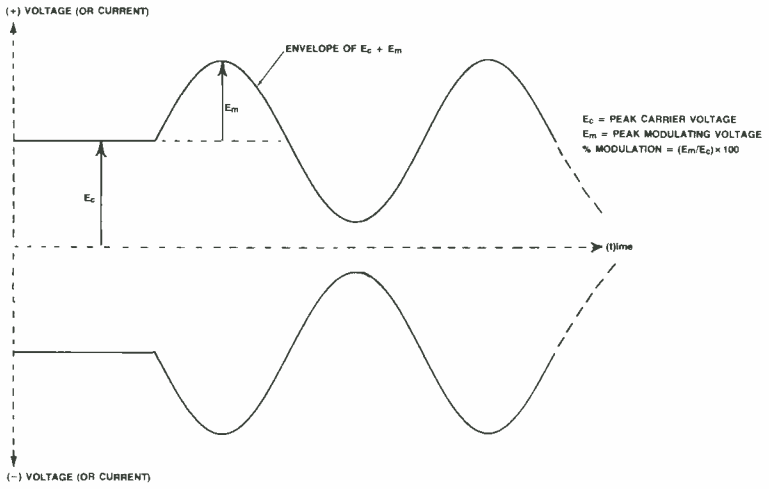


Fig. 1. Time domain representation of a carrier wave signal amplitude modulated by a sinusoidal audio signal to a peak modulation depth of 70%.

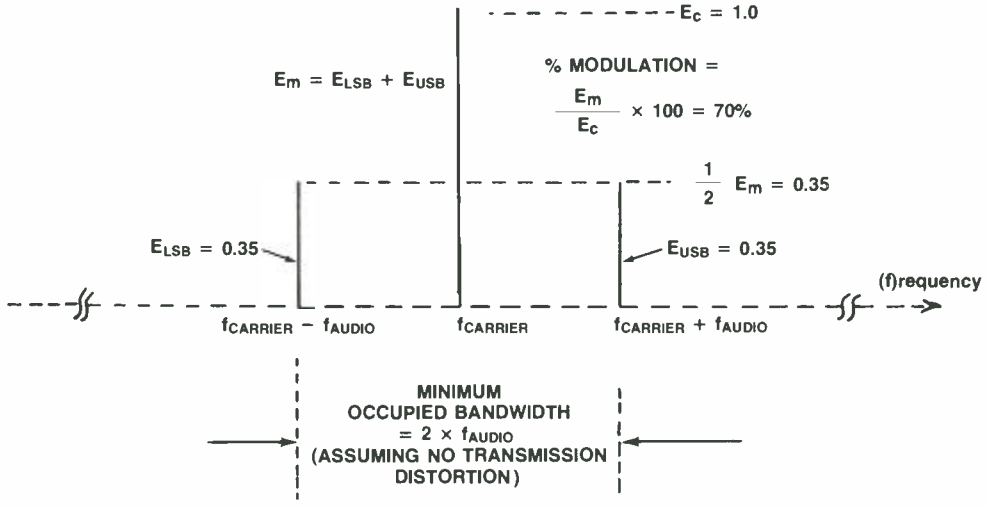


Fig. 2. Frequency domain representation of an amplitude modulated signal showing the carrier wave signal and two resultant modulation sidebands at 70% modulation.

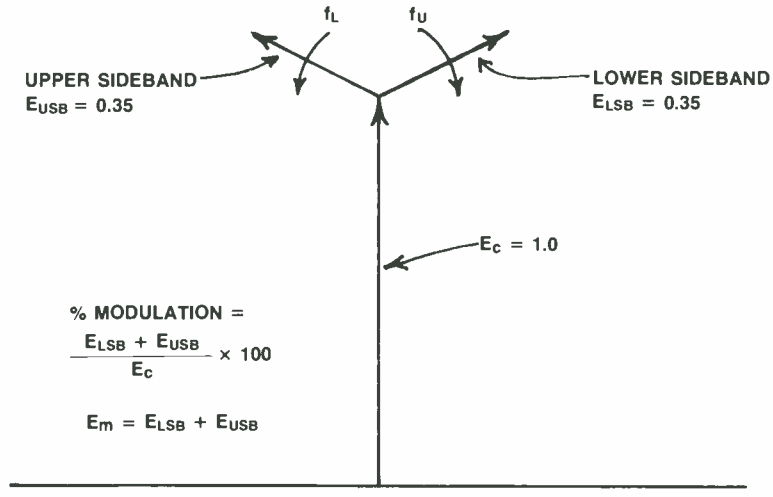


Fig. 3. Vector representation of an amplitude modulation signal showing the carrier wave signal and two resultant modulation sidebands at 70% modulation.

and its defining equation [4], it is clear that the bandwidth of an AM signal is equal to twice the highest modulating frequency if no system distortion is present. High quality music reproductions include frequency components as high as 15 kHz or higher and therefore the required theoretical bandwidth of a DSB-FC-AM signal capable of high quality music reproduction is at least 30 kHz. Harmonic and inter-modulation system distortion have the effect of widening the effective occupied bandwidth of the system. However, most modern transmitters have sufficiently low distortion characteristics that bandwidth stretching is not normally a significant problem. The occupied bandwidth characteristics of an AM broadcast transmitter are discussed in more detail in the section on "Factory Tests."

RADIO FREQUENCY POWER AMPLIFIERS

A common AM transmitter major system component is the power amplifier circuit. High power amplifiers that produce 0.25 to 50 kilowatts (kW) of carrier power are common for AM broadcast transmitters in North America. Carrier power levels up to one megawatt and higher are common in other parts of the world for medium wave broadcasting. Transmitters delivering these high power levels should be designed for highest operating efficiency within the circuit constraints of the particular manufacturer and/or modulation system used. The most common amplifier used to meet the demands of high output power and high efficiency is the vacuum tube class 'C' amplifier. Class 'B' RF power amplifiers, very popular in early transmitters, are still used occasionally at lower power levels and for driver stages of final class 'C' or 'D' stages. Solid state class 'D' amplifiers up to 5 kilowatts are becoming more common as driver stages for final vacuum tube amplifiers and for the final power amplifier modules in transmitters of up to 10 kW carrier power. As stated in the introduction, the most common major concerns for both manufacturers and users of modern AM broadcast transmitters is operating reliability and efficiency, hence operating cost. To achieve high overall operating efficiency, the stages which consume the most power, the modulator and/or the final RF power amplifier stages must be designed for highest possible operating efficiency.

The basic tuned anode vacuum tube amplifier is described in graphical form in Fig. 4. The vacuum tube can be either a triode, tetrode, or pentode. Tetrode final amplifiers are most common in modern high power transmitter designs. The RF excitation voltage is supplied to the grid of the power amplifier tube and the ratio of dc grid bias voltage-to-peak RF excitation voltage, shown sinusoidal in Fig. 4, determines the conduction angle of anode current, given as

$$\theta_c = 2 \times Arc\ Cos(E_{cc}/(E_g - E_{cc})) \qquad [5]$$

where the exciting grid signal is sinusoidal as shown in Fig. 4a.

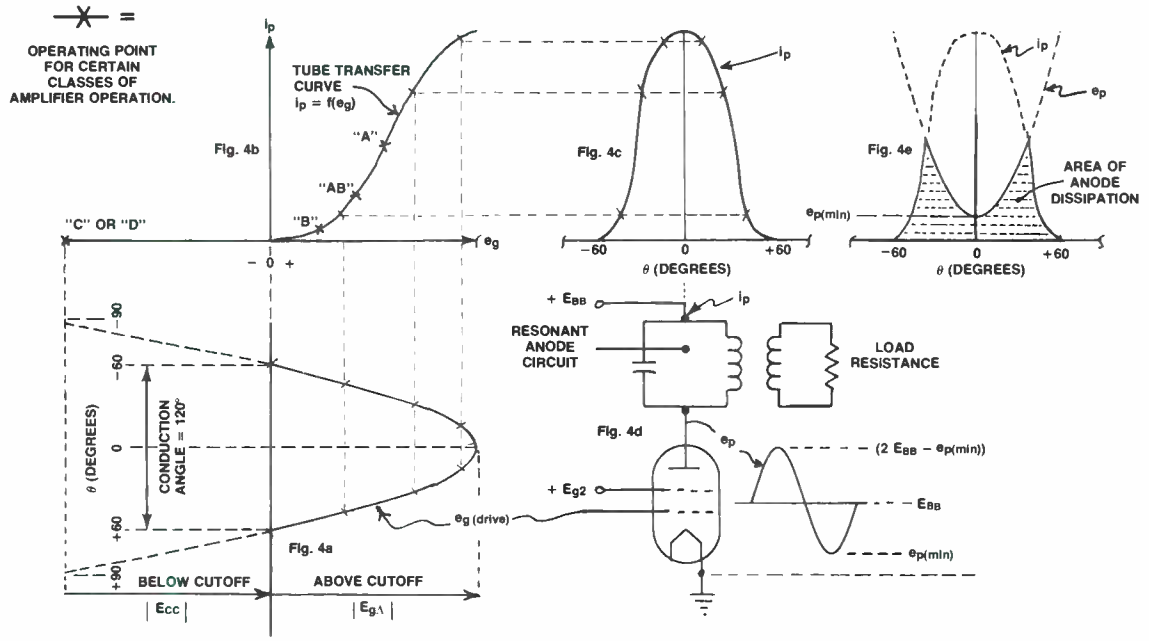


Fig. 4. Classical vacuum tube Class "C" Amplifier with sinusodial grid drive, 120° anode current conduction, and resonant anode load.

The shape of the anode current pulse is determined by the vacuum tube transfer characteristics and input waveshape. The pulse of current thus generated, Fig. 4c, is supplied by the dc power supply, E_{BB}, and passed through the resonant anode tank circuit shown in Fig. 4d. The resonant anode tank circuit is assumed to have sufficient operating Q to force anode voltage, ep, to be essentially sinusoidal and of the same periodic frequency as the RF excitation voltage and resultant anode current pulse. The instantaneous anode dissipation, shown in Fig 4e, is the product of instantaneous tube anode voltage drop and anode current. The tube transfer characteristic is a variable dependent upon many tube factors as well as maximum drive signal, Eg. The exact shape and magnitude of the current waveform is normally obtained from a load-line plot on constant current characteristic tube curves supplied by the tube manufacturer. The resonant anode load impedance is chosen and adjusted to allow ep(min) to be as low as possible without causing excessive screen grid (in the tetrode case) or control grid dissipation. Some manufacturers increase anode efficiency beyond the limits for typical Class 'C' amplifiers by using a circuit employing a third harmonic resonator between the output anode connection and the fundamental resonant circuit. This has the effect of squaring up the anode voltage waveform (ep) thus causing the integral of the ep × ip product, or anode dissipation, to be smaller; resulting in lower anode dissipation for a given RF power output. An amplifier employing the third harmonic anode trap is commonly referred to as class 'C-D'; suggesting an efficiency rating somewhere between conventional class 'C' operation (nominal 120 degree conduction angle) and true class 'D' operation with rectangular anode or collector voltage waveforms. Anode efficiencies can be increased typically to values of 90 percent for transmitters up to approximately 10 kW carrier power and approximately 85 percent for transmitters higher than 10 kW carrier power by using the third harmonic trap technique. Table 1 shows a comparison of anode efficiency for six classes of high power tuned RF amplifiers.

DISCUSSION OF BASIC AM SYSTEMS

High Level Anode Modulation

The first practical method of generating the amplitude modulation signal was Heising constant current modulation[4, 5], a method of applying audio modulation to the anode supply voltage of a class 'C' RF amplifier. This general class of modulation has since been known as high level anode (or plate) modulation. The Heising modulator was used at least as early as 1920 and was usually used to modulate a low power RF amplifier or master oscillator stage which was followed by several linear amplifier stages until the desired power level was attained. In some cases the Heising modulator was used to modulate the final RF amplifier stage of lower power transmitters. The Heising shunt modulator operated in the class 'A' mode and therefore was low in operating efficiency. The early linear amplifiers were tuned class 'B' amplifiers operating with carrier level anode efficiencies of 30% maximum. The Heising and similar systems of audio amplification were also used to modulate the grid bias level of RF amplifier stages in order to obtain the AM signal to be used for further linear amplification. Heising constant current anode modulation was very popular in military and aviation radio sets used through the end of World War II.

Class 'B' High Level Anode Modulation

Historically the most popular method of applying the audio modulating voltage to the anode circuit of a class 'C' RF power amplifier was by a high power push-pull class 'B' audio amplifier. This type of modulation was first used to improve the operating efficiency and to increase the output power of AM broadcast transmitters. Class 'B' push-pull audio amplification was first used

[4] "The Equivalent Circuit of the Vacuum Tube Modulator". John R. Carson, Proc. IRE, Vol. 9, No. 4, Aug. 1921, p. 243.

[5] "Modulation in Radio Telephony". R.A. Heising, Proc. IRE, Vol. 9, No. 3, June 1921, p. 305.

TABLE 1. Comparison of Tuned RF Amplifier Anode Efficiencies

Amplifier Class	Conduction Angle (degrees)	Anode Efficiency (%)	Defined Conditions of Operation
A	360	30	$E_{b(min)} = 0.10 \times E_{BB}$
A-B	240	60	$E_{b(min)} = 0.10 \times E_{BB}$
B	200	67	$E_{b(min)} = 0.10 \times E_{BB}$
C	120	84	$E_{b(min)} = 0.05 \times E_{BB}$
C-D	120	90	$E_{b(min)} = 0.05 \times E_{BB}$
D	120	95	$E_{b(min)} = 0.05 \times E_{BB}$

to improve distortion and output power of telephone transmission amplifiers. The invention was soon recognized by broadcast engineers and applied to high level anode modulation. With the final RF power amplifier operating at approximately 80% anode efficiency and the class 'B' audio modulator total static currents approximately one-tenth that of an equivalent Heising modulator, total anode efficiencies at carrier level rose to approximately 72% compared to 37% for the Heising system and 30% for conventional linear amplification. A simplified drawing of a typical high level class 'B' anode modulation system is shown in Fig. 5. The vacuum tubes shown in Fig. 5 may be either triodes, tetrodes, or pentodes. The output circuit of the class-B modulator shows the output modulation transformer (MT), an audio coupling capacitor (C), and a dc shunt feed inductor (L).

This arrangement was used in all high level class-B high power broadcast transmitters until about 1960 because of a transformer design constraint that would not economically allow unbalanced direct currents to magnetize the transformer core material without poor low frequency distortion. Advanced technology core materials and careful magnetic transformer design allowed elimination of the coupling capacitor and the dc feed shunt inductor, first in some 100 kW European transmitter designs in the early 1960's, and in an American shortwave transmitter design in the later 1960's. Many of the more advanced modern AM broadcast transmitter designs still using high level class-B anode modulation have eliminated the extra C and L components from the modulator output circuitry, and the dc current to the modulated RF amplifier anode flows directly through the secondary of the output modulation transformer. Elimination of these C and L components is necessary for optimum operation of modern AM stations. With the extra C and L components, the modulator output is effectively a three pole high-pass filter which causes low frequency transient distortion to be generated when driven with the complex waveforms that are produced by many modern and popular program audio processors. Eliminating the C and second L component, causes the output modulator circuit to become a single pole high-pass filter, greatly reducing low frequency transient distortion.

Another problem with transformer coupled high level class-B anode modulation is with high frequency audio transient distortion. Stray internal winding capacitances and leakage inductances form multi-pole low pass filtering at the high frequency end of the audio spectrum. This equivalent multi-pole low pass filter generates transient overshoot distortion when driven by the same type of processed complex program waveforms mentioned above. Transient overshoot up to 12% is typical for squarewave modulator input signals and results in a required modulation level reduction of the same 12% in order to maintain peak modulation levels within FCC allowed limits. This high frequency transient overshoot distortion can be effectively minimized by filtering the audio input to the transmitter with linear phase filters, resulting in somewhat lower high frequency audio response, and/or by careful control of the

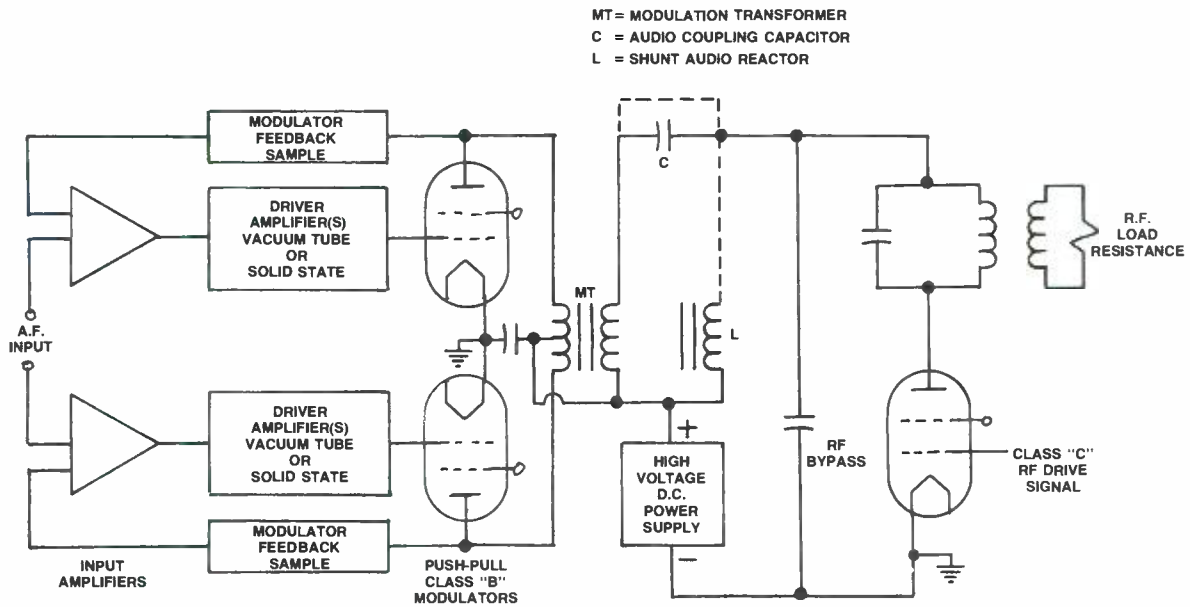


Fig. 5. High level anode modulation employing transformer coupled push-pull Class-B modulators.

modulation transformer equivalent circuit yielding more linear audio phase characteristics for the entire modulator circuitry. Balanced modulator negative feedback is used to reduce modulator non-linear distortion and noise. Negative feedback, however, usually worsens high audio frequency transient distortion characteristics.

Pulse Width High Level Anode Modulation

Pulse width modulation (PWM) of the dc anode voltage of a class-C RF amplifier was first used in commercial high power broadcast transmitters in Europe in the early 1960's. It was the first commercially successful attempt to significantly improve upon the efficiency of the popular high level class-B modulation system by applying and improving basic PWM concepts that were described decades earlier.[6] Since this first success, pulse width modulation has become a preferred method of high level anode modulation by many broadcast engineers, and is employed in several broadcast transmitter designs by several manufacturers world wide. The basic pulse width modulation system and two ingenious improvements to the basic system are shown in Fig. 6. The circuit in Fig. 6a graphically describes the basic principle of PWM. An inherent practical deficiency in the basic concept, Fig. 6(a), is caused by the relatively high shunt circuit capacitance of the modulator tube filament transformer plus stray capacitances. Though special low-capacitance isolation transformers can be used to supply modulator filament and auxiliary power to minimize capacitive switching losses, typical realizable values of capacitance can cause excessive switching losses and audio distortion in lower power transmitters.

For example, the switching losses at carrier level of a typical PW modulator for a 5 kW transmitter can be higher than the quiescent modulator losses of an equivalent power class-B modulator even when the stray modulator tube capacitances are as low as 100 pF. The power lost per modulator switching cycle is

$$P_{modsw} = (CV^2/2) + P_{td} \qquad [5]$$

Where:

C is the shunt modulator filament transformer plus stray capacitance to ground and;

V is the pulse switching voltage to ground at the cathode of the tube.

P_{td} is the saturated tube and diode losses during the respective on and off conduction states

Besides causing switching losses, the high stray capacitance to ground is also a cause of major modulator distortion at high negative modulation indices.[7] The circuit shown in Fig. 6b is one ingenious way to overcome the stray modulator capacitance problem. It is identical to the circuit in Fig. 6a, in principle, except that the high voltage pulse modulated wave is at a point in the circuit where the shunt capacitances to ground are inherently minimized. The circuit in Fig. 6c is basically the same as in 6b except the system ground has ingeniously been placed at another point in the circuit. PW Modulator anode efficiencies approach 92% in some higher power transmitter designs yielding a combined modulator and carrier tube anode efficiency of approximately 74% at all levels of modulation. An added efficiency advantage over high level class-B anode modulation is that a PWM transmitter may have only two high power vacuum tubes, one modulator and one final RF amplifier, thus eliminating the filament heating power of one large vacuum tube required in push-pull modulator designs. A significant disadvantage of PWM as described in Fig. 6b and 6c is that the cathode and grid circuits of the modulated RF amplifier are operated at high voltage levels off ground, adding complications to the circuitry in these areas that are avoided with the classical PWM circuit of Fig. 6a and conventional high level class-B anode modulation. Another major disadvantage of PWM in any form is that of transient distortion caused by the phase non-linearity of the multi-pole PWM filter, similar to that previously discussed for high level class-B anode modulation. The switching frequency is typically 70 kHz for most transmitters manufactured in North America. This frequency is chosen to ease compliance with FCC regulations which requires all spurious radiation more than 75 kHz removed from the carrier frequency to be 80 dB or more below the carrier level. Present FCC regulations require transmitter spurious output between 30 kHz and 75 kHz removed from the carrier to be only 35 dB below the carrier level. To meet these spurious requirements (most manufactures of PWM transmitters far exceed these requirements), a very steep cutoff lowpass filter is required at the output of the PW modulator. Most manufacturers of PWM transmitters make a valiant attempt to maintain linear phase characteristics in this filter to as high an audio frequency as possible, but the laws of nature prevent required linear phase characteristics to the highest third audio harmonic to be achieved within the major attenuation constraints noted above. As

[6] "Transmission System". R. A. Heising, U.S. Patent No. 1,655,543, Jan. 1928.

[7] "Distortion in Pulse Duration Modulation". Ernest R. Kretzmer, Proc. IRE, Vol. 35, No. 11, Nov. 1947, p. 1230.

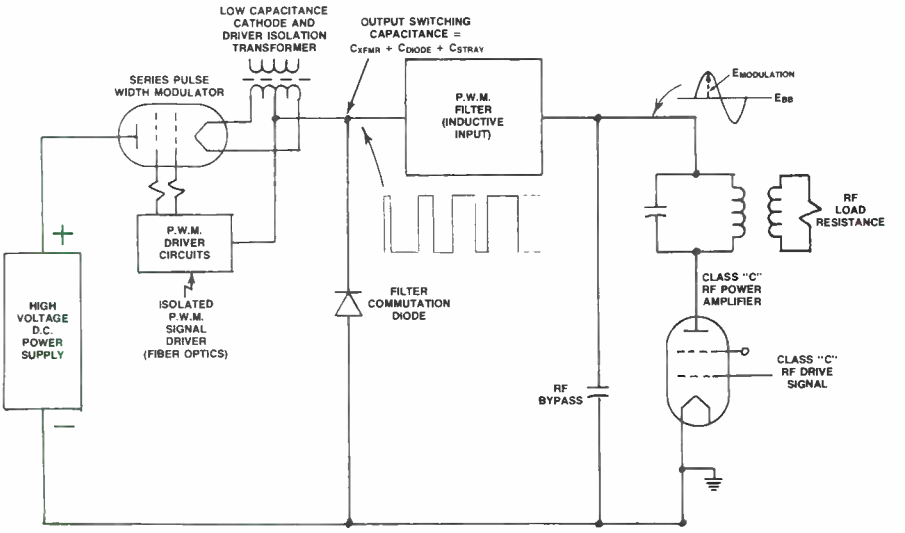


Fig. 6a. Basic classical high level anode pulse width modulation of a vacuum tube Class "C" amplifier.

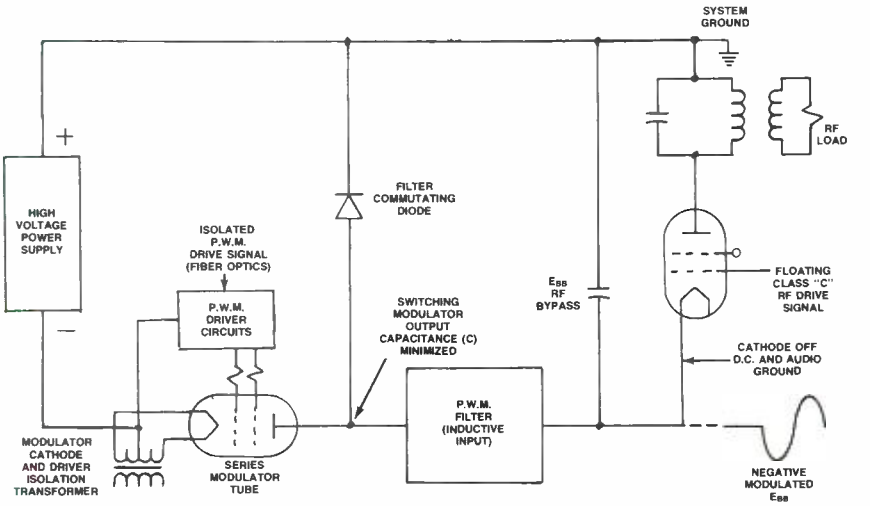


Fig. 6b. Collins Radio/Continental Electronics patented modification to basic high level PWM System to minimize modulator losses by minimizing switching modulator output capacitance.

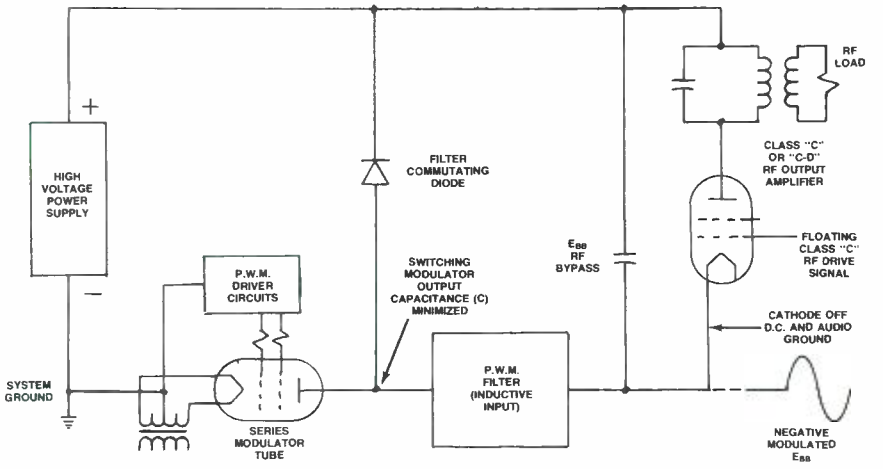


Fig. 6c. Harris Corp. patented modification to basic high level PWM System to minimize modulator losses by minimizing switching modulator output capacitance.

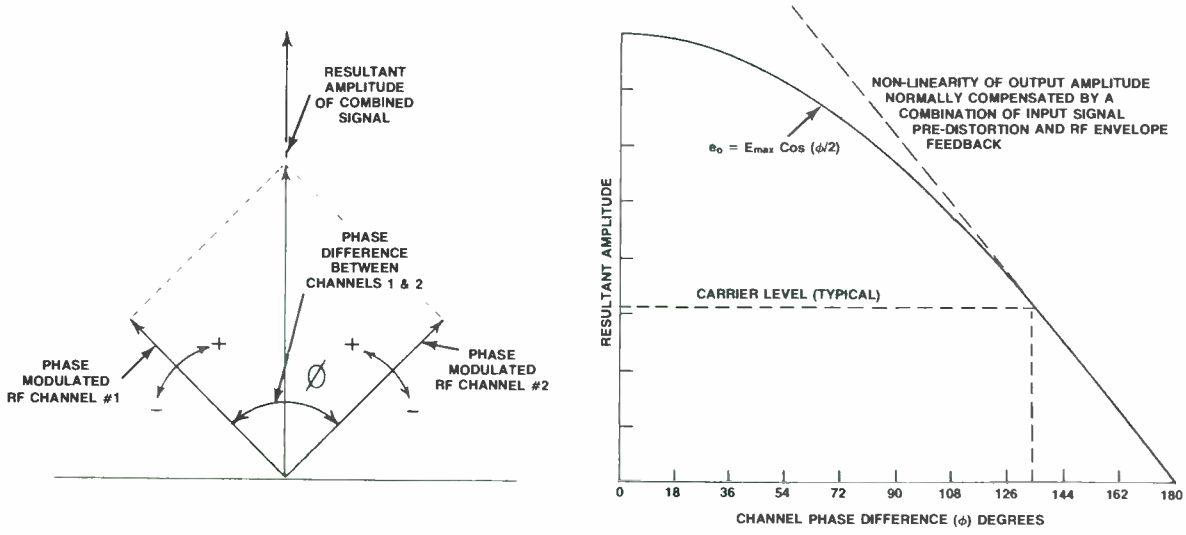


Fig. 7. Principle of Chireix "outphasing modulation".

a result, transient response to a square wave input can result in peak overshoot of approximately 6 %. As with Class "B" modulation, this overshoot can be effectively eliminated by the use of linear phase (Bessel) filtering of the input modulation signal at the expense of a small reduction in modulation frequency response capability.

Chireix "Outphasing" Modulation

Outphasing modulation was originally described in the literature by its inventor Henry Chireix in 1935.[8] It is a unique and ingenious method of obtaining the AM signal by use of counter-phase modulation and vector addition of two separate radio frequency signals. It was marketed for many years by RCA under the trade name "Ampliphase" and many of those transmitters and some of European manufacture are on the air still today at power levels of 100 kW and higher. This system of modulation is described graphically in Fig. 7. Two RF signals are derived from a common excitation source and then split into two separate channels. Each channel is shifted in phase, one positive and the other negative. The two channels are then each phase modulated by the modulating signal, again, in opposing polarity. The two channels are amplified and then recombined in a vector additive network which has the effect of producing the desired amplitude modulation. The main advantage, as with all systems previously discussed, is in operating efficiency. The two independent channels contain only phase modulated RF signals and therefore each can be amplified to the desired power levels in high efficiency Class 'C' or 'D' amplifiers. The actual modulation process takes place both at low level, in the phase modulators, and at high level, in a passive output network combiner.

There are two major disadvantages of this system of modulation. First, the efficiency of the output power amplifiers is not quite as high as the simple description above would imply, due to the fact that at all instantaneous levels of modulation, except one, the anode circuits must work into a reactive load. Secondly, output carrier power setting is sensitive to tuning of any stage anywhere down the chain; operators of early versions of this type of equipment soon learned of the consequences of "trimming" a tuning control of some lower power stage. Later designs used broadband amplifying stages for the lower levels to circumvent the problem of tuning sensitivity of the lower power stages.

Another major disadvantage of the Chireix system in older transmitters was the generation of incidental phase modulation (IPM) in excessive amounts when the two low level phase modulators were not well balanced in opposing PM characteristics. It was common for such an unbalance to exist producing as much as 12 to 18 degrees of peak IPM at either 100% modulation crest. Modern solid state circuitry for the phase modulators using digital phase modulation techniques would completely remove this disadvantage were the system still being commercially produced. The outphasing system of amplitude modulation ceased to be produced commercially when RCA discontinued its AM transmitter manufacturing in the mid-1970's.

Doherty High Efficiency Linear Amplifier

The Doherty high efficiency linear amplifier was first described in the technical literature in

[8]"High Power Outphasing Modulation". Henry Chireix, Proc. IRE, Vol. 23, No. 11 Nov. 1935, p. 1370.

1936 by its inventor, W.H. Doherty.[9] So contrary were the term "linear" and "high efficiency", in the context of amplitude modulated waves, that many engineers in broadcasting refused to accept the concept as workable, similar to the reaction Armstrong received when he proposed that frequency modulation was a practical mode of radio transmission. Nevertheless, the Doherty high efficiency linear amplification system was soon proven to work by 1938[10], and has been used at power levels up to 500 kW carrier power in both the original and in the patented Weldon[11] modified form in many installations throughout the world on the medium wave broadcast and international short-wave broadcast bands, as well as the long wave broadcast band in Europe. Its implementation was the result of true inventive genius, using one or more known basic scientific principles to create a totally new and necessary product. The Doherty linear amplifier is described graphically in Fig. 8. As with conventional linear amplifiers, the AM signal is generated at low levels and applied to the input of the final amplifier stage. The Doherty system employs two output amplifier stages, one defined as the carrier amplifier and the second as the peak amplifier.

The outputs of the two stages are combined in phase at the anode of the peak amplifier tube. At carrier level the carrier tube is operated as a nearly saturated Class 'B' amplifier and thus delivers almost all of the carrier power at Class 'B' efficiencies; i.e., approximately 70% anode efficiency. The peak tube at carrier condition is biased and driven just above cutoff and therefore supplies a small amount (approx. 2 to 6%) of carrier power. The anodes of the two tubes are connected together through a 90 degree impedance inverting RF network. As the modulated signal increases in the positive direction to both peak and carrier tubes, the current supplied to the output load by the peak tube increases. The saturated voltage drop at the anode of the carrier tube remains constant over the entire positive modulation half-cycle, thus causing the current at the output of the inter-anode 90 degree network also to be constant during the same positive modulation half-cycle. The rising current from the peak tube anode has the effect of raising the impedance being presented to the inter-anode network. Since the current from the network is constant, the net effect is an increase in output power from the carrier tube; i.e., $I^2 \times R_1$ increases because R_1 increases. At the 100% positive modulation crest, both tubes are producing exactly twice carrier power to the load, satisfying the requirement that Peak Envelope Power (PEP) = $4 \times P_{carrier}$. During the negative half-cycle of modulation, the peak tube is cut-off and the carrier tube behaves as a normal linear amplifier, allowing the envelope power output to drop linearly to zero at the 100% negative modulation crest. The anode efficiency of the Doherty high-efficiency linear amplifier at carrier level is more than twice the efficiency of conventional AM class 'B' linear amplifiers.

The Doherty linear amplifier also has two other important advantages for high power broadcast transmitters. First, and most important, the peak anode voltage at either tube is only about one-half that required for an equivalent carrier power high level PWM or class 'B' anode modulated transmitter thus allowing reliability and usable tube life to increase significantly. Secondly, no large modulation transformer or special filtering components are used in the final amplifier stages to cause transient overshoot distortion as previously discussed for Class 'B' anode modulation or pulse-width anode modulation. The main problems of the Doherty linear amplifier are non-linear distortion and an increase in the complexity of tuning. The major sources of non-linear distortion are the non-linearity of the carrier tube at or near the 100% negative modulation crest and the non-linearity of the peak tube at or near carrier level when it is just beginning to conduct. Both sources of distortion are effectively reduced by use of moderate amounts of overall envelope feedback. The tuning complexity problem is usually overcome by experienced and trained operators and simplified tuning procedures aided by built in test equipment used in modern designs since approximately 1948.

High Efficiency Screen/ Impedance Modulation

In 1938, Terman and Woodyard[12] described a modification to the basic Doherty high efficiency linear amplification system previously described. In the new system, the grid bias level of two tubes operating class 'C' is varied at the audio modulation rate thus creating a higher efficiency system of amplitude modulation rather than amplification while still using the impedance inverting

[9] "A New High Efficiency Power Amplifier for Modulated Waves". W. H. Doherty, Proc. IRE, Vol. 24, No. 9, Sept. 1936, p. 1163.

[10] "A 50-Kilowatt Station Utilizing the Doherty Amplifier and Designed for Expansion to 500-Kilowatts". W.H. Doherty and O.W. Towner, Proc. IRE, Vol. 27, No. 9, Sept. 1939, p. 531.

[11] "Amplifiers". J. O. Weldon, U.S. Patent No. 2,836,665, May 1958

[12] "A High Efficiency Grid-Modulated Amplifier". Proc. IRE, Vol. 26, No. 8, Aug. 1938, p. 929. F.E. Terman and John R. Woodyard.

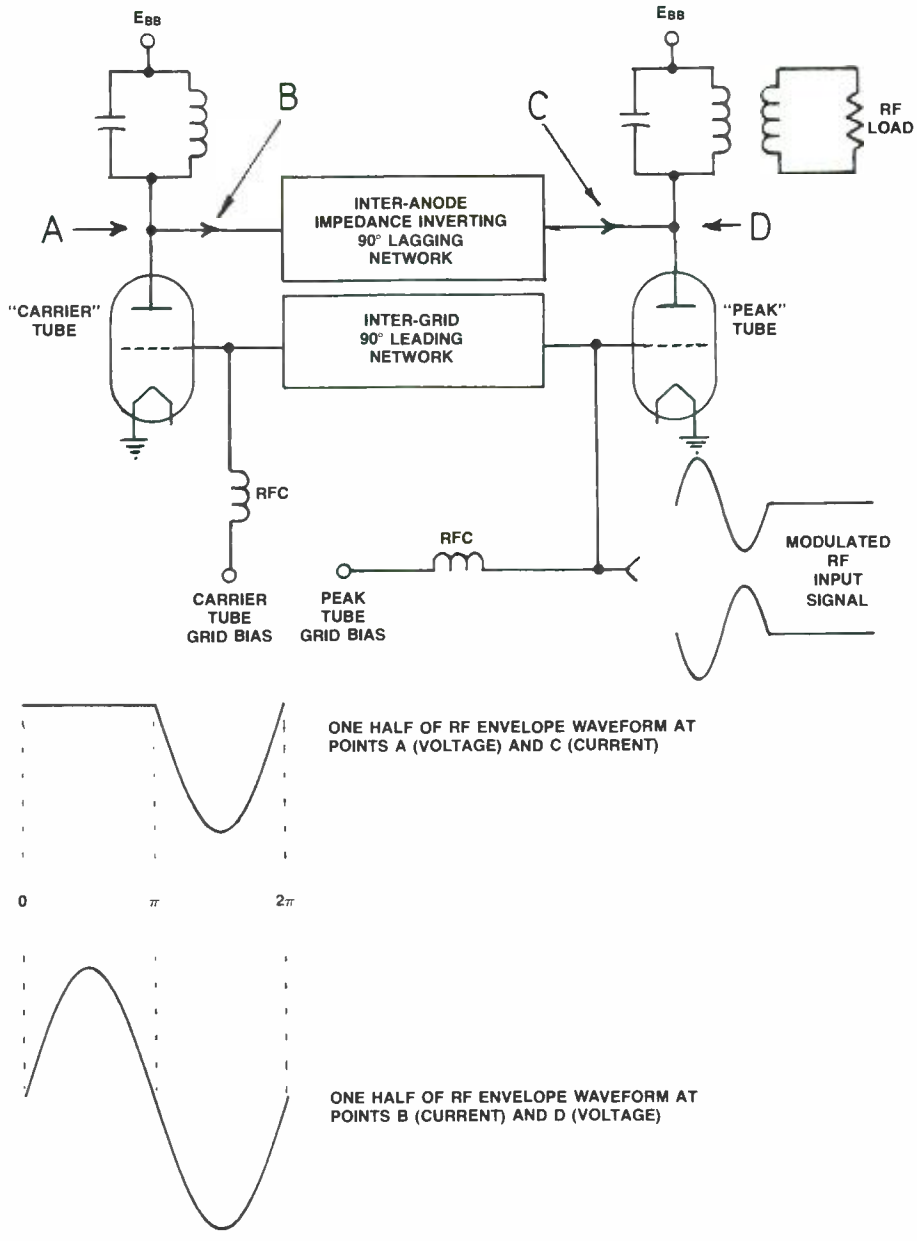


Fig. 8. Doherty high efficiency linear amplifier for modulated waves.

properties of the inter-anode network described by Doherty. The Terman-Woodyard system of modulation, however, was not extensively used in high power commercially successful transmitter designs.

High efficiency screen/impedance modulation[13] is similar to the Terman-Woodyard modulation system except that the audio modulating signal is applied to the screen grids of two tetrode vacuum tubes operating as class 'C' carrier and peak amplifiers. Invented by J.B. Sainton in 1965, the screen/impedance modulation system exhibits significant improvement to the Terman-Woodyard scheme due to the fact that RF excitation voltages and audio modulating voltages are isolated from each other thereby eliminating a troublesome source of tuning vs. modulation interaction. The screen/impedance modulation system is shown and described graphically in Fig. 9. The peak and carrier tubes are biased and driven in quadrature as Class 'C' amplifiers from the continuous wave RF drive source. At carrier level, the screen voltage of the carrier tube is adjusted so that the carrier tube is near anode saturation and delivering approximately 96% of the carrier power; while the screen voltage of the

[13] "High Efficiency Amplifier and Push-pull Modulator". J. B. Sainton, U.S. Patent No. 3,314,024, April 1967

peak tube is adjusted so that the peak tube is just into conduction and supplying the remaining approximate 4% of carrier power. The combined anode efficiency at carrier level is better than 77% as shown in equation [6].

$$n_{at} = 1/\ (pc/n_{ac}) + (pp/n_{ap}) \qquad [6]$$

$$n_{at} = 1/\ (0.96/0.8) + (0.04/0.40) = 0.77$$

Where:

pc = percent carrier power supplied by carrier tube (as a decimal)
pp = percent carrier power supplied by peak tube (as a decimal)
n_{ac} = carrier tube anode efficiency at carrier level (as a decimal)
n_{ap} = peak tube anode efficiency at carrier level (as a decimal)
n_{at} = total anode efficiency at carrier level (as a decimal)

The modulation of the RF carrier wave occurs when the screen voltage of the peak tube begins to rise during the positive modulation half-cycle, thus causing the peak tube to supply more RF current to the output load. This increase of current into the output network causes the resistance seen by the inter-anode network to increase and, due to the impedance inverting characteristic of

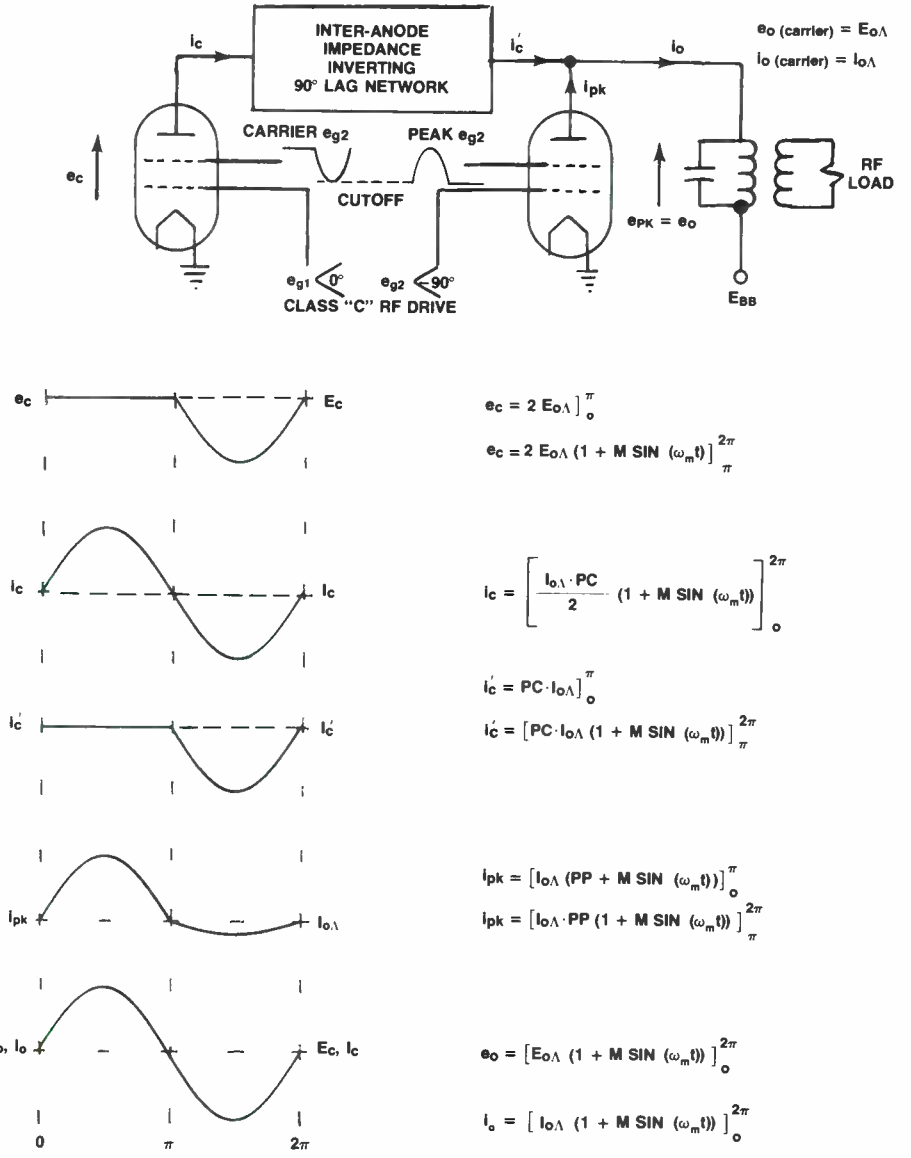


Fig. 9. Principles of Sainton high efficiency screen/impedance modulation.

the 90° inter-anode network, causes a proportional decrease in the load impedance presented to the carrier tube anode. The carrier tube resonant anode voltage drop is fully saturated over the entire positive modulation half-cycle and is therefore effectively a constant voltage source. The power output of the carrier tube thus increases during the positive modulation half-cycle due to the modulated decreasing impedance at its anode until both peak and carrier tubes deliver twice carrier power at the 100% positive modulation crest. During the negative modulation half-cycle, the peak tube is held out of conduction while the carrier tube output voltage decreases linearly to zero output at the 100% negative modulation crest. Simple alterations to the inter-anode 90 degree network characteristic impedance gives the screen/impedance modulation system the capability of full FCC allowed positive modulation up to 125% peak without added distortion. The advantages of screen/impedance modulation are the same as mentioned for the Doherty linear amplifier except that screen/impedance modulation has higher efficiency at all depths of modulation and, is less critical to misadjustment of RF amplifier tuning. Screen/impedance modulation has been successfully used in medium wave transmitters throughout the world at the two megawatt carrier power level and up to 250 kilowatts in automatically tuned transmitters used for international shortwave broadcasting.

In 1980, the British Broadcasting Corporation completed a four year study of known amplitude modulation systems, and selected the screen/impedance modulation system for their upgrade of 50 kW AM broadcast transmitters used in the BBC domestic and worldwide network.

SOLID STATE BROADCAST TRANSMITTERS

Developments in solid state technology in the last few years has allowed solid state devices to be used in broadcast transmitters at high power RF levels. While many engineers maintain that vacuum tubes will continue to have definite operating cost and reliability advantages over solid state devices at most higher RF power levels for sometime because of potentially destructive energy in lightning strikes, power line surges, and other surprises of nature; the facts are clear that present solid state device technology and circuit developments in some military and commercial RF applications up to two megawatts and beyond have already established high power solid state RF technology as a force in future high power transmitter development. Fully solid-state and proven reliable AM broadcast transmitters up to the 10 kilowatt carrier power level are currently commercially available. It is generally believed that higher power levels are not far in the future. The debate will probably continue for some time regarding solid state vs. tube reliability in regard to lightning strikes, power surges, ability to withstand abuse, maintenance cost, etc., but ultimately, most design engineers believe, totally solid state designs will be the standard designs of the future. The reason for this belief is the same reason that has led the AM transmitter industry from the Heising modulator of the 1920's to the best of the modern designs, the continuous attempt of broadcasters and equipment design engineers to improve efficiency, reliability, and total equipment operating cost.

Solid State Designs

Most solid state designs of AM broadcast transmitters currently available on the commercial market employ Class 'D' final RF power amplifiers yielding dc to RF efficiencies of approximately 95%. Pulse width modulation (PWM) of the final, and sometimes driver, RF amplifier supply voltage is employed yielding modulator efficiencies also of approximately 95%. The total dc to RF carrier efficiency is therefore approximately 90%, somewhat higher than normally achieved with tube type class 'C' or quasi-Class 'D' power amplifiers. Furthermore, there is no additional filament heating power required in solid state transmitters and therefore the transmitter auxiliary power consumption is further minimized yielding overall transmitter efficiencies greater than 70% at the 10 kW carrier power level, approximately 10% higher than most tube type transmitters of the same power level. Most solid state designs employ modularization of major system components to ease corrective maintenance procedures as well as providing manufacturing economies.

TRANSMITTER CIRCUITRY

Detailed transmitter circuit design is as varied as the individual designers. In a later section of this chapter will be brief and general discussions of some current production transmitter models which are representative of a particular power level, modulation system, or other unique feature. There is, however, some basic circuitry which is common to all transmitter types and models which will be briefly discussed in this section.

Carrier Frequency Generator/Exciter

The stable frequency source for all transmitters manufactured since about 1930 has been the

quartz crystal oscillator. The quartz crystals used in older model transmitters were large cuts of natural quartz, vacuum sealed in glass envelopes, similar to small power vacuum tube envelopes, and occasionally mounted in temperature controlled ovens to obtain the required FCC carrier frequency stability. It is more common in modern designs for the quartz crystals to be enclosed in small hermetic sealed metal cans, made popular and proven reliable by the military and commercial communications equipment industry, and without special temperature controlled circuitry. Modern quartz crystal manufacturing technology and the use of proven solid state crystal oscillator designs allows these types of small metal sealed units to adequately maintain the FCC's current requirement of ±20 Hz carrier frequency tolerance. Stability of the quartz oscillator circuits is normally adequate over the full lifetime of the equipment. Should frequency adjustment ever be required to bring a unit back inside the FCC limits, mechanically stable adjustment components, usually a glass or ceramic piston type of capacitor, are provided for use by a qualified station engineer using certifiably calibrated frequency measuring equipment. (Ref: FCC Rules and Regulations Volume III, October 1982, Part 73.1540 and 73.1545). Exciters for all proposed AM-Stereo systems provide the carrier frequency excitation for the transmitter as well as the stereo generating circuitry. Because of manufacturing advantages, some manufacturers of AM-Stereo exciters generate the desired carrier signal with frequency synthesizer techniques. This method of generating the basic carrier frequency is generally equal to or better than the discrete quartz oscillator method with regard to frequency tolerance but can produce higher phase modulation noise if improperly designed or adjusted.

RF Power Amplifier

Practically all modern AM broadcast transmitters employ Class 'C' amplification in the final RF power amplifier stage(s). Some employ designs using third harmonic trap circuitry yielding quasi-class 'D' operation for improved efficiency. Most solid state transmitters currently available in the North American market use Class 'D' RF final power amplification. Refer to paragraph 3 for a discussion of power amplifier theory.

RF Output Networks

The purpose of the RF output network is to match the impedance of the load; i.e., the common-point impedance of one or more antenna matching and combining networks, to the impedance required by the final RF power amplifier tube(s) or transistor(s) to produce the desired carrier and sideband power. The output network circuit also is designed to provide the attenuation characteristics necessary to meet the FCC's requirements for spurious and harmonic output. There are many techniques to accomplish these basic tasks. One simple and effective method is shown in Fig. 10 as an illustrative and typical example. The terminating load impedance for the network shown in Fig. 10 is defined by the Smith chart representation of Fig. 11, which is a typical common point impedance characteristic of a multi-tower AM broadcast directional antenna array.

Fig. 12 shows the impedance vs. frequency characteristics at the input of the network; i.e., at the anode of the final RF amplifier tube.

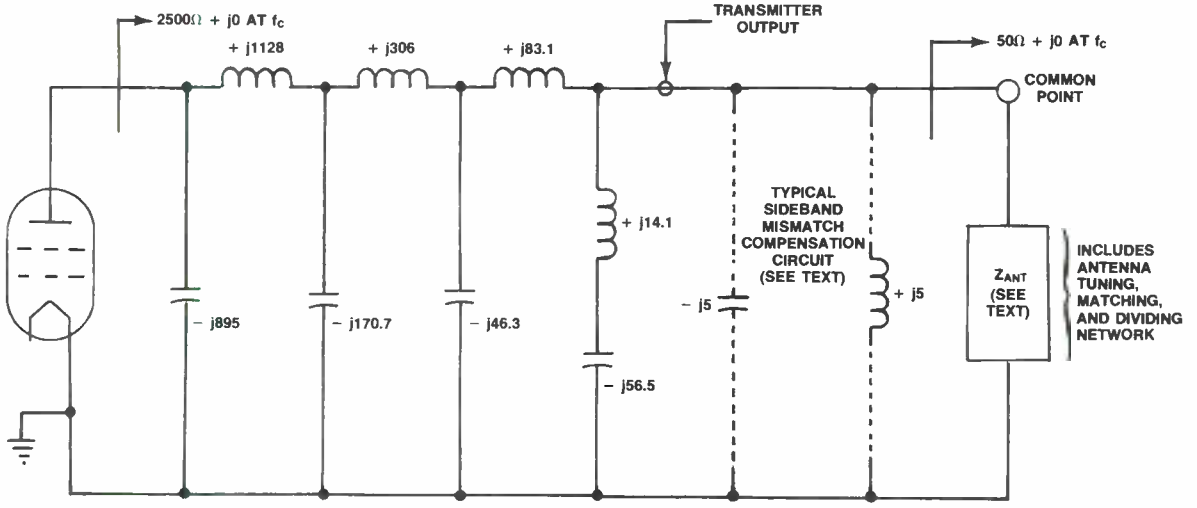


Fig. 10. Typical output matching network yielding 80dB or better harmonic attenuation and a compensated symmetrical sideband load at the anode(s) of the RF output amplifier.

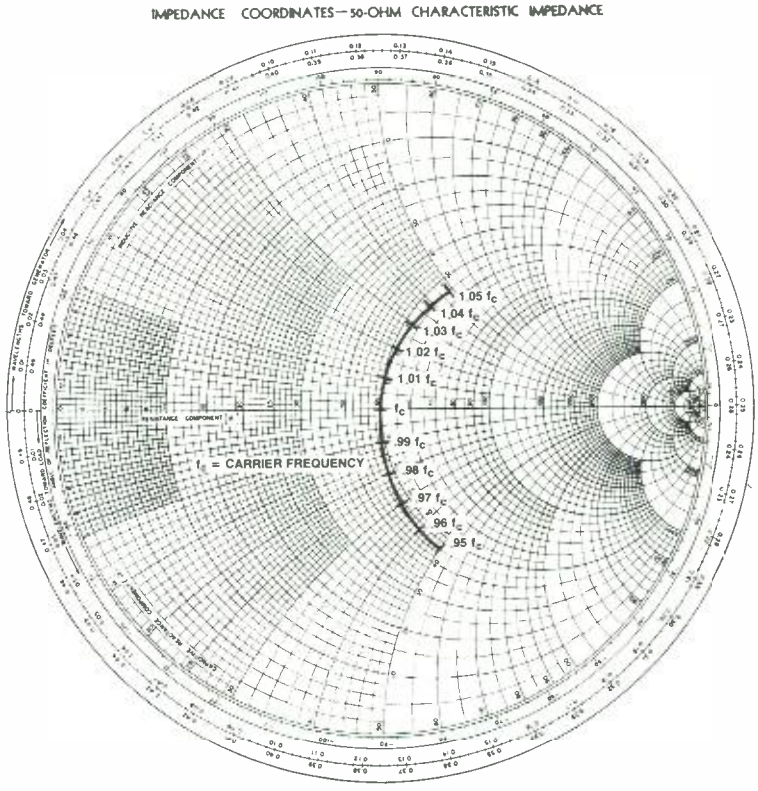


Fig. 11. Typical impedance vs. frequency characteristic of antenna common point.

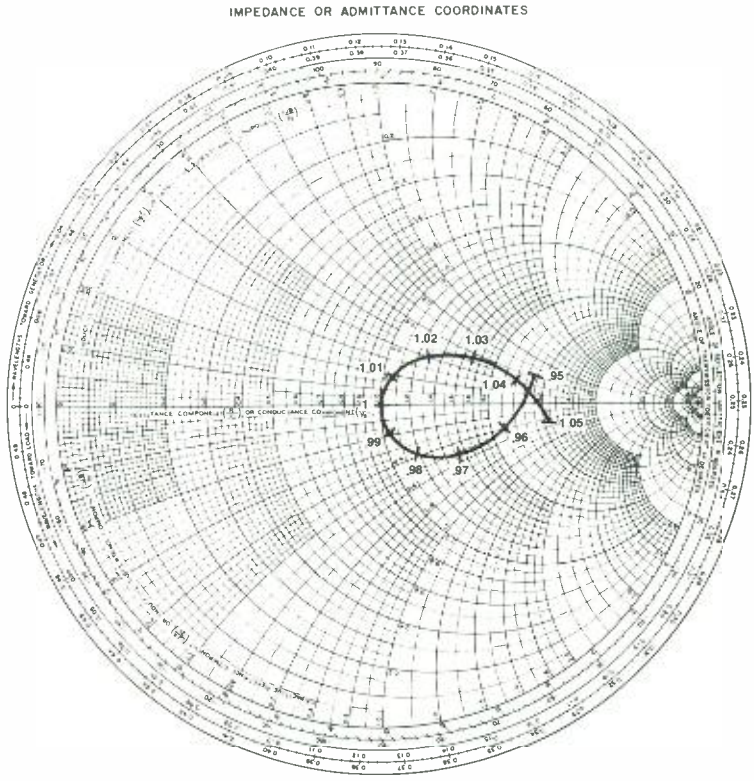


Fig. 12. Impedance vs. frequency characteristic at anode of final RF power amplifier.

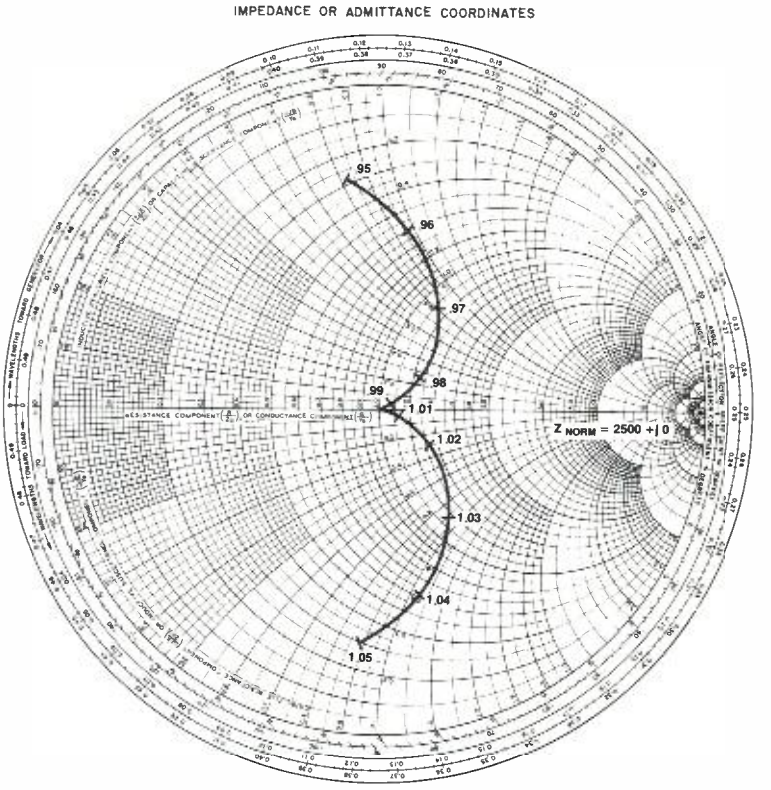


Fig. 13. Impedance vs. frequency characteristic at output anode with sideband mismatch corrective network added.

The shape of the impedance curve in Fig. 12 differs significantly from the shape of the terminating impedance curve shown in Fig. 11 due to the narrowing of bandwidth caused by the output matching network. The VSWR (normalised to the resistive carrier impedance) at ± 10 kHz is about 1.2 in both Figs. 11 and 12 but at ±50 kHz the VSWR at the input to the network has increased from about 2.4 to approximately 3.0. The shape of the impedance vs frequency curve at the anode(s) of the RF output amplifier tube(s) [or transistor collector(s)] has an important role to play in the high audiofrequency performance characteristics of the transmitter, such as frequency response and harmonic distortion.[14] The shape of the impedance vs. frequency curve should be symmetrical about the resistive axis of the Smith Chart and should yield lowest practical VSWR values at the highest expected fundamental sideband frequencies. Fig. 13 shows the result of an attempt to lessen the magnitude of the mismatch at the input to the matching network by the addition of the dotted components shown in Fig. 10. The result of adding the dotted components in Fig. 10 is a significant reduction in tube anode load mismatch at sideband frequencies of ±10 kHz; i.e., from about 1.2 VSWR in Fig. 12 to approximately 1.1 VSWR in Fig. 13. The reduction of mismatch at ±10 kHz, however, comes at the expense of a worsening of mismatch at sideband frequencies greater than ±30 kHz. The worsening mismatch at higher sideband frequencies is normally not a problem and often tends to improve transmitter harmonic distortion performance, acting as an output bandpass filter to higher order harmonics. There is theoretically no limit to the amount of sideband mismatch correction that can be achieved with more complex network circuitry. The most important criteria is symmetry about the Smith Chart resistive axis. Station engineers or their engineering consultants should work with the transmitter manufacturers and antenna system designers to, first determine, then achieve the desired impedance vs. frequency curve at the output RF amplifier tube(s) anode connection. The example given above for load sideband mismatch correction is for illustrative purposes only. It is quite common for the complex impedance at the sideband frequencies to present a more severe mismatch at the antenna common point than shown in Fig. 11. More severe mismatch and im-

[14]"Operation of AM Broadcast Transmitters into Sharply Tuned Antenna Systems". W. H. Doherty, Proc. IRE, Vol. 37, No. 7, July 1949, p. 729.

pedance dissymmetry require more complex sideband mismatch corrective networking.

Transmitter Control and Monitoring

AM broadcast transmitter control circuitry is normally very basic and uncomplicated. It is common to find the task of transmitter control performed with discrete digital IC logic circuitry in modern designs that used to be accomplished with simple relay control logic. Some manufacturers are incorporating microprocessor technology in their latest equipment designs to replace discrete digital logic circuitry. The aim of manufacturers is normally to provide the operating engineers and technicians with the most basic, reliable, and easy to maintain and troubleshoot transmitter possible. Experience has shown that well designed relay control logic, discrete digital IC logic, and microprocessor-based logic are all about equal in terms of reliability and ability to perform the required basic transmitter control functions. Future microprocessor-based transmitter control logic offers the promise to provide self and remote assisted diagnostics of transmitter problems and remote interrogation of transmitter operating parameters. Future microprocessor based logic offers the added promise of altering the basic characteristics of a transmitter control system through software control, allowing the basic transmitter design to be more easily "customized" to individual users' operating requirements. Because of the high voltage and high current faults that can exist in any high power transmitter component, extra care must be taken by designers and manufacturers of high power AM broadcast transmitters to prevent the potential destructive energy in these faults from affecting the performance and operation of the relatively delicate solid-state control logic circuitry. High speed vacuum contactors and solid state regulator/controllers are being used in many modern designs to control the high voltages and currents encountered in all levels of high power AM transmitters, which previously had been controlled by slower though equally reliable air-magnetic contactors and relays.

Remote control systems are commercially available that will allow remote control of almost any transmitter, old or new. These remote control systems, like the basic transmitter control system, use relay, discrete digital IC, microprocessor-based logic circuitry, or combinations of these, depending on the manufacturer of the remote control equipment and the complexity of the remote control functions desired. Many transmitter equipment manufacturers provide limited built-in remote control functions and circuitry.

The FCC requires manufacturers of AM broadcast transmitters to provide certain basic control and monitoring functions for operator safety and convenience and proof of certain performance parameters. These requirements are contained in the FCC Rules and Regulations Volume III (October, 1982) Parts 73.49 and 73.1215.

High Voltage Power Supplies

High voltage power supplies in AM broadcast transmitters must be designed to provide minimum acceptable performance in two basic areas: power supply ripple, which affects transmitter hum and noise output, and dynamic regulation, which affects low frequency modulation transient response. It is typical for transmitters of five kilowatts carrier power and lower to operate from a single phase ac power sources, usually 240 volts. Transmitters with carrier power ratings of ten kilowatts operate with single phase or three phase power source, depending upon the manufacturer of the transmitter. Transmitters with carrier power ratings of 50 kW or higher operate only from three phase power source, usually 480 volts for power levels up to 100 kW and 4160 volts in North America for higher carrier power levels. Three phase power has the advantage of being easier to filter and usually providing better dynamic regulation of critical modulator voltages than single phase supplies. Single phase power, on the other hand, is more readily available, which is the only reason it is used at the lower transmitter power levels, because initial installation cost would be disproportionately increased were three phase power required. Single phase rectifier power supply systems generally require L/C filtering to provide the necessary low ripple output for low transmitter hum and noise specifications. L/C filtering also creates, however, power supply resonances in the audible to sub-audible range of modulating frequencies, and therefore is a source of poor dynamic power supply regulation when the modulator circuitry of the transmitter is excited by vowel sounds or musical percussion sounds. It has been common since about 1970 for higher power transmitters to use special high voltage supply transformers to generate a six-phase ac supply from the basic three phase power source. The six-phase supply, when full wave rectified, yields a 12 pulse rectified dc waveform that has both lower ripple content and a higher ripple frequency than conventional three-phase full wave rectification. As a result, the output of the rectifier can be sufficiently filtered with no additional filter inductors, thus improving low audio modulating frequency dynamic power supply regulation and hence, low frequency transient distortion.

TRANSMITTER PERFORMANCE MEASUREMENTS

Certain basic AM transmitter performance parameters should be measured on a periodic basis in order to assure that certain minimum broadcast quality standards are provided the listening public. Excluding the performance standards for AM-Stereo, these are listed below. (From Volume III of the October 1982 edition of the FCC Rules and Regulations). Some are specifically required by the FCC, while others are a matter of good engineering practice.

a) Operating power
[Part 73.51]

b) Carrier output power delivered to the antenna system
[Part 73.54]

c) Modulation capability

d) Total audio frequency distortion

e) System frequency response

f) Carrier-amplitude regulation (Carrier Shift)

g) Hum and noise output level

h) Carrier frequency tolerance
[Part 73.1545(a)]

All audio measurements are to made from a demodulated signal at the antenna system common point.

Regarding item b above, the measurement of transmitter power output by the direct method described in Parts 73.51 and 73.1215 is subject to more than 13% error if allowed FCC measurement inaccuracies are taken to the limit. For example, assume that a common point impedance of 50 ohms resistive can be measured to within 2% accuracy with a radio frequency impedance bridge, a realistic tolerance. Further assume a direct reading RF ammeter having a full scale reading of 100 amperes and an FCC allowed tolerance of ±2% of full scale is used for this measurement and indicates 33.33 amperes of common point current; i.e., just meeting the minimum FCC accuracy and indication requirements in Part 73.1215(b)(2) and (3). Under these conditions, the actual power delivered to the antenna is between the limits of (35.33 × 35.33 × 51) 63.65 kW, as a maximum, and (31.33 × 31.33 × 49) 48.10 kW, as a minimum; yielding a total measurement error of approximately +14/−13%. Using an RF ammeter with a 50 ampere full scale reading, the same FCC allowed inaccuracies, and the same meter indications as above, would result in power output measurement errors of approximately ±8%.

FACTORY TESTS

When buying or looking for an AM broadcast transmitter to buy for replacement or new equipment, it is advisable to ask manufactures for specific and detailed test and performance data at the start of the buy investigation. Before a final decision is made, specific and detailed tests should be made at the manufacturers factory under strict control of an experienced engineer or engineering consultant. Most manufacturers of AM broadcast equipment welcome this kind of intelligent approach to the decision making process. Some hints on what kind of tests and a discussion on the details of each test is given below.

Demodulated Characteristics (Audio Performance)

As stated earlier in the chapter, most audio performance characteristics reached a plateau in the late 1940's to early 1950's which has not seen significant improvement in even the most modern AM broadcast transmitter designs.

Audio Frequency Response

At one time the term "broadcast quality audio" meant a standard to which all other system equipment, by comparison, was inferior. Today the audio quality of consumer high fidelity and stereo equipment surpasses, with one exception, the signal quality which can be broadcast by any AM transmitter manufactured today or likely to be made in the future. The one exception is audio frequency response. Practically all mass production AM receivers made in any country of the world have IF and audio amplifier bandpass characteristics that limits receiver -3 dB high end audio frequency response to between approximately 2500 Hz and 5000 Hz, with 2500 Hz the more common of the two figures. Typical low end -3 dB frequency response of consumer AM radios is between 100 Hz and 300 Hz, with approximately 200 Hz a common value. AM transmitter frequency response characteristics, referred to a reference frequency of either 400 Hz or 1000 Hz, typically is well within ±1 dB from 50 to 10000 Hz at any depth of modulation.

Audio Harmonic and Inter-Modulation Distortion

Current production AM broadcast transmitters typically produce less than 2% total harmonic

distortion (THD) up to 90% modulation at any frequency of modulation between 50 and 10000 Hz for monophonic transmission.

Intermodulation distortion (IMD) has been known for years, and has been documented in technical audio journals, to be a more disturbing kind of distortion than harmonic distortion; though both are important. The CCIR method of IMD measurement is the preferred method for radio broadcast transmitters. With this method, two equal audio tones separated by 170 Hz are input to the transmitter and the peak modulation level adjusted to between 85 and 95% modulation. The level of odd and even order products are measured using an audio wave or spectrum analyzer connected to the test output terminals of a high quality modulation monitor. Two IMD measurements should be taken, one with the two tones near mid audio band, for example: 400 and 570 Hz, and one test with the two tones near the upper audio end, for example: 7000 and 7170 Hz. High quality broadcast transmitters should produce IM distortion products more than 30 dB below the level of either of the two modulating tones. The RSS value of all IM products, relative to the level of either modulating tone, should also be less than 7% at 90% peak modulation levels.

Residual AM Hum and Noise

The FCC requirement for AM noise of about 60 dB below the 400 Hz/100% modulation level can be achieved by most current production AM broadcast transmitters. The bandwidth of noise measuring equipment should be 20 kHz. Typical modulation monitor demodulated audio bandwidth is approximately 25 kHz to accommodate both of these FCC bandwidth requirements.

Residual PM Hum and Noise

Residual Phase Modulation (PM) noise is normally not a problem for modern AM broadcast transmitter designs for monophonic broadcasting. The quartz crystal oscillator circuits and even moderately careful RF component mechanical designs produce quite acceptable phase noise characteristics. However, for AM-Stereo applications, where a frequency synthesizer may be used for the RF signal generation, is it wise to perform a test to determine the purity of the synthesizer circuitry. Very excessive residual PM noise can convert to AM noise over certain nighttime propagation paths and appear to distant listeners as objectionable AM hum and noise. An acceptable value of PM noise is -25 dB rms relative to one radian peak, measured in a 15 kHz bandwidth, for monophonic medium wave band AM transmission. Transmitters with quartz crystal oscillator exciters typically exceed this recomendation by 25 dB or more. Transmitters used for international short wave broadcasting (4 to 26 MHz) require PM noise levels of approximately -45 dB relative to a one radian peak because of more severe skywave PM to AM conversion at higher frequencies.

Incidental Phase Modulation (IPM)

Like residual PM, IPM is more important in stations using or planning to use AM-Stereo transmission. IPM can be defined as the peak phase deviation *of the carrier frequency* (in radians) resulting from the process of amplitude modulation. IPM values of several radians were common in the very early days of broadcasting. Typical values of IPM for modern transmitters that have not been specifically designed or adjusted to minimize IPM range from about 0.1 to 0.5 radians peak (approx. 6 to 30 degrees). A maximum acceptable value of IPM required for present or future AM-Stereo operation is generally considered to be approximately 0.05 peak radians with a desired value of better than 0.02 peak radians. State-of-the-art modulation meters such as the Hewlett-Packard model HP-8901 and other similar instruments are preferred for accurate PM and IPM measurements.

Carrier Amplitude Regulation (Carrier Shift)

The amount of carrier level shift in a given transmitter has more importance to overall transmitter performance than many broadcast engineers realize. Large values of negative carrier shift can have as much effect on effective transmitted sideband power as poor transient overshoot distortion. The term "carrier shift" may be somewhat confusing, especially to newcomers in radio broadcasting who often equate the terminology with frequency shift instead of level or amplitude shift, hence, the new terminology of "carrier amplitude regulation". The older terminology, however, is still used quite extensively by older engineers as well as new engineers. The CCIR refers to the same characteristic as "carrier level shift", which appeals to many engineers because of its closer adherence to the original terminology, but without the ambiguities.

"Carrier level shift" is the effective shift in apparent carrier level due to the amplitude modulation process. Carrier level shift can be caused by either poor power supply regulation, or modulation even order harmonic distortion, which generates a dc offset component in the modulated RF envelope, or both. Carrier level shift can

be either positive or negative, though is usually negative because power supply regulation is most often the major source of carrier level shift and power supply regulation is most generally negative in sign i.e., lower voltage output at higher current loads. Poor power supply regulation is not always caused by the transmitter power circuitry, it can also be, and often is, caused by poor supply line voltage regulation or, more generally a combination of the two.

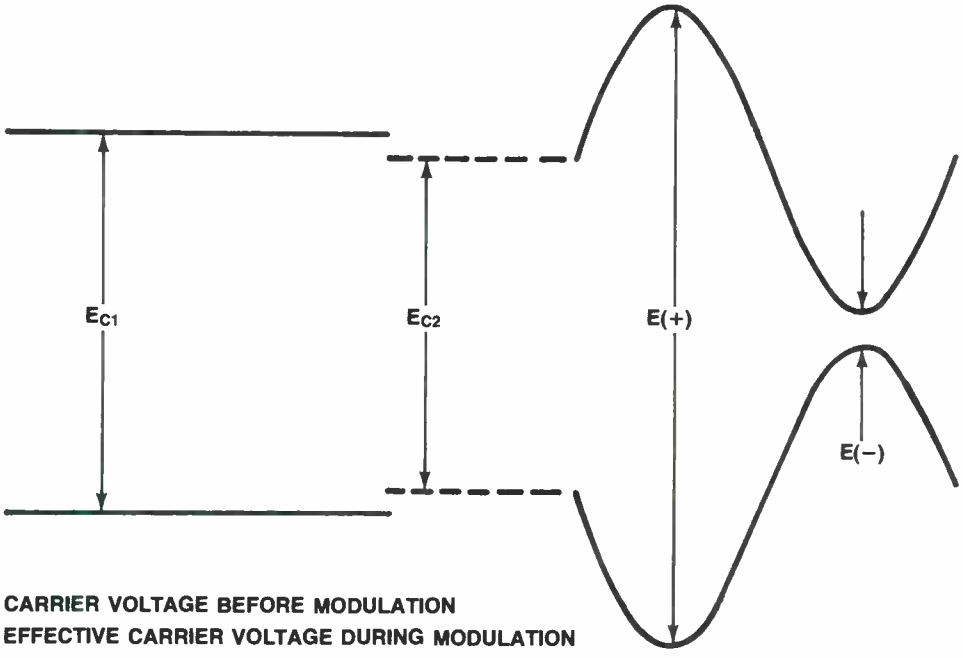
Another common misconception regarding carrier level shift is that the defined level shift is direct shift in carrier power. Actually, carrier level shift is defined as the shift in effective carrier voltage or current due to the process of modulation. This means that a carrier level shift of minus 5% is equivalent to a carrier power shift of approximately minus 10% i.e.,

$$P_{carrier\ (mod)} = Pcarrier \times (1-0.05)^2$$
$$= 0.9025 \times Pcarrier$$

Transmitters having no carrier level shift produce an average output power of 1.5 times the carrier power level with 100% sinusoidal tone modulation. Transmitters that exhibit -5% carrier level shift produce an average output power only 1.35 times the carrier level at the same conditions of sinusoidal tone modulation. A broadcast station engineer or engineering consultant needs to have complete understanding of these and other equally important transmitter characteristics in order to be able to make an intelligent buying decision based upon measurable and proven technical merit. Fig. 14 gives a graphical representation of carrier level shift.

Audio Phase Linearity

Proper attention is given to phase linearity by most station engineers and engineering consultants. Station managers and engineers are usually properly concerned about the "sound" of their stations; and loudness, or perceived loudness, is a common criteria of "quality" in many stations with diverse programming formats. However, it is not uncommon to learn that many



E_{C1} = CARRIER VOLTAGE BEFORE MODULATION
E_{C2} = EFFECTIVE CARRIER VOLTAGE DURING MODULATION

$$\text{CARRIER LEVEL SHIFT (CS)} = \frac{\frac{E(+) + E(-)}{2}}{E_{C1}}$$

$$\text{\% MODULATION} = \frac{E(+) - E(-)}{E(+) + E(-)} \times 100$$

Fig. 14. Graphical representation of carrier level shift and formulas for calculation of carrier level shift and % modulation.

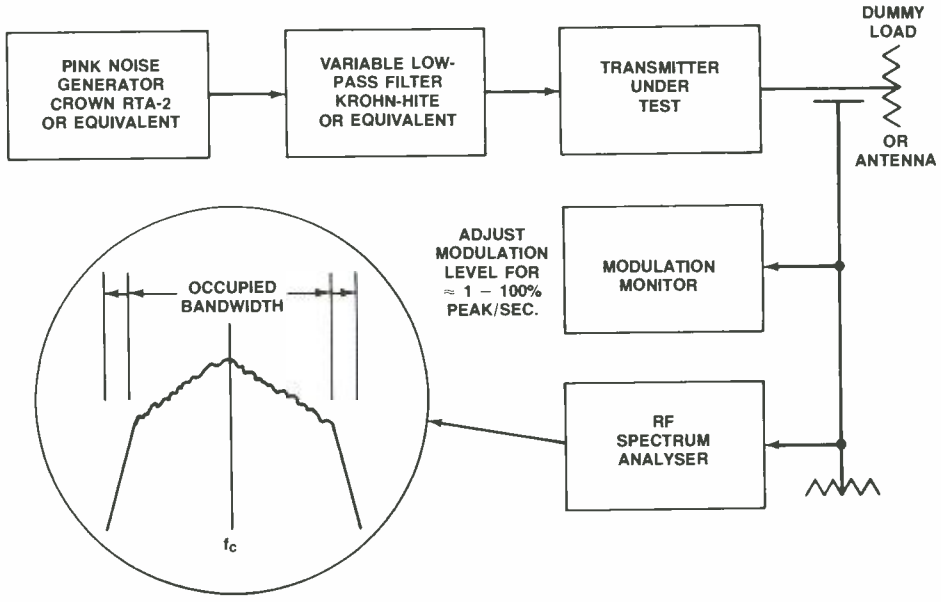


Fig. 15. Block diagram test procedure for determining transmitter occupied bandwidth.

station engineers and program directors spend more time researching the various objective and subjective merits of program processing equipment than the one characteristic in their potentially more expensive transmitter purchase that could partially neutralize the potential advantage from a new or different program processor; that one characteristic is audio phase linearity.

Audio phase linearity, or more accurately audio phase non-linearity, and its major detrimental result, transient overshoot, has been discussed in previous sections of this chapter. Before the popularity of modern broadcast audio processing and some modern broadcast programming format, audio phase linearity of a transmitter or any component in the program audio chain, was not as significant as it is today. (Modern programming philosophy, and the program processors that philosophy has caused to be manufactured, have made transmitter audio phase linearity characteristics a more important performance criteria.) In the late 1960's, at the long and persistent insistence of the AM broadcast industry, the FCC reluctantly authorized 125% positive program modulation, allowing AM transmissions to accomodate certain naturally occuring asymmetry in voice and music thus achieving a gain of 2 dB of real loudness or actual program sideband power; i.e., 20 log(1.25) = 2 dB. As stated earlier in paragraph 4.1.1, some AM broadcast transmitters in present use exhibit as much as 12% overshoot of a squarewave input, due to phase non-linearity, which has the effect of taking away one of those 2 dB the industry tried so hard to get; i.e., 20 log(1/1.12) = -1 dB.

A simple way to determine the effects of phase non-linearity, is to require the prospective transmitter manufacturer to demonstrate rectangular wave modulation characteristics of the transmitter under investigation. When such a test is performed, the overshoot produced by the transmitter will be directly visible and measurable on the oscillographic display of the transmitter output envelope. The station engineer or his engineering consultant should also investigate the effects that antenna system phase non-linearity may have on the total system transmission transient characteristics.

Occupied Bandwidth

Occupied bandwidth of an AM broadcast transmitter can best be measured with the use of a band limited colored gaussian noise source, similar to pink noise used in certain acoustical tests, to provide a continuous wideband modulating signal to the transmitter. Pink noise has equal energy per bandwidth ratio; i.e., equal energy per octave, per third octave, per tenth octave, etc. White noise has equal energy per bandwidth; i.e., equal energy per Hz. Both noise signals can have a gaussian or pseudo-gaussian probability density function, a probability density function that closely resembles that of typical voice and music. Fig. 15 shows a block diagram of the test procedure used to measure occupied bandwidth. The reader is also referred to CCIR recommendation 559-1 (Vol X Part 1 Geneva, 1982). The measurement of occupied bandwidth is a dynamic measurement which effectively summarizes two important transmitter static parameters; audio non-linear distortions, which are the source of

IMD, and THD, and incidental phase modulation (IPM).

Harmonic and Spurious Output

Harmonic and spurious output of an AM broadcast transmitter or transmission system can only be effectively measured two ways. One way is to use a sample of the transmitter RF output signal when operating into a dummy load with a known or accurately measurable impedance characteristic out to approximately the tenth RF harmonic. Then, with a calibrated measuring system, measurements and calculations are made to compute the output power of each harmonic according to the formula:

$$P_N = V_N^2 \times R_{pN}$$

Where:
P_N = the power at the Nth harmonic
V_N = the corrected measured voltage of the Nth harmonic at the calibrated impedance point
R_{pN} = The parallel resistive component of the load impedance at the Nth harmonic

A second way to effectively determine the harmonic and spurious output of an AM broadcast transmitter is to measure the actual power radiated from the antenna system at each harmonic frequency or suspected spurious output frequency by standard field intensity measurement techniques. The field intensity method is the most meaningful of the two techniques because it allows the measurement to be made under actual conditions of operation with all systems interconnected. It is normally the new transmitter manufacturer and users joint responsibility to correct any actual interference problems to other broadcast or non-broadcast communication services even when the particular interfering signal meets the standard FCC requirements. (FCC Rules Part 73.44.c.)

Carrier Output Power

The most accurate method of measuring the RF output power of a transmitter is by the calorimetric method, a method which uses the very accurately known and measurable physical and thermal characteristics of water or other similarly well defined liquids. This measurement is usually only done in a transmitter manufacturer's factory because the capital investment required to purchase and maintain calibration of this kind of infrequently used equipment is usually not justified for AM broadcasting operations.

Water is known to have a thermal capacity very close to 4.186 Joules per degree C per gram weight at a mean temperature of 60 degrees centigrade. A Joule is equal to one watt-second. Therefore, the capacity of water to absorb power is 69.8 watts per degree C per liter of water flow per minute, or

Power (kW) = Flow (lpm) $\times$ $DT°C$ $\times$ 0.0698 for water flow measured in liters per minute

or, Power (kW) = Flow (gpm) $\times$ $DT°C$ $\times$ 0.2641 for water flow measured in U.S. gallons per minute (gpm)

The flow of water can be measured with an accuracy of approximately $\pm 1\%$, by even the most common methods. Differential temperature measurement accuracy of approximately $\pm 0.1\,°C$ is commonly practical, which, for temperature differentials of 20 °C, is equivalent to $\pm 0.5\%$ accuracy. Therefore, using calorimetric measurement techniques, the output power of AM transmitters can be measured with total accuracies better than $\pm 2\%$. The RF output amplifier efficiency factor F, referred to in FCC Rules Part 73.51.e.1, can then be determined for future operating and proof of performance reference. However, even with this method of determining the factor F, an accuracy of less than $\pm 2\%$ cannot be maintained over the life of the equipment. The required FCC transmitter voltage and current meters have a $\pm 2\%$ accuracy, in addition to the multiplied power accuracy of approximately $\pm 4\%$. When accuracy levels are combined, this fields a total uncertainty of $\pm 6\%$ for the factor F. Still, this is considerably better than the accuracies obtainable by the direct measurement technique.

Operating Efficiency and Input Power

The determination of transmitter input power should be done under actual or simulated operating conditions. This requires program or simulated program signals for the transmitter modulating source during the period of power input measurement is by use of a standard rotating disk watt-hour meter. The measurement accuracy of these familiar watt-hour meters is typically better than 0.5%, better than four times the accuracy of any other conventional direct ac power measurement technique. The watt-hour metering system should be connected in the main power feed line to the transmitter under test. Sinusoidal test signals, useful for other tests of transmitter performance, are not recommended for power consumption tests because of the distinctly opposite statistical characteristics of sinusoidal signals and typical voice and music program

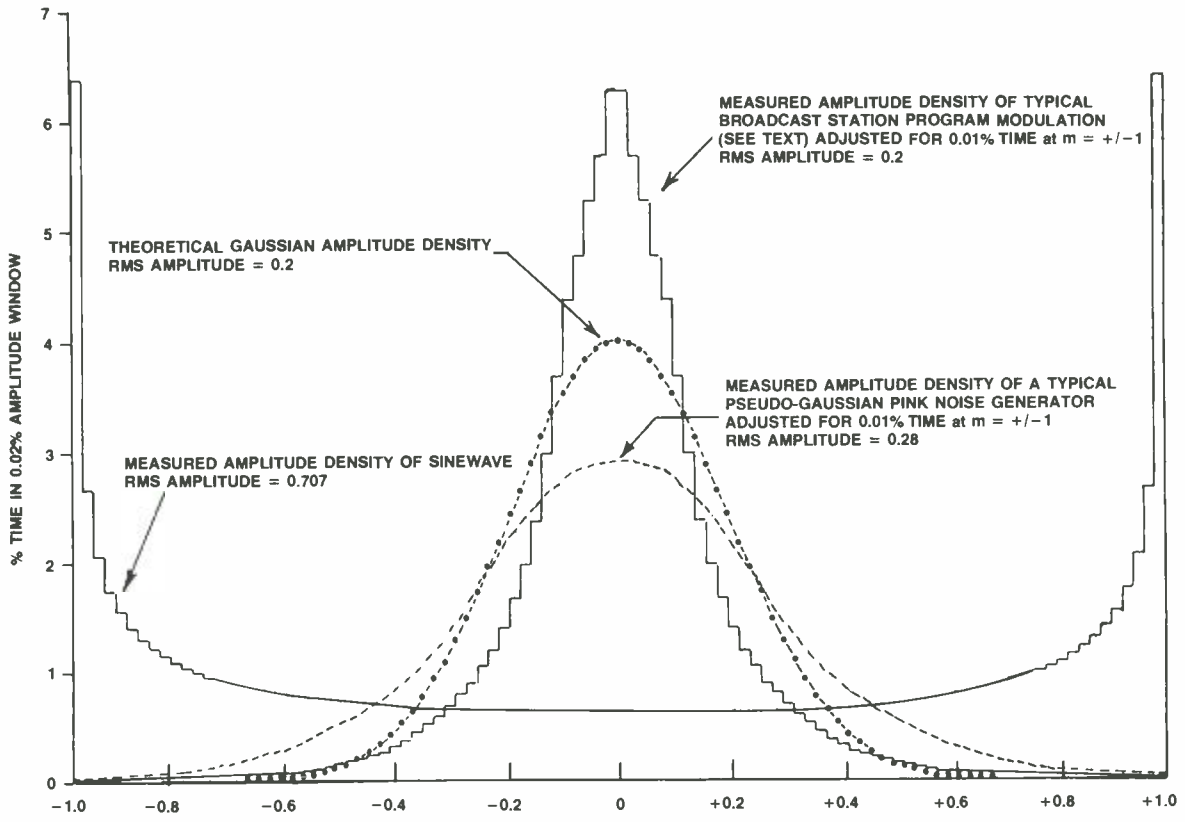


Fig. 16. Amplitude density of sinusoidal test signals and typical program or noise test signals. Program or noise test signals recommended for transmitter efficiency measurements (see text).

material and the effect this difference has on actual operating power consumption measurements. This difference between periodic sinusoidal signals and mathematically random types of signals such as human voice and/or music has been known for decades. The effect this difference produces in AM broadcast transmitter power consumption and operating efficiency measurements, however, was first documented in 1980, by investigators in Europe[15] and was later verified and further explained by investigators in the US[16 & 18] and other countries.

The critical difference between sinusoidal signals and typical program types of signals is explained in Fig. 16 which shows the amplitude density characteristics of a sinusoidal waveform (U-shaped curve) and an amplitude density characteristic of a typical broadcast program modulation (pyramid curve). The totally different shapes of the two curves in Fig. 16 cause the measured transmitter efficiency at identical RMS modulation levels also to be quite different. The program measurement of five differently formatted FM radio stations located in Dallas, TX. Data was taken for continuous ON-AIR hours for each station and averaged for presentation as shown in Fig. 16. FM stations were used in the collection of the data because of their consistent day/night signal levels, symmetrical modulation characteristics for easier comparison to the sine wave, and omni-directional emission patter. Some transmitters, or more correctly modulation systems, are more efficient with program modulation than with equivalent RMS sinusoidal test signals while others have poorer efficiency with program modulation techniques that yield higher carrier efficiencies also yield higher program efficiencies; i.e., lower program power consumption than with an equivalent RMS modulation sinusoidal test signal. It is obvious that the program input power consumption test is the one most meaningful to broadcasters whose purpose it is to broadcast programs, rather than sinusoidal tones. In this discussion, the terms "program efficiency" and "program input power consumption" have generally been given equal weighted

[15] "Efficiency of High Power Broadcasting Transmitters in Regular Programme Service". M. Sempert and W. Tschol, BBC Review, July 1980.

[16] "Efficiency Comparison of AM Broadcast Transmitters". G. W. Woodard, IREE Journal (Australia), Vol.2 ,No. 2, June 1982.

[18] "Simulating Typical Programme Modulation for Measurements of Operating Efficiency and Modulation Capability of AM Broadcast Transmitters". G. W. Woodard, Radio and Electronic Engineer (UK),Vol. 53,No. 9, p. 325.

value. It is correct to equate the weighted value of these two parameters for transmitter to transmitter comparisons if it is assumed or defined that average transmitter-to-transmitter output power is constant for a defined program input. Such an assumption is correct except that transmitters with excessive transient overshoot will have correspondingly less average modulated RF power output for given peak levels of processed program modulation. Experimental methods have been devised to measure average long term transmitter output power; i.e., RF kilowatt-hour output.[17] With such equipment it would be convenient to accurately compute actual program efficiency knowing both kilowatt-hours input and kilowatt-hours output. Until such equipment becomes commercially available, however, only the transmitter input power can be accurately measured with the familiar single phase and multi-phase rotating disk kilowatt-hour instruments.

Fig. 16 also shows a third curve (dashed curve) which is the amplitude density function of a Crown model RTA-2 pink noise generator. It is recommended that either a pink noise signal with amplitude density characteristics similar to the curve in Fig. 16 or a recording of actual program modulation be used as a program source for factory input power consumption tests. Program processing equipment, if used, and peak modulation levels should be adjusted to satisfy normal station operating procedures and transmitter input power measurements then taken during a 30 minute (minimum) segment of the program source material. Refer to FCC Rules Part 73.1570(a) and (b) for modulation setup procedures. The average input power determined by the method described will be very close to the transmitter power consumption during its total operating life and therefore can be used to accurately predict actual operating energy costs. This is the only method of transmitter power consumption tests that will provide accurate energy consumption forecasting data.

IMPORTANT AM-STEREO TRANSMITTER CHARACTERISTICS

Incidental Phase Modulation

Several of the proposed AM-Stereo systems utilize a form of phase modulation for encoding the stereo signal onto the carrier of the AM signal. It is for this simple reason that the most important transmitter characteristic affecting AM-Stereo operation is incidental phase modulation (IPM) which has been previously discussed in section 7.1.5. Excessive IPM can affect stereo separation, single channel distortion, and the occupied bandwidth of a stereo transmission; with the most significant of the three being single channel distortion.

Recognizing the various causes of IPM is the first step in correcting the trouble. There are many potential sources of IPM but the most common source is insufficient amplifier neutralization, either of a final modulated RF amplifier or of a lower power driver stage. The solution is, of course, to perform better neutralization of the offending amplifier stages. This is easier said than done in most cases. Since the inception of AM-Stereo broadcasting, manufacturers of the transmitters have paid more attention to the problems of IPM and in most cases have reduced production levels of IPM in current model transmitters to acceptable levels for AM-Stereo operation. In some cases, for especially difficult problems, field engineers from the manufacturers factory must make special on site adjustment of individual transmitters which are particularly susceptible to excessive IPM. Several engineering consulting firms have developed special knowledge in the AM-Stereo field, having collected data on many transmitters in current use, some of which have been out of production for several years. It is suggested that such a firm be contacted to solve particularly difficult neutralization procedures on old or new equipment which may not have been satisfactorily performed by the original manufacturer.

Phase Noise

Residual phase modulated noise cannot normally be detected by a standard AM broadcast receiver employing envelope detection, while stereophonic AM receivers are sensitive to PM noise. PM to AM conversion can occur on the medium wave band over multi-ionospheric "hops" (night-time skywave propagation) which can then be detected by receivers employing standard envelope detection. Very early transmitters sometimes produced more residual phase noise sidebands than those produced by the desired program amplitude modulation. Night-time reception of distant stations sometimes was accompanied by a 120-360 Hz "roar" which was caused by phase modulation from the master oscillator filament supply. A somewhat subdued "roar" can be heard even today from many shortwave stations using older transmitting equipment, especially on the higher shortwave bands where multi-hop propagation is more prevalent.

Significant phase modulated noise in modern transmitters is virtually nonexistent due to the use of high quality quartz crystal oscillator and syn-

[17] "Measurement of the efficiency of high-power AM transmitters with regular broadcast programmes". A. W. Jaussi and W. Tschol, EBU Review, No. 194, August 1982, p. 169.

thesizer circuitry. Phase noise modulation of 0.6 degrees (0.01 radians) avg. is fully acceptable for monophonic AM broadcasting. Phase noise modulation of approximately 0.2 degrees (0.0032 radians) avg. is usually considered acceptable for AM stereophonic broadcasting. As with measurements of Incidental Phase Modulation (IPM), an HP-8901, or equivalent, Modulation Analyzer is recommended for phase noise modulation measurements.

Stereophonic Phase/Gain Equalization

Standard production exciters for AM-Stereo systems may incorporate built-in circuitry designed to approximately match the phase and gain characteristics of the normal monophonic transmitter transmission path to the transmission path for the encoded stereo signal. Transmitters which have excessive in band non-linear phase characteristics sometimes require special "out-boarded" phase/gain equalization networks to achieve optimum stereo performance.

INTERNATIONAL SHORTWAVE BROADCAST TRANSMITTERS

Introduction

International shortwave broadcasting in the United States and North America began at about the same time as medium-wave broadcasting, about 1920, but did not have any substantial growth until pre-World War II propaganda activities by the influential nations. Until this growth in the mid-1930's, shortwave broadcasting was done primarily by amateur and special industry groups using the higher frequency bands for experimentation and hobby interests. Almost immediately after the invasion of Pearl Harbor, accelerated shortwave broadcast activity in the United States began by the Office of War Information (OWI) which later assumed the wartime responsibility of the then inexperienced Voice of America (VOA) in June of 1942. Later, in mid-1943 the Armed Forces Radio Service began shortwave relay broadcasts to France and other parts of Europe from bases in England. After WWII, the Voice of America resumed control of their wartime expanded facilities and, together with virtually all nations, began continuous operations of native and foreign language broadcasts for information exchange and general entertainment purposes. Other private interest in shortwave broadcasting also began to expand after the war, primarily from various religious and politically based organizations seeking means to advance their cause or provide information and service not otherwise available by government operations. Commercial shortwave broadcasting in the United States has generally not been profitable primarily because of the limited audiences in North America given the popularity of AM, FM, and TV broadcasting. The quality of signal in shortwave listening is not of the same quality as in either of the three other more popular modes of broadcasting, due to the long distances covered and atmosphere-generated fading and noise. Therefore, shortwave broadcasting in North America attracts a different kind of listener; one who is more dedicated to the "hobby" of shortwave listening and therefore more willing to tolerate the disturbances associated with short wave listening. Shortwave listening in the world outside North America is very popular, and necessary, among large segments of the population as a source of news, socio-political or religious view-point, and entertainment.

Shortwave Transmitters

Shortwave broadcast transmitters are similar in many respects to medium wave transmitters and very different in others. The similarities are in methods of modulation, control, and monitoring. The differences are, generally, that shortwave transmitters are higher power, more complex in tuning, and more difficult to operate and maintain than medium wave "standard" broadcast transmitters. Although there are numerous exceptions, the general rule, written or unwritten, is that the minimum usable carrier power level is 50 kW and the maximum economical carrier power level from a single transmitter is 250 kW to 500 kW.

It is not unusual for a shortwave transmitter to operate on five to ten separate frequencies every broadcast day. Modern broadcasting schedules of the prestigious broadcasting organizations are very tight, thus necessitating built-in automatic frequency changing circuitry which allows the transmitter to tune to several programmed frequencies in approximately 10 to 30 seconds, with minimum or no operator intervention. The trend in shortwave transmitter operation is toward unattended or minimum attended sites, with program and frequency changes done by remote and/or computer control.

Single Sideband Operation on the International Shortwave Bands

Since about 1964, the International Telecommunication Union (ITU) and its radio broadcasting special committee, the International Radio Consultative Committee (CCIR) have encouraged the adoption of a form of Single Sideband as the standard modulation system for international shortwave broadcasting. This recommendation has been prompted due to the ever increasing con-

gestion in the shortwave broadcast bands, the competitive increases in transmitter power levels, which contributes to the congestion; and the realization of the increased efficiency of the SSB mode of transmission. A World Administrative Radio Conference Committee, meeting in Geneva in January and February of 1984, adopted a specific and detailed 20 year plan for conversion to SSB on the international shortwave broadcast bands. The committee report addressed necessary changes in both transmitter and receiver technologies, thus creating the beginning and emphasizing the importance of the changes which can double the available channel space and improve reception quality in the current international broadcast bands.

Figs. 35 and 36 show a block diagram and photograph of a 250 kW international broadcast band transmitter with ten channel semi-automatic tuning capability in use since 1980 by Radio Free Europe/Radio Liberty.

REPRESENTATIVE COMMERCIAL PRODUCTION TRANSMITTERS

This section shows examples and a brief description of some current model production transmitters which are representative of some of the basic transmitter types discussed in previous sections.

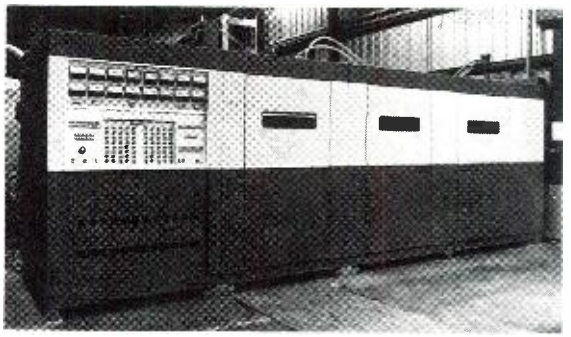


Fig. 36. Continental Electronics Model 419F semi-automatically tuned 250kW shortwave transmitter.

LPB Model AM-150

The LPB Model AM-150 is the highest power model of a line of low power transmitters used for various special broadcast applications such as Pre-Sunrise operation of daytime only stations, travelers information services, standby transmitters for emergency use, Armed Forces radio services, etc. None of these family of transmitters carries FCC type acceptance for broadcast use since there are no standard catagories for the use of these power levels in broadcasting. Some of the family line is approved or pending approval by the Department of Communications of Canada for continuous broadcast service.

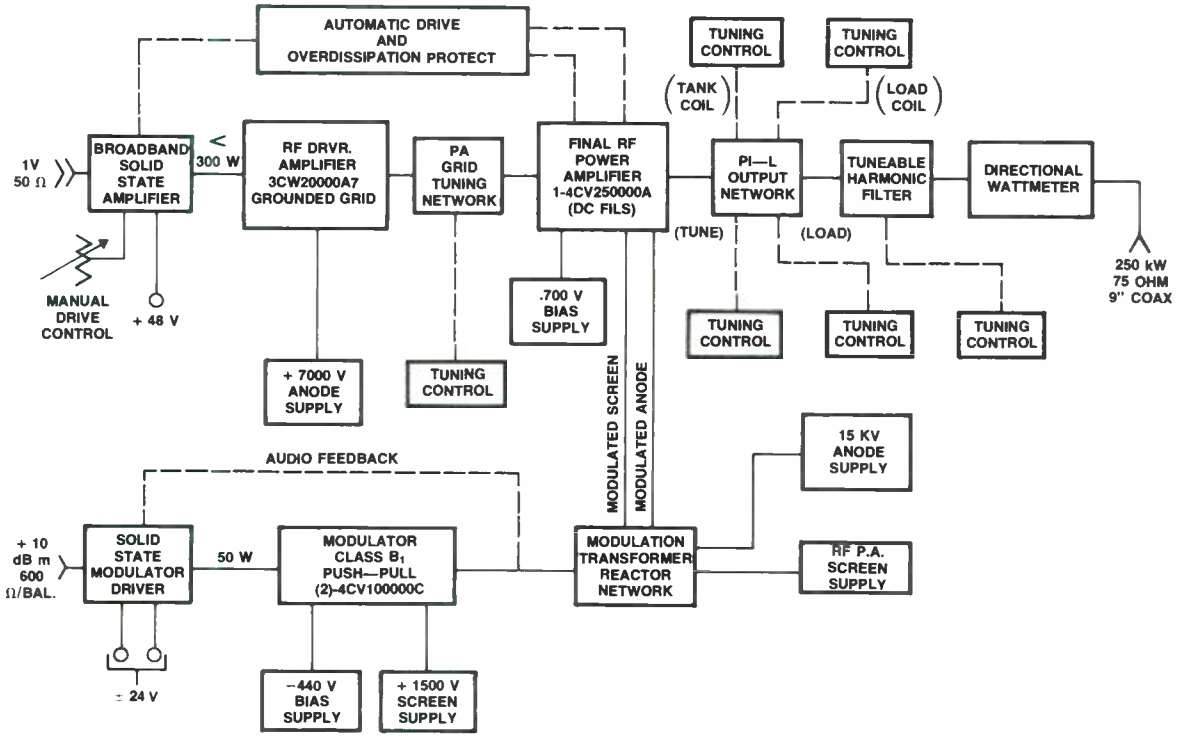


Fig. 35. Block diagram, Continental Electronics Model 419F 250 kW shortwave transmitter.

The transmitters use low level modulation followed by one or more conventional linear amplifier stages until the desired power output level is attained. The entire family of transmitters are completely solid-state and many have built in modulation limiting and modulation level metering. The Model AM-150 is shown in the photograph of Fig. 17.

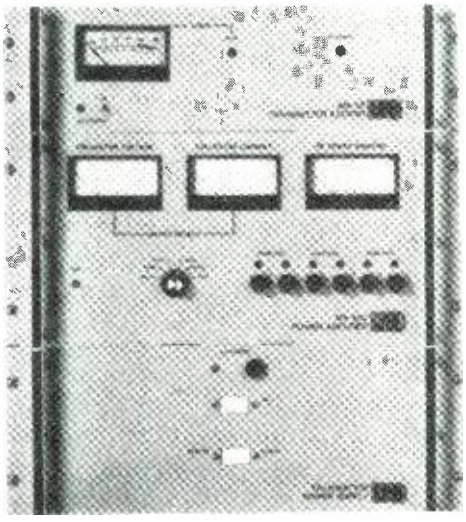


Fig. 17. LPB Model AM-150 pre-sunrise post-sunset low power AM transmitter.

McMartin Model PS-1K

The McMartin Model PS-1K is not a transmitter but is a unique product which is designed specifically for use in post-sunset pre-sunrise operation of daytime only stations in the United States. It is a passive device that reduces the power of any 250, 500, or 1000 watt transmitter to an authorized pre-sunrise level through the use of resistive attenuation networks. All controls for automatic or manual power change are built into the unit with facilities for proper transmitter interface during the switchover period. The unit requires no tuning or special external ancilliary items. A photograph of the Model PS-1K is shown in Fig. 18. For information regarding pre-sunrise authorization, the reader is referred to the FCC Rules and Regulations at Section 73.99 (may be found in Title 47 of the Code of Federal Regulations).

McMartin Model BA-1K 250-1000 Watt Transmitter

The McMartin Model BA-1K is a conventional Class "B" high level anode (plate) modulated transmitter. The BA-1K uses only one tube type, a 4-500A or 4-500B power tetrode,—two in the push-pull class "B" modulator final amplifier and

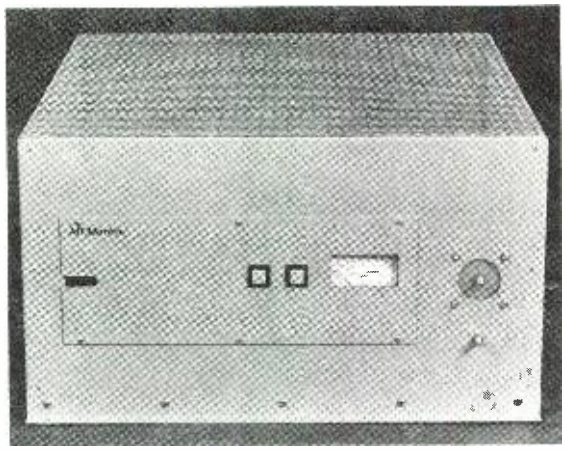


Fig. 18. McMartin Model PS-1K pre-sunrise post-sunset transmitter power reduction unit.

two in the final modulated RF power amplifier. All other stages are completely solid state. The BA-1K transmitter, employing an oil filled modulation transformer, was first manufactured in 1974, and has proven reliability in nearly 250 stations; approximately one-half in the United States. A block diagram and photograph of the unit is shown in Fig. 19 and 20 respectively.

Harris Models SX-1, -2.5, -5

The Harris family of all solid state transmitters employ high efficiency Class"D" final RF stages and high efficiency polyphase-pulse width modulation for high overall transmitter efficiency, typically greater than 72%, at all conditions of modulation. The transmitters are of modular construction to ease maintenance procedures and are the first in the industry to use a microprocessor control system. A block diagram (block diagrams of all models are identical) and a photograph of the Model SX-5 are shown in Fig. 21 and 22 respectively.

Nautel Models AMPFET 1, 5, 10

The Nautel family of all solid state broadcast transmitters first entered the market in 1982 and have established a good record of reliability and performance. The transmitters employ modular construction of the RF and Modulator units. The family of transmitters all employ high efficiency MOS-FET Class "D" final RF output amplifiers which are collector modulated by a high efficiency MOS-FET series pulse width modulation system. The manufacturer lists overall transmitter efficiency at better than 72% at all conditions of modulation. Approximately 20 transmitters of each power level are presently in operation or planned operation. A block diagram and photograph of the Nautel model AMPFET 10 is shown in Fig. 23 and 24 respectively.

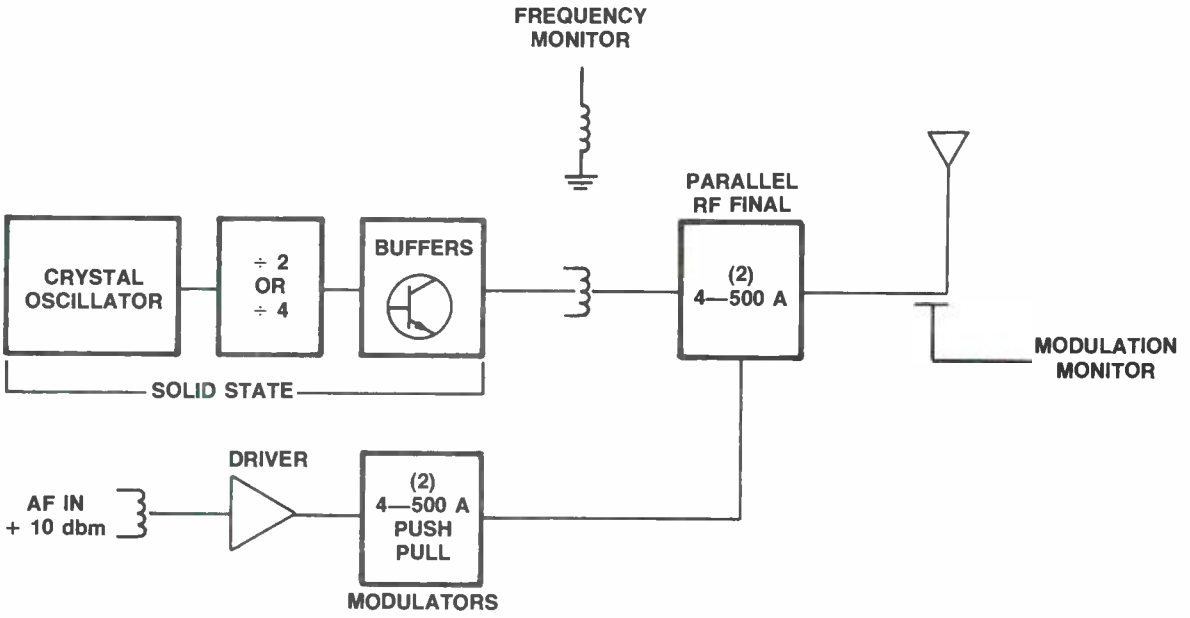


Fig. 19. Block diagram, McMartin Model BA-1K, 1 kW transmitter.

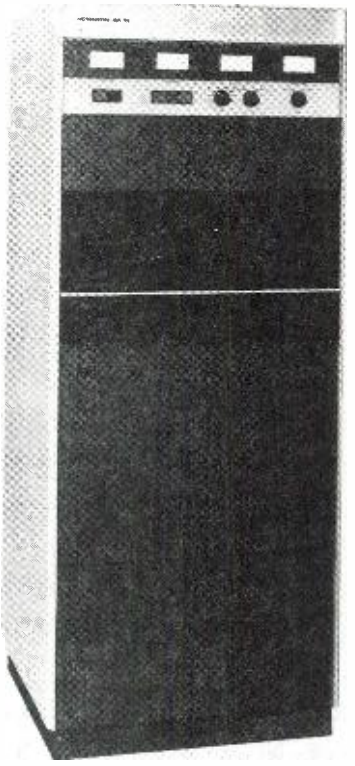


Fig. 20. McMartin Model BA-1K.

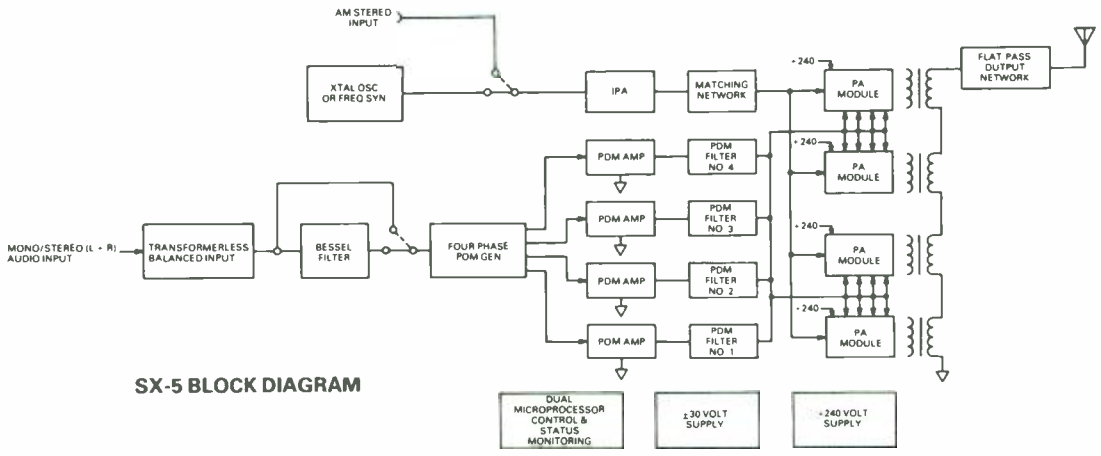


Fig. 21. Block diagram, Harris Model SX-5, 5kW transmitter.

Fig. 22. Harris Model SX-5.

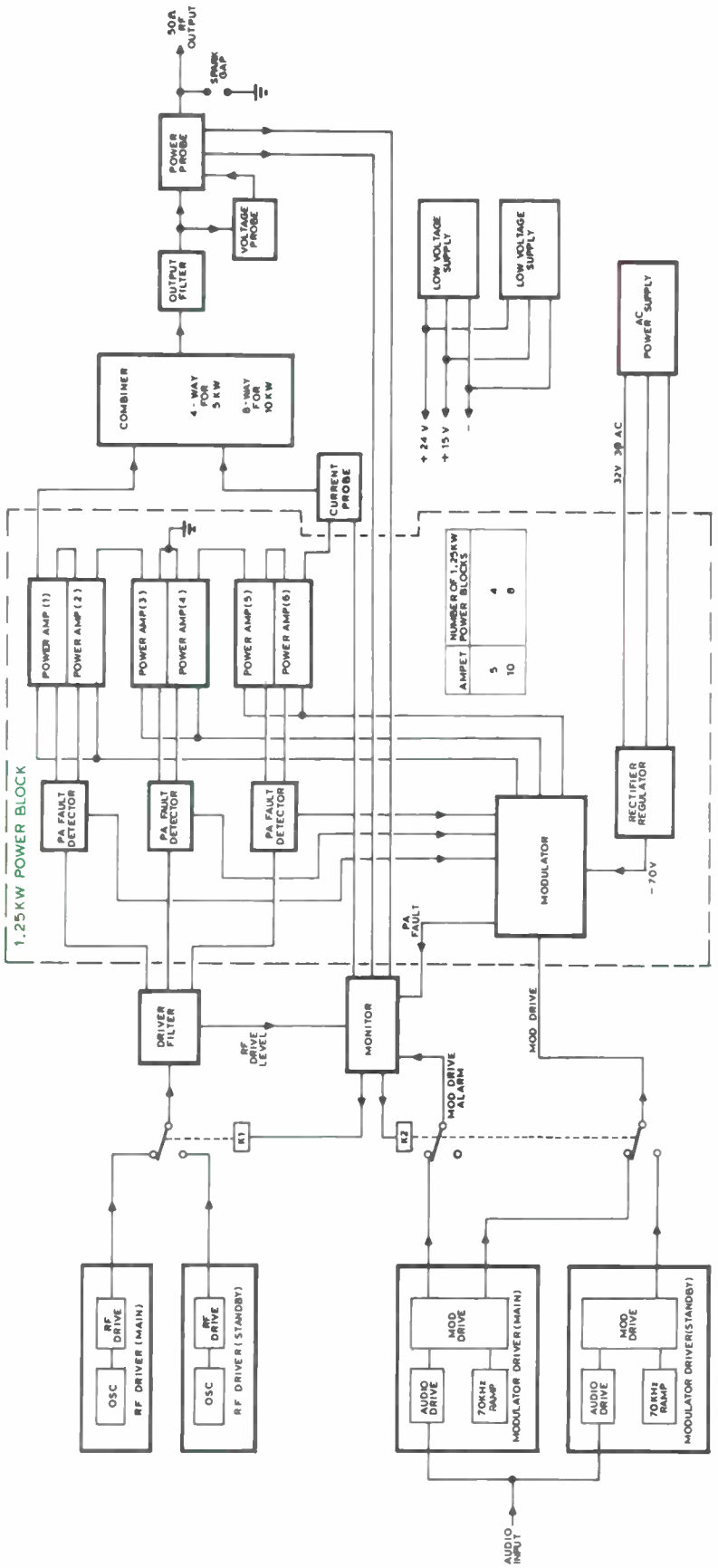


Fig. 23. Block diagram, Nautel Model AMPFET 5 and AMPFET 10, 5 & 10kW AM broadcast transmitters.

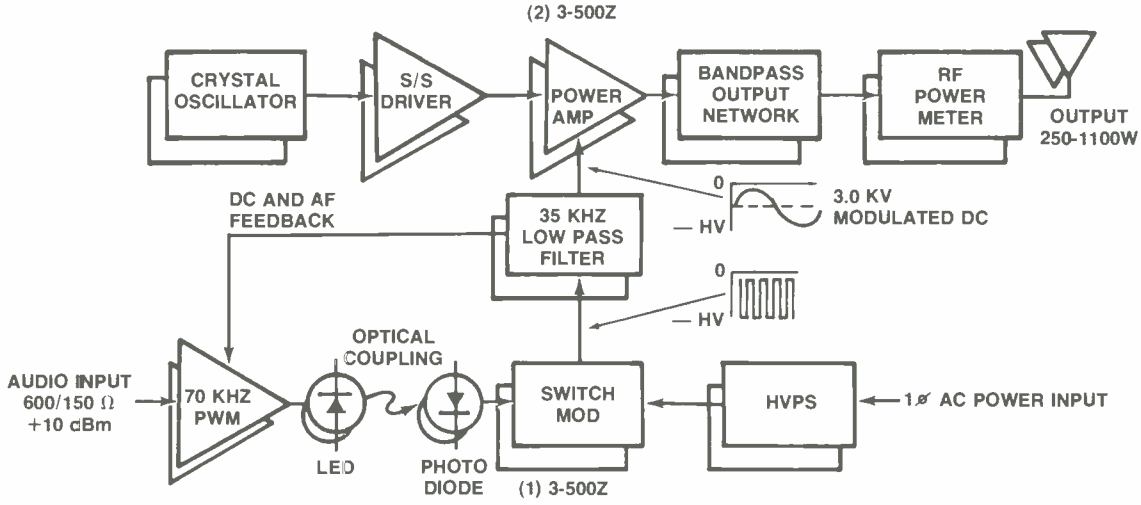


Fig. 25. Block diagram, Continental Electronics Model 314R-1 1kW AM broadcast transmitter.

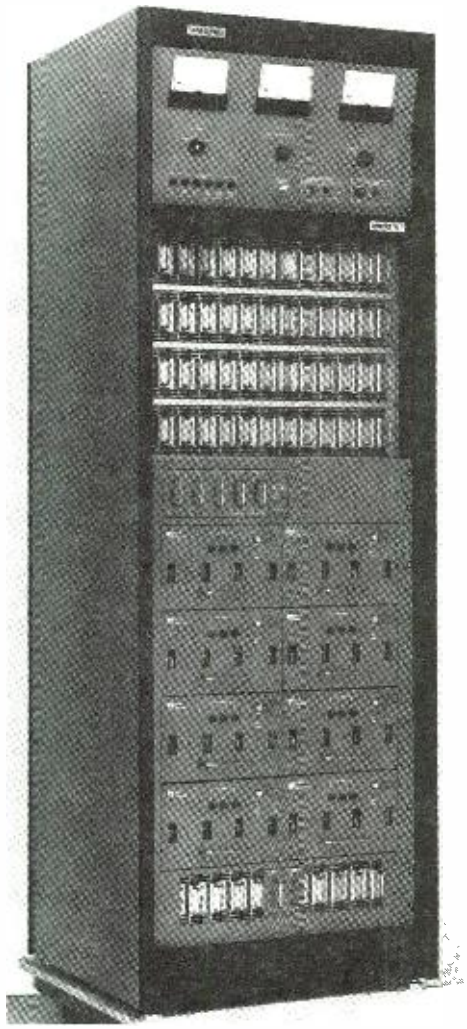


Fig. 24. NAUTEL Ampfet-10 transmitter.

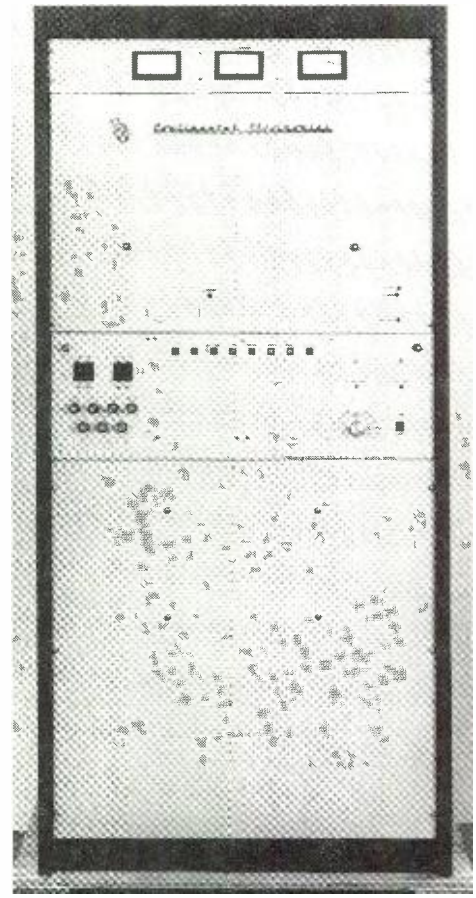


Fig. 26. Continental Electronics Model 314R-1 1kW transmitter.

Continental Electronics Model 314R-1, 1 kW Transmitter

Formerly the Collins Radio Co. Model 828C-1 before the sale of the Collins Radio Broadcast Division to Continental in 1981, the 314R-1 1kW transmitter has been in continuous production since 1977. A single tube type (3-500Z) is used three times in the transmitter, two in the high efficiency quasi-Class "D" final RF amplifier and one in the patented high efficiency series pulse width modulator (see Fig. 6(c)). All other circuitry is solid state. The transmitter has an overall efficiency of greater than 43% at any condition of modulation and a proven performance record in approximately 128 stations throughout the world. A block diagram and photograph of the model 314R-1 is shown in Fig. 25 and 26 respectively.

Continental Electronics Model 315R-1, 5kW Transmitter

Formerly the Collins Radio Co. Model 828E-1, the 315R-1 5 kW transmitter has been in continuous production since 1978. One tube type (3CX3000F7) is used in the transmitter, one in the high efficiency quasi class "D" (Class C-D) final RF amplifier and one in the patented high efficiency series pulse width modulator (See Fig. 6(c). All other circuitry is solid state. The transmitter has an overall efficiency of greater than 57% at any condition of modulation and a proven performance record in more than 300 stations throughout the world. A block diagram and photograph of Continental Electronics model 315R-1 are shown respectively in Fig. 27 and 28.

McMartin Model BA-50K

The McMartin model BA-50K employs conventional high level anode (plate) push-pull class "B" modulation. Four tubes are used, EIMAC 4CX20000B, two in the push-pull final modulator and two in the modulated final RF power amplifier. All other circuitry is solid state.The manufacturer lists an overall efficiency of better than 60% at average depths of modulation. The transmitter was first manufactured in 1982 and four are in use at this writing. A photograph of the McMartin model BA-50K is shown in Fig. 29.

Harris MW-50C

The Harris model MW-50C 50 kW transmitter is a four tube high level anode (plate) modulated transmitter employing pulse width modulation. It uses two 4CX35000C power tetrodes, one as a quasi class "D" anode modulated final RF amplifier, and one as the series pulse width modulator described above, see Fig. 6(c). Each 4CX35000C is driven by a 4CX1500A power tetrode vacuum tube. All other circuitry is solid state. The power consumption at 30% sinusoidal modulation is rated at 87 kW yielding an overall efficiency of 66% at that condition of modulation. The MW-50B has a switchable audio input linear phase (Bessel) filter to reduce transient overshoot distortion. The MW-50B is an improved version of the older MW-50A model which was first introduced in 1973. Approximately 100 MW-50 models are in service throughout the world. A block diagram and photograph of the Harris MW-50B are shown in Fig. 30 and 31 respectively.

Continental Electronics Model 317C-2

The Continental Electronics model 317C-2 employs the patented high efficiency and reliable screen/impedance system of modulation. Having almost linear audio phase response to 30 kHz, the 317C-2 can produce high modulation density levels without transient overshoot distortion and with only approximately one-half the high peak anode voltages encountered with high level anode systems of modulation. The overall efficiency of the 317C-2 is better than 60% at any condition of modulation. First manufactured in 1968, more than 250 units are in operation throughout the world at this writing. Fig. 32 and 33 respectively show the block diagram, and a photograph of the Continental Electronics model 317C-2 transmitter.

Continental Electronics Model 419F 250 Kilowatt Shortwave Transmitter

The model 419F transmitter uses conventional class "B" high level anode (plate) modulation. The final RF amplifier uses a single EIMAC vapour cooled 4CV250000B power tetrode and the modulators employ two EIMAC vapour cooled 4CV100000C power tetrodes in a special push-pull arrangement that allows very low modulator static currents for highest possible program efficiency. The modulation transformer is an oil-filled unit designed to allow the RFPA dc anode current to flow directly through its secondary without saturation, thus eliminating the need for high pass coupling of the audio signal from the modulator output to the RFPA anode. The final RFPA is driven by an EIMAC 3CW20000A7 power triode. All other circuitry is solid state. Overall efficiency of the 419F is better than 60% at any condition of program modulation. The 419F is capable of ten channel preset tuning by local or remote control without operator intervention. First manufactured in 1980, there are twelve units in operation in Europe and the Middle East at this writing. The 419F is the largest of a family of similarly designed 50 and 100 kW transmitters, Continental models 417C and 418D.

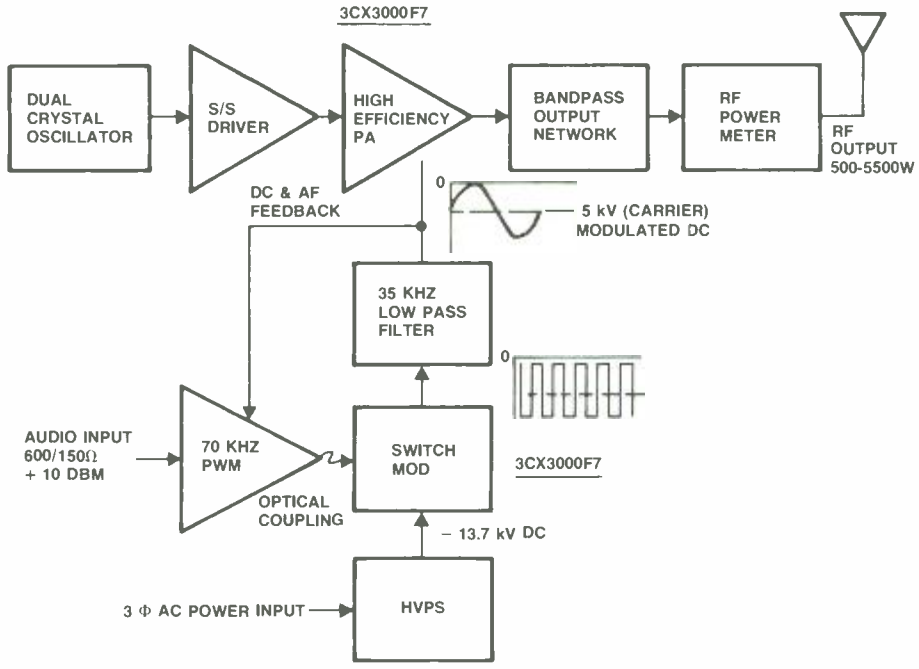


Fig. 27. Block diagram, Continental Electronics Model 315R-1 5kW AM broadcast transmitter.

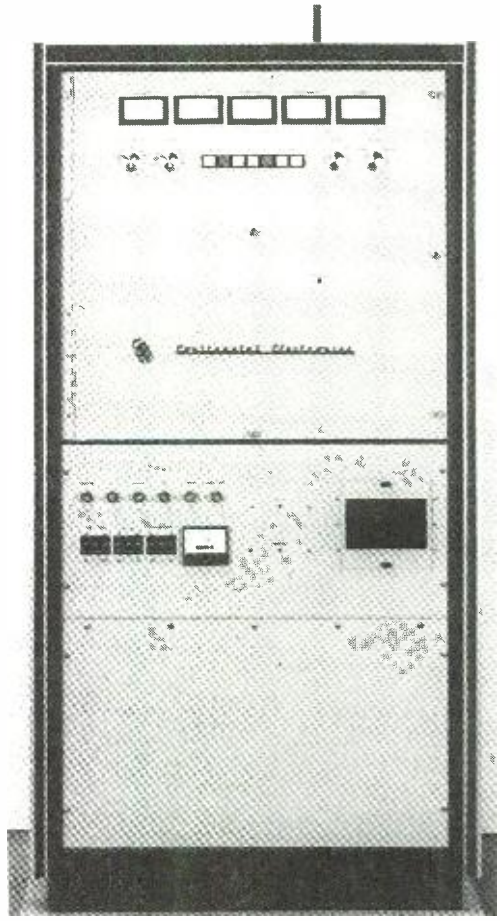


Fig. 28. Continental Electronics Model 315R-1.

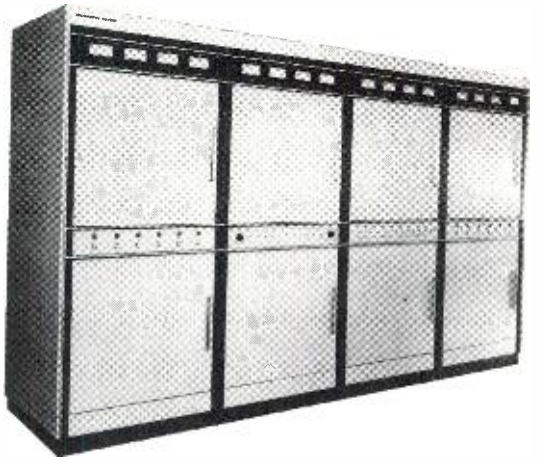


Fig. 29. McMartin Model BA-50k, 50kW AM broadcast transmitter.

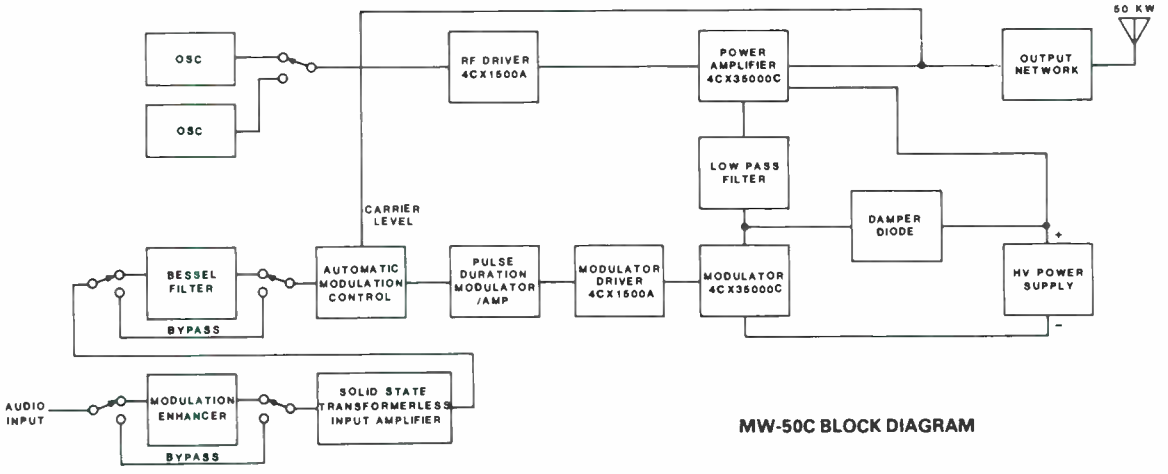


Fig. 30. Block diagram, Harris Model MW50C, 50kW broadcast transmitter.

Fig. 31. Harris Model MW 50C transmitter.

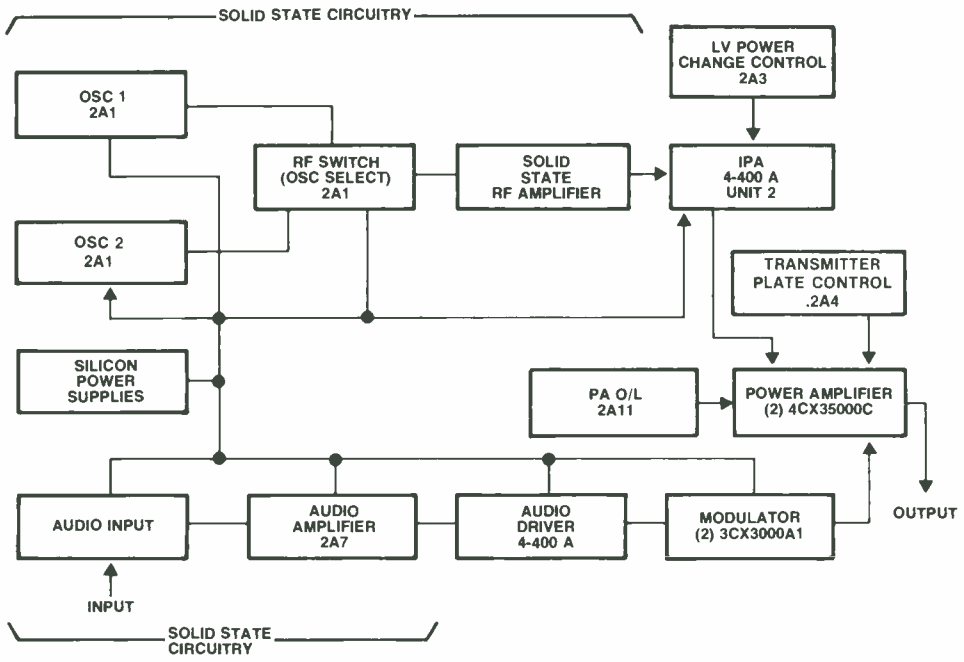


Fig. 32. Block diagram, Continental Electronics Model 317C-2 50kW AM broadcast transmitter.

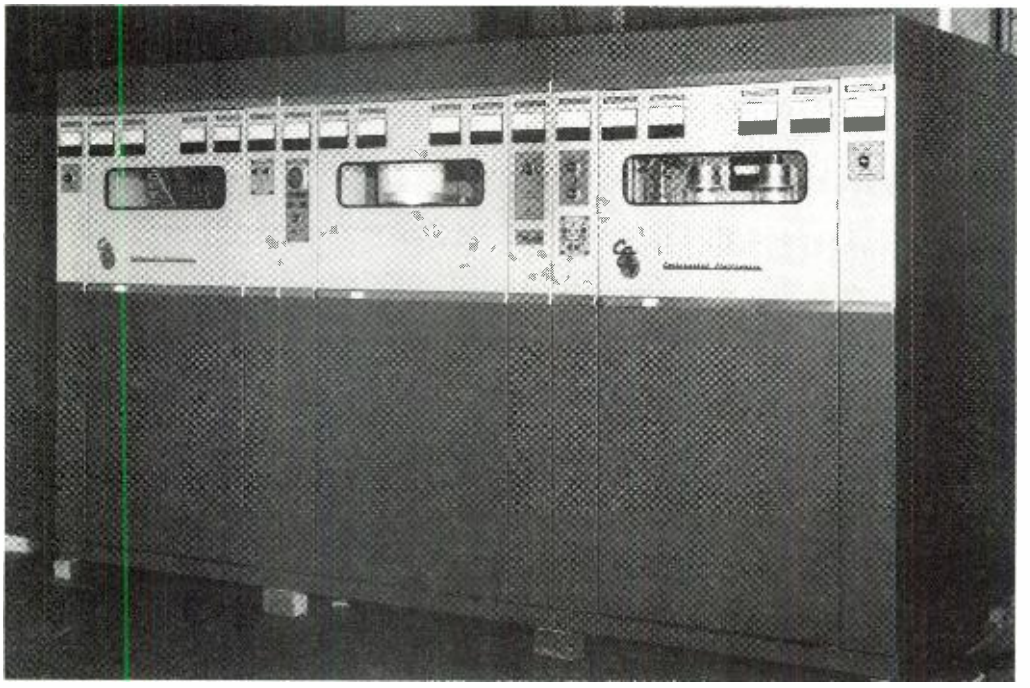


Fig. 33. Continental Electronics Model 317C-2.

3.2

AM Stereo Systems
An Overview

Edmund A. Williams
Staff Engineer
Department of Science and Technology
National Association of Broadcasters
Washington, DC

INTRODUCTION

The idea of stereophonic transmission on an AM broadcast station is not new or remarkable. While AM is an efficient mode of transmission providing the maximum amount of information in a minimum of spectrum, additional spectrum economies can be achieved which can be used for stereo information.

AM stereo was approved by the Federal Communications Commission in 1981 in a Report and Order which introduced a new concept in the process of selection of new broadcast transmission standards—selection by the "marketplace". Because no single system of the several offered by various manufacturers was approved by the Commission it was left to broadcasters to decide which system to implement. As a result neither AM broadcaster nor receiver manufacturer were willing make decisions on their own but instead preferred to wait for the other to act. This has caused the implementation of AM stereo to be delayed while each group carefully tests the stereo waters. Proponents of AM stereo systems developed two distinctly different means of transmitting two audio channels on a single AM broadcast carrier. Both are capable of producing good high quality stereo sound and cause no significant increase in interference levels. Both are compatible with monophonic receivers. However, the two systems are not compatible with each other and require entirely different means to detect the signals. One approach is to independently modulate the two sidebands with the left (L) channel on one sideband and the right (R) channel on the other sideband. The second is to modulate the main AM carrier with the sum (L + R) information and to use any one of several variations of quadrature or phase modulation for the difference (L-R) audio channel. Best receiving performance will be achieved by designing the detector to a specific modulation format. However, a single compromise detector may be used to produce adequate stereo performance from any of the quadrature or phase modulation techniques. As a result receiver designs will evolve around one or two detection methods while broadcasters will select between four and five transmission systems.

The two forms of modulation for AM stereo each have distinct advantages and disadvantages as described by the proponents in the following chapter. Each AM station, in addition to deciding to make the transition to stereophonic transmission, must also decide upon which of the several transmission systems to employ. This decision will be based on economic as well as technical factors. Obviously the cost of modifying existing transmission facilities for stereo will weigh heavily for the lowest cost system. However, the technical aspects of selecting an AM stereo system must necessarily include the range of the station, the nature of the programming, proliferation of

receivers able to detect the transmissions, the ability of the manufacturer to support the equipment and, of course, the technical quality of the signal itself. Other factors, such as sensitivity to transmitter and antenna system tuning tolerances, ease of conducting a "proof", compatibility with directional antenna systems and general maintenance must also be considered when selecting the transmission system.

It is not the intent of this chapter to add confusion to the selection process by interjecting too many selection criteria into that process. Rather, it is to point out the fact that broadcasting is no longer simple AM and FM. Technological advances in communication during the past two decades have proven that there may not be a single "best" system for anything in the future. Instead there will be more emphasis on permitting the marketplace to have a hand in the process in addition to the need for broadcasters to adopt new transmission modes according to their business instincts. The marketplace will react by adapting to the new transmission systems either by accommodating several with automatic receiver switching or evolving toward the lower cost or higher quality system. The broadcaster will influence the process by selecting and advocating, at the earliest opportunity, the approach which will provide the greatest benefit to the audience.

The marketplace approach to the selection of AM stereo is a clear indication of trends broadcasting will take in the future. The extent to which broadcasters lead the way will determine the direction of the trend of that marketplace.

3.2

AM Stereo Systems

Motorola C-Quam AM Stereo System

Chris Payne
Motorola Corporation
Schaumburg, Illinois

Many attempts have been made to develop an AM stereo system using quadrature modulation. However, the basic problem with quadrature systems has always been monaural compatibility; that is, high levels of distortion in typical AM receivers. Previous attempts to solve the incompatibility problem have resulted in poor coverage, reduced stereophonic information, poor separation, or a combination of these ill effects. The Motorola C-Quam (Compatible Quadrature) system solves the usual incompatibility problem without incurring losses in range, separation, or distortion.

AUDIO PERFORMANCE

The Motorola system is, in concept, without flaws. This means that the theory tells us that the system is capable of zero distortion, infinite frequency response, and infinite separation. In practice, the performance is limited primarily by the fidelity of the broadcast transmitter and receiver. In the laboratory, frequency response of 20 Hz to 15 kHz, separation of more than 40 dB and distortions of less than 0.3 percent, have been readily attained. In the field, performance has exceeded FM stereo proofs and won the support of major receiver manufacturers.

AUDIO PROCESSING AND PREEMPHASIS

Actual broadcasting experience with the Motorola system has proven that high degrees of audio processing and preemphasis may be used without difficulty. Stations, in fact, report that the received monophonic sound is as good or better when operating with Motorola AM Stereo as with previous monophonic operation.

SPECTRUM

The Motorola AM Stereo system, when operating with typical state-of-the-art audio processing equipment with preemphasis, occupies essentially the same spectrum as does a monophonic station with the same processing. The Motorola exciter has been FCC-type accepted for broadcast use, without any special stereo filter restrictions.

THE C-QUAM TRANSMITTER

The C-Quam transmitter is shown in Figure 1. Note that pure quadrature is generated by taking $L+R$ and $L-R$ and modulating two balanced

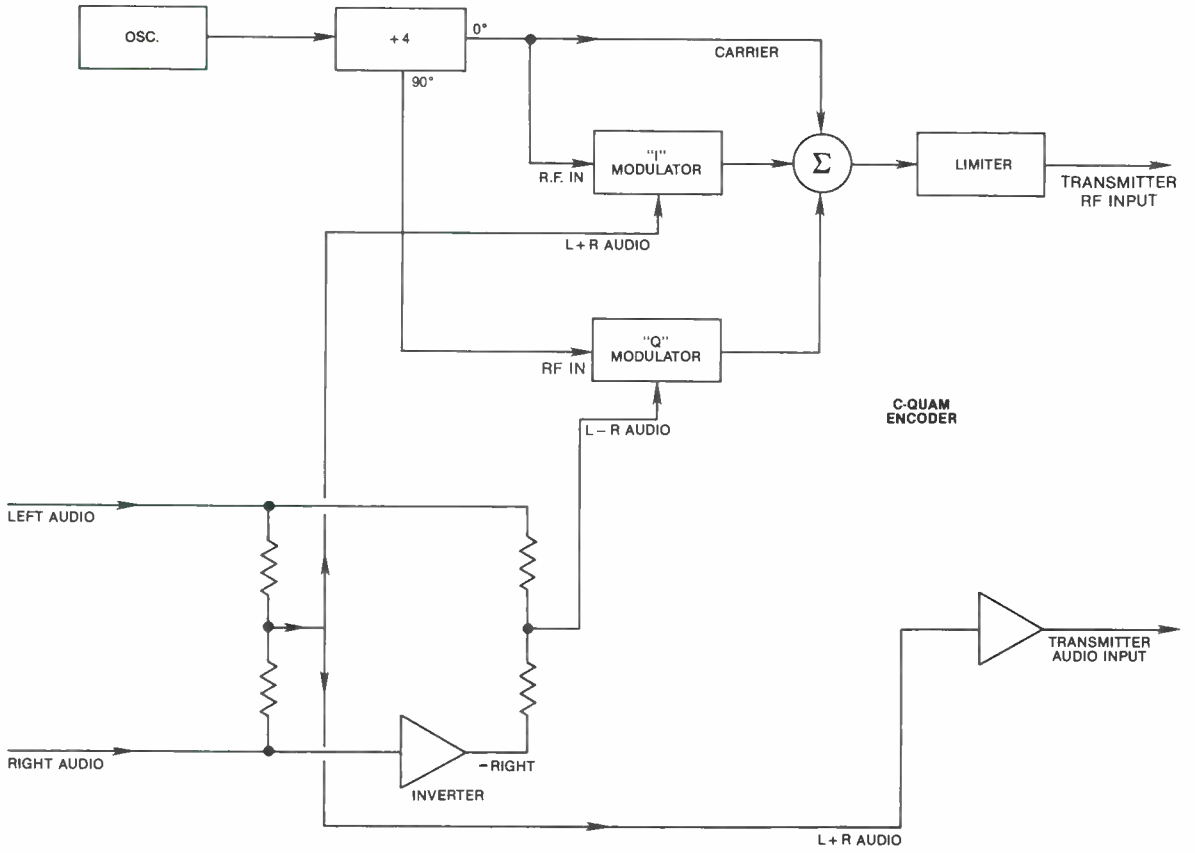


Fig. 1. C-Quam transmitter.

modulators fed with RF signals out of phase by 90 degrees. In this case the 90 degrees phase shift is derived by using a Johnson counter which divides an input frequency (four times station carrier frequency) by four and automatically provides digital signals precisely 90 degrees out of phase for the balanced modulators. The carrier is inserted directly from the Johnson counter. At the output of the summing network, the result is a pure quadrature AM stereo signal. From there it is passed through a limiter which strips the incompatible AM components from the signal. The output of the limiter is amplified and sent to the broadcast transmitter in place of the crystal oscillator.

The left and right audio signals are precisely added and sent as normal and compatible $L+R$ to the audio input terminals of the broadcast transmitter. That's the Motorola C-Quam encoder.

DECODING C-QUAM

C-Quam is decoded by simply converting the broadcast signal (which is already close to a quadrature signal) to pure quadrature and then using a quadrature detector to extract and $L-R$. Refer to Figure 2. Note that the demodulator contains a section which is a pure quadrature demodulator. In order to prepare the received signal for the quadrature demodulator, it has to be converted from the envelope detector compatible signal that is broadcast to the original quadrature signal that was not envelope detector compatible. This is done by demodulating the broadcast signal two ways; with an envelope detector, and with an "I" detector. The two signals are compared and the resultant error signal is used to gain modulate the input of the "I" and "Q" demodulators.

When the transmitted signal is $L+R$ (monaural, no stereo) the transmitted signal is pure AM or only "I" sidebands. In this case the envelope detector and the "I" demodulator see the same thing. There is no error signal, the input modulator does nothing and the signal passes through without change. However, when a left or right only signal is transmitted, both AM and PM is transmitted and the input signal is shifted in phase to the "I" demodulator and loses some of its "I" amplitude. The envelope detector sees no difference in the AM because of the phase modulation, and when the envelope detector and

the "I" demodulator are compared, there is an error signal. The error signal pushes up the input level to the detector. This makes the input signal to the "I" and "Q" demodulators look like a pure quadrature signal and the audio output gives a perfect and $L-R$ signal. The demodulator output is combined with the envelope detector output in a matrix to give left and right audio out.

SYSTEM PERFORMANCE UNDER HEAVY MODULATION

There are many advantages of the Motorola system. One is its performance under 100 percent negative amplitude modulation conditions. When the carrier momontarily goes to zero, as in 100 percent negative modulation, the output of the envelope detector becomes zero. Because of the action of the comparator and inverse modulator, the output of the "I" demodulator goes to zero. Simultaneously, therefore, the output of the "Q" demodulator also is forced to go to zero. This means that there will be no severe noise or interference popping from the stereo channel under 100 percent negative amplitude modulation.

THEORETICAL AUDIO PERFORMANCE

There is no theoretical limit to the audio frequency response, to the lower limit of distortion or to the separation of the Motorola system. All of these characteristics are primarily limited by the performance of the encoder, AM transmitter, and modulation monitor or receiver. The only other limit would be due to the bandwidth of emissions under stereo modulation conditions with single tone modulations above 7500 Hz. It is theoretically possible to force the system with tone modulations, to exceed the FCC bandwidth limits permitted for AM stations by a few dB. However, under the most heavily processed and preemphasized stereo program conditions, the emissions are well below FCC requirements for bandwidth.

ACTUAL STEREO PERFORMANCE

The actual measured performance of the Motorola system connected to a typical plate modulated AM broadcast transmitter is excellent, nearly that of FM stereo. The frequency response of left or right only transmissions is basically the

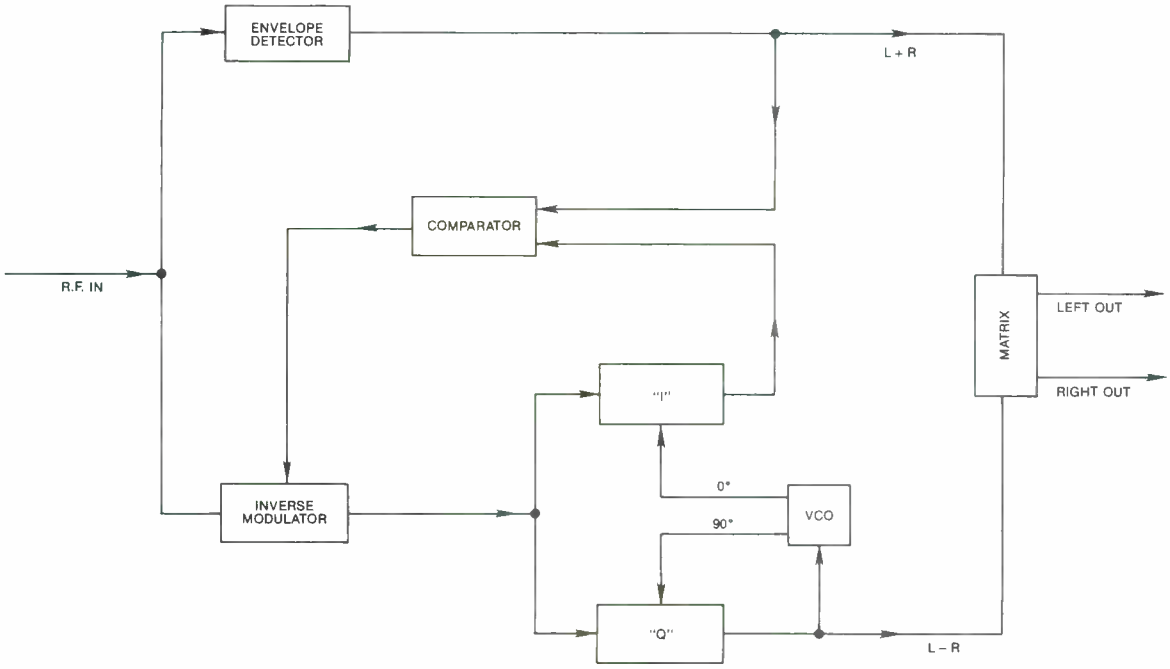


Fig. 2. C-Quam decoder.

same as the AM response of the transmitter. (In the case of tests made at WIRE in Indianapolis, about 1 dB down from 30 Hz to 12 kHz). The separation was held to better than 30 dB from 100 Hz to 7.5 kHz and within 20 dB from 50 to 10 kHz. Distortion of the left or right only transmissions were below 1.5 percent from about 80 Hz to 7.5 kHz. This data is taken from actual measurements made from an AM stereo modulations monitor.

RECEIVER AUDIO AND COVERAGE

Because the Motorola AM Stereo system acts like a full quadrature system under normal stereo conditions, its signal to noise characteristics are excellent. Under typical stereo programming, the increase in noise is estimated to be about 1.5 dB which is nearly imperceptible. In other words, the stereo coverage of the Motorola system is essentially the same as the monaural AM coverage.

The audio fidelity that can be expected from AM stereo radios depends upon the receiver design. In the past, receiver manufacturers were generally not willing to make AM radios with better fidelity because they felt that there was no demand for such equipment. With AM stereo, the ability to offer "stereo" means a much more attractive product which will allow a high price. Therefore, the AM stereo radio designer will have a much wider latitude in designing the receiver selectively and will be more able to achieve higher fidelity while holding down the susceptibility to adjacent channel interference. With slightly more expensive IF selectivity, the receiver designer can obtain audio response well beyond 5 kHz while still rejecting the adjacent channel interference. Two bandwith receivers, variable bandwidth receivers, and fixed bandwidth receivers to 7 kHz may be excepted for AM stereo.

CONCLUSION

The Motorola AM Stereo system is the system designed to meet the needs of AM radio. In other words, designed to perform well yet to be received inexpensively so that millions of radio listeners can enjoy AM stereo. While the design is adaptable for cost effective radios, it is also the best overall technical performer for the broadcaster because it is capable of FM-like audio performance with full amplitude modulation capability and stereo coverage essentially the same as monaural coverage.

3.2

AM Stereo Systems

The Harris Linear AM Stereo System

David Hershberger
Harris Corporation
Quincy, Illinois

INTRODUCTION

Harris promotes linear quadrature modulation and synchronous detection for AM stereo. Although envelope detectors produce some distortion when receiving linear quadrature modulation, the distortion is almost entirely second harmonic, which is seldom audible and not objectionable. The Harris AM stereo sytsem incorporates special patent pending audio processing techniques which ensure that envelope detector distortion will not be objectionable to the listener. Major broadcasters using the Harris linear system are very pleased with both stereo performance and monophonic compatibility.

AM stereo can appear deceptively simple to the casual investigator. Although amplitude modulation is a "low-technology" mode, AM stereo, and especially the selection of an AM stereo standard, is a complex issue requiring special insight. First impressions are usually wrong in AM stereo.

A thorough investigation of AM stereo, including a fundamental evaluation of compatibility, will show that linear systems are best suited for AM stereo.

The primary reason for AM stereo is to allow AM stations to compete more effectively with FM by improving the technical quality of the AM service. Although AM does have a higher noise level than FM, the audio quality limitation is primarily due to poor radios. Most AM stations transmit audio to beyond 10 kHz, but most radios have a frequency response of only 2 to 3 kHz. Virtually all radios use the antiquated envelope (diode) detector to recover modulation. Envelope detectors are inherently prone to the production of various types of distortion and other undesireable effects. AM radios can be vastly improved by extending the bandwidth for better frequency response, and by replacing the envelope detector with a synchronous detector for reduced distortion.

NONLINEAR SYSTEMS

A linear system is one in which superposition applies; that is, the system response to several inputs applied simultaneously is the same as the sum of the system responses when the inputs are applied individually. A nonlinear system is one in which superposition does not apply.

Proponents of nonlinear modulation use it in an attempt to obtain compatibility with envelope detectors. If receiver bandwidth were infinite, there would be perfect compatibility.

One way of analyzing nonlinear modulation is as a predistorted system. Because the envelope detector is also a nonlinear device, nonlinear systems must predistort the upper and lower sidebands of an AM stereo signal in order to force the envelope to be $L+R$.

This is equivalent to transmitting distortion 180 degrees out of phase with the distortion the

envelope detector generates. Although such a signal is perfectly compatible with envelope detectors, it is unfortunately incompatible with another circuit found in all AM radios: the bandpass filter.

It can be shown that nonlinear systems have an infinite number of sidebands, and in practice three or four orders of these sidebands are significant. The high order or predistortion sidebands must all be present at the receiver's detector for proper operation and compatibility. But by the time a nonlinear AM stereo signal passes through the IF bandpass filter of a typical narrow bandwidth radio, the relative amplitude and phase relationships of the required predistortion sidebands may be altered such that distortion is unacceptable, even though the radio may be correctly center-tuned. Truncation of the spectrum by the bandpass filter's amplitude characteristic, and phase distortion caused by the filter's group delay characteristic, will cause the predistortion sidebands to arrive at the wrong amplitude and at the wrong time to "cancel" the envelope detector distortion.

There are two significant types of compatibility distortion with nonlinear systems: harmonic distortion and difference tone intermodulation distortion. Of the two, the difference tone distortion is more objectionable to listeners.

It may be argued that these types of distortion are of little significance since program material generally contains little high frequency energy. That argument, however, is invalid because of the general use of preemphasis on AM. To partially compensate for the limited frequency response of AM radios, most AM broadcasters boost the higher modulating frequencies. Since the improvement in received signal quality can be quite dramatic, broadcasters will be unwilling to sacrifice the use of preemphasis.

Preemphasis, which frequently boosts the higher frequencies as much as 20 to 30 dB, severely aggravates the filtering-related compatibility problem of nonlinear signals.

LINEAR SYSTEMS

Linear systems are those for which superposition applies. Two important characteristics of linear systems are:

1. Only one set of sidebands is produced—bandwidth is the same as mono.
2. Linear product detection is both $L+R$ and $L-R$ channels means that there is no "noise burst" problem whatever.

Linear quadrature modulation is simply expressed as:

$$S(t) = [\,1 + L(t) + R(t)\,]\sin(wt) + [\,L(t) - R(t)\,]\cos(wt) \quad [1]$$

Where:

$S(t)$ = stereo AM signal
$L(t)$ = left channel modulating signal
$R(t)$ = right channel modulating signal
w = carrier (radian) frequency
t = time

The stereo signal consists of a monophonic sum signal (the sine term) with the linear addition of a double sideband suppressed carrier left minus right signal in quadrature with the carrier (the cosine term). Since both signals (sine and cosine terms) have only one set of sidebands, and since addition is a linear process, the resulting stereo signal also has only one set of sidebands—no new frequencies are created by adding the two signal components.

Linear quadrature modulation is highly desirable for AM stereo broadcast application because of its many advantages over nonlinear systems.

1. Same RF bandwidth as mono
2. No distortion from spectrum truncation
3. Compatible with preemphasis
4. Compatible with synchronous detection
5. Compatible with envelope detection (with audio processing)

Synchronous detectors, in turn offer the following advantages over envelope detectors:

1. No distortion due to receiver mistuning
2. No distortion due to selection fading or AM multipath
3. No distortion from directional transmitting antennas (far-field overmodulation)
4. No distortion from modulation overshoots
5. No distortion due to co-channel interference
6. No inherent cross modulation
7. Some reduction of impulse noise.

COMPATIBILITY WITH HUMAN HEARING

Compatibility is without doubt the most complex AM stereo requirement. To determine the extent to which a system is compatible, it is necessary to evaluate the end result, which is the listenability of a system on a narrowband envelope detector radio, transmitting real program material to real human beings. The final test of compatibility comes when the radio station transmitting AM stereo goes into its ratings period.

Other tests, such as transmitting tones through wideband envelope detectors to instruments, while valuable in the quantitative sense, are not necessarily measurements of compatibility with human hearing.

It is in the determination of compatibility that errors in system evaluation are most likely to be made. If compatibility is not thoroughly investigated, it is very likely that one could conclude that a compatible system should be rejected in favor of another system that is actually incompatible with existing radios.

When defining compatibility, one's first impulse would be to state that a compatible system should have low distortion. Distortion usually is taken to mean total harmonic distortion or THD. This is the pitfall to be avoided—a simplistic view of distortion.

The point is this: the criteria for the evaluation of distortion should accurately represent the sensitivities of the human ear. For example, second harmonic distortion is only objectionable when very large. On the other hand, difference tone intermodulation distortion is quite objectionable to the ear and should weigh heavily in any system evaluation.

Linear systems have excellent potential in every area except one: there is an apparent lack of compatibility with envelope detectors. The envelope of eq. [1] is:

$$e(t) = ([1 + L(t) + R(t)]^2 + [L(t) - R(t)]^2)^{1/2}$$

Which is a distorted version of the desired signal, $1 + L(t) + R(t)$. If a simple total harmonic distortion (THD) calculation or measurement were made, the value would appear to be too high. For example, envelope THD values for several single channel modulation levels are given in Table 1.

TABLE 1. Envelope distortion vs. single channel modulation.

Left Channel Modulation	THD
75%	28.9%
50	16.1
25	6.7

But what simple THD values do not convey is that the distortion is primarily second harmonic, which makes the distortion relatively innocuous.

Second harmonic is the least objectionable of the harmonics. In general, even-order harmonics, such as second, fourth, sixth, etc., are less objectionable than odd-order harmonics such as third, fifth, seventh, etc. Furthermore, the lower the order of the harmonic, the less objectionable than is, say eleventh harmonic.

These general characteristics of human hearing are in turn due to the physiology of the ear/brain combination, and how we hear sounds. The ear, for instance, has a large amount of second harmonic built in. If two flutes are played at moderate volume, the ear will create a third tone due to the difference in frequencies between the two flutes. In fact, some pieces of music take advantage of the phantom difference tone created by the ear. Several Telemann flute sonatas created a difference tone part which harmonizes with the "real" parts. A more familiar example of music with a third part created by the ear is "Yankee Doodle."

In fact, there is some indication that second harmonic distortion is in some instances actually desirable. One example is a popular piece of studio equipment which is essentially a second harmonic generator. This unit is widely used by recording studios to process music for increased appeal.

The addition of second harmonic, instead of sounding "distorted," sounds like increased treble response. While conventional "equalization" or high frequency boost also increases the noise, artifical highs from a second harmonic generator will not boost the noise. In summary, adding second harmonic sounds basically like treble boost, but without a background hiss boost.

CONTROLLED—COMPATIBILITY LINEAR QUADRATURE

It has been the finding of Harris and other investigators that linear quadrature modulation is "almost compatible." If something minor could be done to obtain compatibility without sacrificing the linearity of the system, then a truly superior AM stereo system would be feasible.

Harris has developed a special audio processing technique which ensures compatibility with envelope detectors, while not significantly affecting the stereo signal. The audio processing (compatibility control) works by determining the distortion which would occur in an envelope detector; when the envelope distortion exceeds an acceptable level, single channel negative modulation constraints are reduced. Normally, single channel left or right signals are allowed to modulate up to +80% and −80%. When envelope detectors produce excessive distortion, the negative modulation constraint for single channel signals is reduced from 80% to something less; typically −70% or −60%. The negative constraint is reduced until the envelope detector distortion is within acceptable limits.

A block diagram of the AM stereo signal generator is shown in Fig. 1.

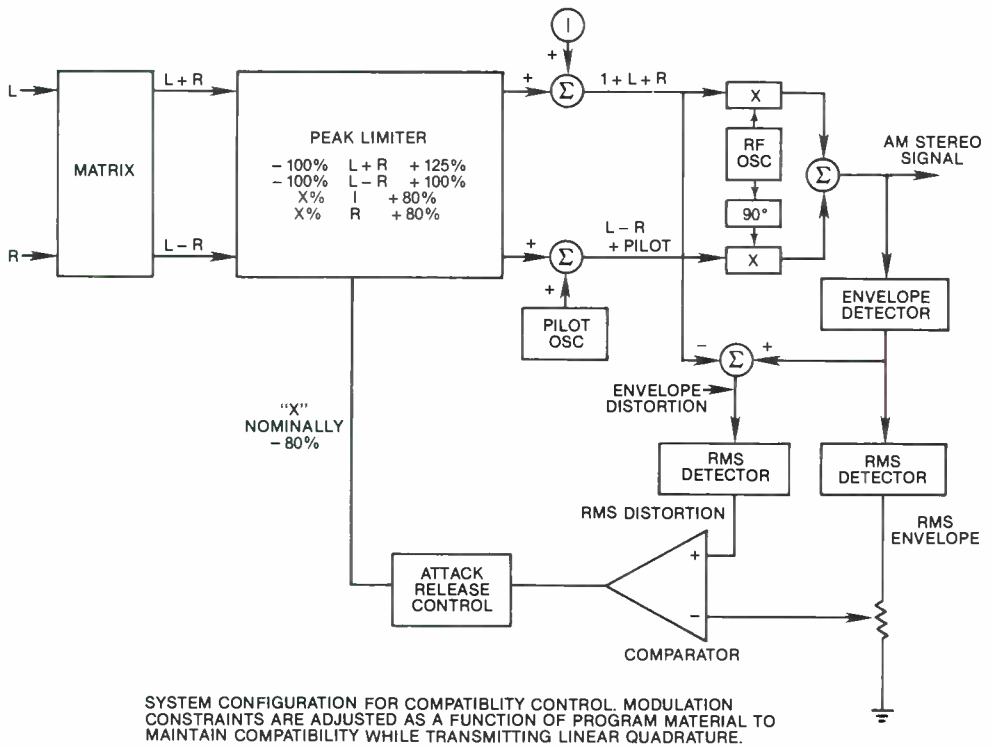


Fig. 1. Block diagram of the AM stereo signal generator.

The time constant associated with the compatibility control processor is somewhat slow, in the hundreds of milliseconds. The deliberately slow time constant reflects the design philosophy of having a system which is designed for the human ear rather than for the sake of instrumentation. In order for the ear to detect low orders of distortion (such as second order), the distortion must be present for some time. Unlike crossover distortion, for example, which can be detected immediately, quadrature envelope distortion must be present for several hundred milliseconds before it is detectable. Accordingly, the audio processing, whose purpose it is to model the ear, is made to have a similarly slow time constant.

Broadcasters using the Harris linear quadrature system for AM stereo are unanimous in finding both excellent stereo performance and good quality compatible reception on monophonic radios. The "bottom-line" proof of the system's compatibility lies in the ability to satisfy program directors, and in station market share ratings.

CONCLUSION

Linear quadrature modulation is very appealing for application in AM stereo. Many early attempts at using quadrature modulation compromised the benefits of the system. Some systems simply reduced the amplitude of the $L-R$ channel, thereby incurring a signal-to-noise ratio penalty. Other systems sacrificed to be $1+L+R$. These nonlinear systems occupy excessive bandwidth, and in spite of the fact that the transmitted envelope is $1+L+R$, radio IF bandpass filtering causes the nonlinear system to generate distortion at the radio's envelope detector. Nonlinear systems, in the final analysis, have serious compatibility problems.

The supposed "incompatibility" of linear quadrature modulation is not a real problem. When human beings are used to determine compatibility, minor audio processing makes the use of linear quadrature modulation an ideal solution to the AM stereo problem.

Broadcasters using the Harris linear system are pleased with both stereo and mono performance, while broadcasters using nonlinear systems often voice dissatisfaction with monophonic compatibility, especially when preemphasis is used.

The use of linear quadrature modulation will encourage the development and marketing of long-overdue improvements to the AM sections of radios: synchronous detection and wider IF bandwidths, for less distortion and wider frequency response. These improvements and the use of linear quadrature modulation are most consistent with the goals of the AM broadcaster and the consumer: to make AM stereo sound competitive with FM stereo.

3.2

AM Stereo Systems

AM Stereo System Transmission and Reception

Leonard R. Kahn
Kahn Communications, Inc.
Garden City, New York

The AM Stereo system proposed by Kahn Communications and the Hazeltine Corporation is an Independent Sideband System wherein the lower sideband represents the right stereo channel. Thus, this system is essentially a frequency separation system as distinguished from the other major systems which are essentially phase separation systems in that the stereo separation is achieved by detecting the phase difference of stereo components.

It is the author's belief that this distinction; i.e., frequency separation vs phase separation, is the basis for the differences in performance of the systems especially under adverse conditions such as co-channel and adjacent channel interference, multipath conditions such as skywave/ground wave interference, sensitivity to transmitting and receiving antennas, and capability of using advanced receiver technology such as Asymmetrical Sideband Selectivity.

While the means for generating an ISB wave is, for the block shown below, phase sensitive, nevertheless, once the independent sideband wave is generated stereo separation is insensitive to phase as the wave is passed through the transmitting antenna, the propagation path, the receiving antenna, the receiver's IF and RF circuits, and the input circuit feeding the stereo demodulator.

TRANSMITTING EQUIPMENT

Please see Fig. 1 which is a simplified block diagram of the type of AM Stereo generator used in the STR-77 unit. The left and right inputs are summed and fed through a constant amplitude, phase difference network. The output of this network feeds an audio frequency amplifier which produces an output suitable for modulating conventional AM transmitters.

The difference between the L and R components is fed to a companion phase difference network which assures a quadrature relationship between the output of the sum circuit and the difference circuit. This output is then fed to a phase modulator. The resulting phase modulated wave is frequency translated to the carrier frequency of the station. An RF amplifier is used to raise the level to 3 watts, sufficient for exciting most AM transmitters. This phase modulated wave is then envelope modulated in the station's transmitter to produce an independent sideband wave wherein the lower sideband carries the left information and the upper sideband carries the right information.

In a practical configuration, circuitry is provided for insuring proper time delay so that the AM and PM components arrive at the transmitter's modulated stage coincidentally. Additional

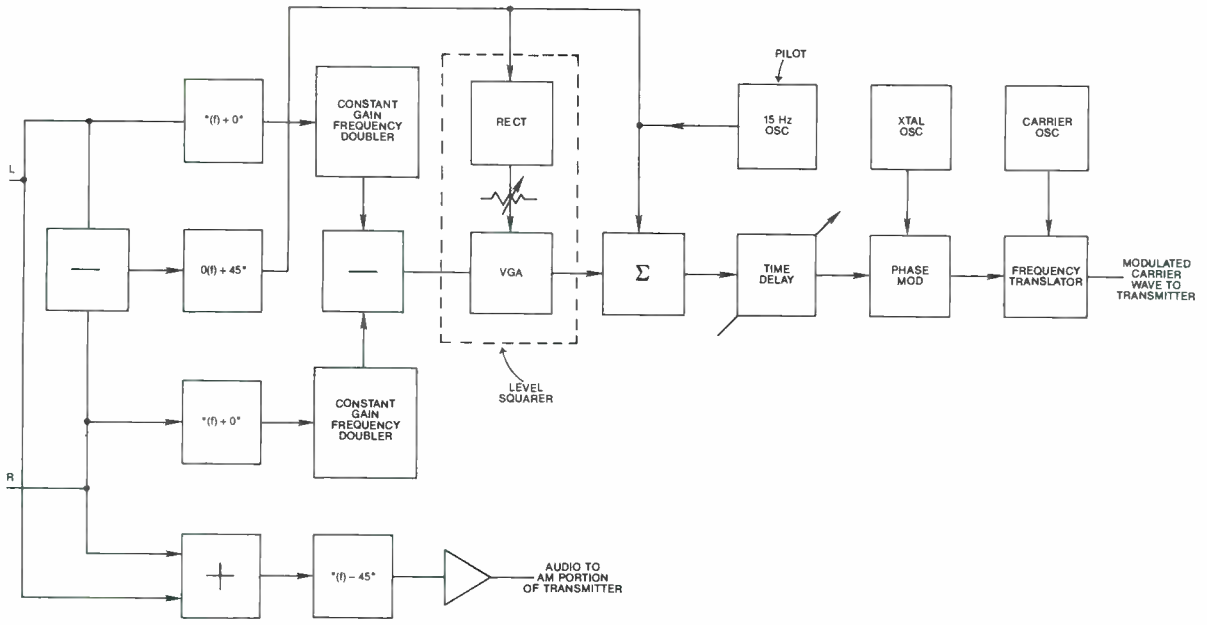


Fig. 1. Single side band AM stereo system.

circuitry is shown in Fig. 1 for producing a second order $L-R$ wave component which is added to the fundamental $L-R$ audio wave fed to the phase modulator. This second order component minimizes bandwidth and allows low distortion reception.

Fig. 2 shows a simplified phasor sketch showing how the first order sideband components line up so that the lower sideband represents the left stereo information and the upper sideband represents the right stereo information. The following equation is a descriptive equation of the modulated wave:

$$e_s = E_c \left[1 + m_L L(t) e^{J\pi/4} + m_R R(t) e^{J\pi/4} \right] \times \cos \left[w_c t + m_L L(t) e^{-J\pi/4} - m_R R(t) e^{-J\pi/4} - .532 \left[m_L (L(t))^2 - m_R (R(t))^2 \right] \times k/T \int_0^T |m_L L(t) - m_R R(t)| \, dt + \lambda \sin 2\pi 15t \right] \quad [1]$$

RECEIVER

Fig. 3 is a simplified block diagram of a receiver suitable for demodulating an independent sideband stereo wave. Details concerning the carrier track circuitry and the inverse modulation circuit is contained in the referenced patents and Hazeltine's report.*

ASYMMETRICAL SIDEBAND SELECTIVITY

The ideal receiver for the instant stereo system provides enhanced selectivity for adjacent channel interference by taking advantage of the fact that adjacent channel interference is naturally separated so that lower channel interference falls solely in the left stereo channel and higher channel interference falls in the right stereo channel. This natural characteristic is the basis for the "cocktail party effect" which causes interference to fall full to the right or full to the left edge of the stereo stage according to whether the interference is above or below the desired channel.

In contrast, phase separation systems produce interference in both the left and right channels, causing the interference to fall "on stage." The natural separation of the interference on one channel or the other in the present system also allows the use of a new form of selectivity which is called Asymmetrical Sideband Selectivity.

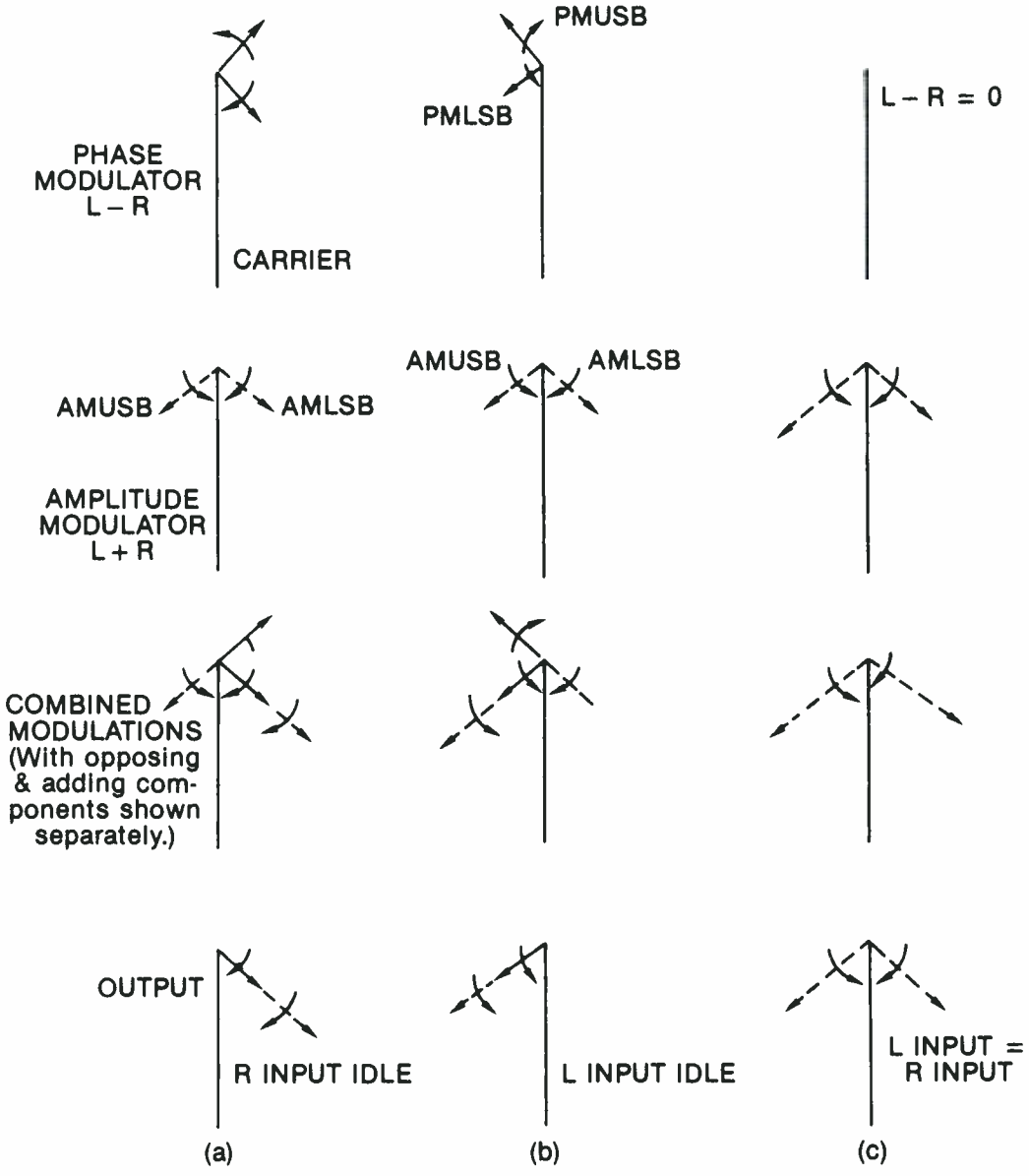


Fig. 2. Simplified phasor sketch.

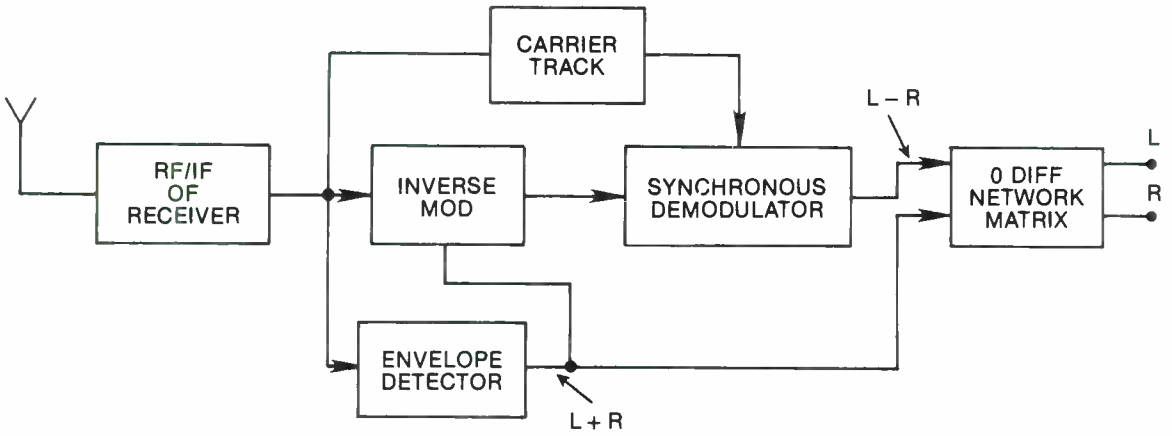


Fig. 3. Simplified block diagram of a receiver suitable for demodulating an independent sideband stereo wave.

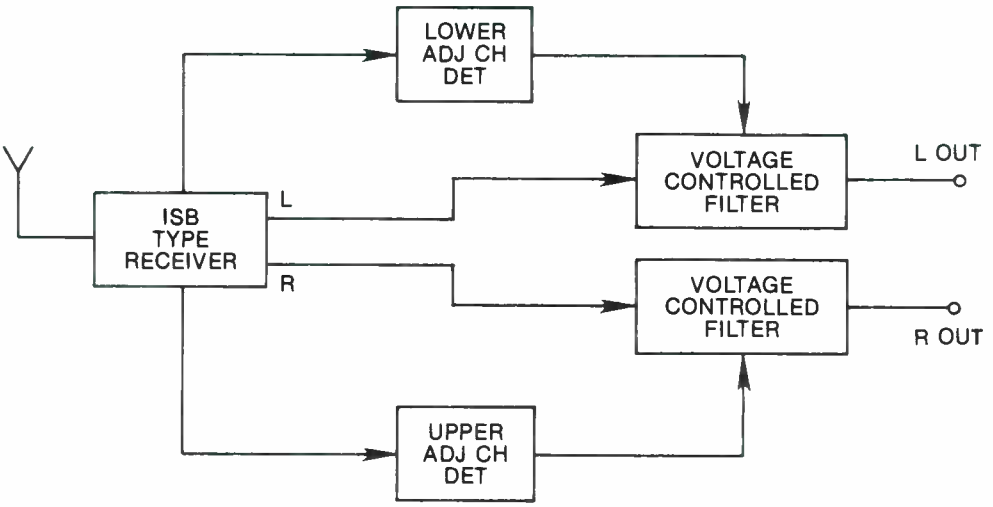


Fig. 4. Simplified block diagram of asymmetrical sideband selectivity.

(Please see Fig. 4 which is a simplified drawing of asymmetrical sideband selectivity.)†

It is noted that the interference above and below the desired channel is constantly monitored. Under low interference conditions, as would be expected when listening to the local stations or during daytime reception, the receiver's bandpass is wideband, providing high fidelity performance. When significant interference is detected, the channel with interference is automatically reduced in bandwidth, attenuating the offending adjacent channel interference.

Since under normal conditions the interference is not symmetrical the frequency response of the overall system is restricted by stereo channel (*L* or *R*) having the higher response because it has the least interference. However, there is a 6 dB step in the overall response because only one channel would have a 10 kHz signal level, for example. Thus, by use of the "mixed highs" concept the frequency response is degraded by much less drastic loss; i.e., 6 dB rather than say, 20 dB or more. This, of course, is substantially better response than would be the case if both channels were reduced in bandwidth symmetrically. It is important to note that this type of adaptive selectivity is also usable for monophonic reception of mono signals.

It is the author's opinion that this improvement in effective selectivity, since it can be implemented by use of newly developed** IC technology at very low cost, may well be the main advantage in implementing the ISB AM Stereo system and may have a major effect on the future growth of AM broadcasting.

---

*L.R. Kahn, U.S. Patent 4,018,994 dated April 19, 1977.
L.R. Kahn, U.S. Patent 3,973,203 dated April 3, 1976.
Hazeltine Research Inc., Note 1, April 5, 1982, "ISB AM Stereo Receiver Practices."

†L. R. Kahn, U.S. Patents 4,192,970 and 4,206,317.

**R.W. Broderson, P.R. Gray and D.A. Hodges, "MOS Switched-Capacitor Filters," PIEEE, vol. 67, pp. 61-75, January 1979.

3.2

AM Stereo Systems

BELAR AM Stereo System

Arno M. Meyer
BELAR Electronics Laboratory, Inc.
Devon, Pennsylvania

The Belar AM-FM System is a matrixed system which uses left and right channel audio material to form a sum signal ($L+R$) and a difference signal ($L-R$). The sum signal is applied to the amplitude modulation circuitry of a conventional AM transmitter, as currently done in monophonic broadcasting. Stereo ($L-R$) information is used to angularly modulate the AM carrier. The angular modulation has FM characteristics for low audio frequencies, and PM (phase modulation) characteristics for mid audio frequencies. The $L-R$ signal from the audio matrix circuit is applied to a pre-emphasis circuit. This FM-to-PM changeover is accomplished with a controlled preemphasis network. Preemphasis, combined with deemphasis in the receiver, serves to reduce the detected noise in the stereo signal; primarily for the low audio frequency range. The Belar system has a significant advantage over competing systems in this regard. Peak FM deviation of the lowest audio frequencies transmitted is 312.5 Hz or 6.25 radians at 50 Hz. Similarly, the phase modulation index of the highest audio frequencies is 0.85 radians/sec. The preemphasis network has a controlled time constant to limit deviation at high audio frequencies, which will limit the occupied bandwidth of the stereo signal. A 10 Hz tone with a deviation of 2 radians is used as an indicator for receivers of the transmission of a stereo signal.

The receiver is essentially a complementary system to the transmitter. A conventional diode detector detects the L + R signal in the envelope. A limited IF signal (free of AM modulation) is applied to an FM discriminator. An audio high-pass filter rejects the pilot tone. The deemphasis network is the complement of the preemphasis network in the transmitter. The L + R and L − R signals are applied to an audio matrix which produces the original left and right audio signals. The output of the discriminator is applied to a band-pass filter centered at 10 Hz so that most program material and noise is removed from around the pilot tone. The presence of a signal at the output of this filter triggers a stereo indication mechanism.

The use of transmitted preemphasis and a deemphasis receiver (as is done in the Belar system) will reduce the low frequency microphonic and tuning noise which occurs naturally in non-synthesized (and some synthesized) receivers. This is one of the significant advantages of the Belar systems, and is one of the reasons the Belar system received a #2 rating in the FCC original analysis (FCC "Further Notice").

3.2

AM Stereo Systems

AM Stereo and the PMX AM Stereo System

Robert D. Streeter, P.E.
Consultant for
N.A.P. Consumer Electronics Corp.
Knoxville, Tennessee

INTRODUCTION

The PMX AM STEREO broadcast system is based on simple fundamental technical concepts, yet it offers a high level of technical and operating performance. The broadcast signal uses frequency modulation for the stereo identification tone, linear phase modulation for the stereophonic content (the vector difference of the left and right audio channels), and conventional envelope modulation for the monaural content (the vector sum of the left and right audio channels). The system was initially selected as the USA standard, and achieved top scores in both technical analysis conducted by the Federal Communications Commission.

MATHEMATICS

The broadcast signal equation for the PMX AM Stereo system is:

$$[1 + (L(t)+R(t))] \sin [w_c t + (L(t)-R(t)) + B + P\sin(10\pi t + A)]$$

Where: $L(t)$ is the left channel audio signal
$R(t)$ is the right channel audio signal
$-1 < (L(t)+R(t)) < +1.25$ [am limits: -100% to $+125\%$]
$-1 < (L(t)-R(t)) < +1$ [pm limits: ± 1 radian]
w_c is the angular carrier frequency
B is an arbitrary phase constant
P is the pilot tone phase deviation [$3.0 < P > 3.6$]
A is an arbitrary phase constant
t is time

It should be noted that the pilot tone is actually a frequency modulated signal, although the single tone phase equivalent equation is given for simplicity. The generalized pilot tone phase equivalent equation would contain the integral of the frequency modulation input signal.

SYSTEM IMPLEMENTATION

A block diagram of the encoder and transmitting system is shown in Fig. 1. The audio processor is shown to emphasize the importance of correct processing to obtain the full capabilities of am stereo. Standard FM Stereo audio processing may allow as much as a 6 dB modulation and loudness loss in conventional monaural AM receivers. The processed audio is applied to the AM stereo exciter unit.

The processed left and right channels are matrixed in the stereo exciter unit to form the

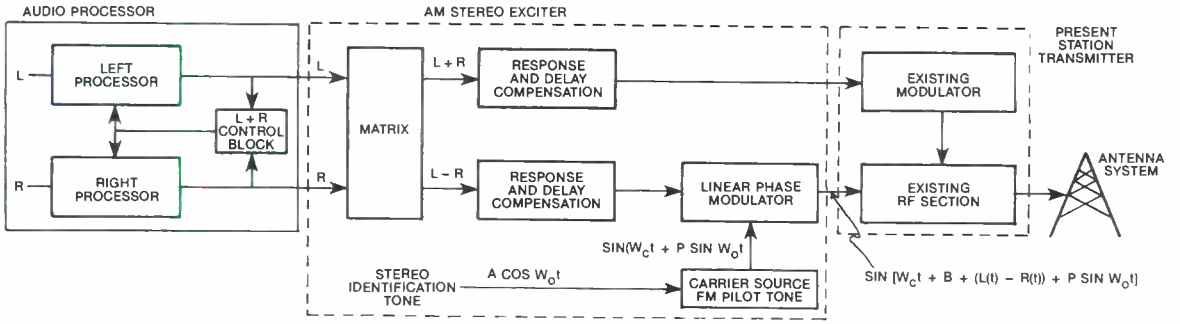


Fig. 1. AM/FM system block diagram.

L+R and L−R audio signals. The L+R and L−R signals are compensated for amplitude and time delay effects in the transmitter. The purpose of the compensation is to match the response of the amplitude and angular modulation channels, and to insure that the amplitude and angular modulation audio components will be broadcast at exactly the same instant from the antenna. This optimizes the receiver performance. The L−R audio signal is applied to a linear phase modulator, which varies the instantaneous phase of the transmitted RF signal at an audio rate. A peak phase deviation of 1 radian is used. The carrier signal is also frequency modulated by a sub-audio signal to generate a stereo identification tone. The stereo identification tone (pilot tone) deviates the carrier by about 17 Hz peak, at a 5 Hz rate. The pilot tone may also be a digital data signal (SCA), proving that the receiver will recognize it as a pilot signal. This AM SCA is provided now.

The stereo exciter supplies the RF signal to be transmitted. The master oscillator in the transmitter is disabled, and the exciter RF signal is substituted in its place. This RF signal contains the angular modulation of the pilot tone and the L−R audio signals. The RF signal is amplified in the transmitter to full power, and is amplitude modulated with the L+R audio signal from the exciter. For best stereo performance, the transmitter should have optimum monaural performance and have any extraneous angular modulation signals reduced or eliminated. No other changes to the transmitter are necessary.

Fig. 2 is a block diagram of the stereo receiver. It is the inverse process of the transmitter function. The received signal is envelope detected in the normal manner to recover the L+R audio signal. The stereo decoder detects the L−R audio signal by first reducing (or removing) the envelope modulation from the IF signal. The resultant signal is then linearly phase detected to obtain the audio L−R component. The pilot tone is also detected to provide an indication of a stereophonic transmission. The receiver operation can be made automatic if the pilot tone is used to control the operation of the receiver matrix circuits. Reception of the pilot tone would add the L−R audio to the matrix and provide stereo, while the absence of the pilot tone would provide just the L+R audio signal to the left and right audio channels.

The transmission and reception shown here is mathematically correct. That is, under ideal conditions there is no limit to the excellent fidelity, separation, and distortion performance of the system. Any performance less than perfect is due to the imperfections of the transmitting or receiving hardware.

It is impossible to detect stereo when the envelope is completely cut off (−100% modulation) for ANY stereo system. While such a signal can be transmitted easily, its detection would require the instantaneous recovery of the angular modulation signal when the signal has completely disappeared, an impossibility. All stereo systems either provide some form of receiver control to mask this impossible condition or restrict the transmitted signal so the condition will not occur (or both). The PMX system imposes a minimum of restrictions, and is capable of employing several types of receiver control.

ACTUAL SYSTEM PERFORMANCE

AM stereo hardware should be expected to operate with near perfection under laboratory conditions. The inability of the stereo exciter to produce high performance data with an ideal envelope modulator operating into a correct AM stereo detector is proof of an unacceptable stereo system. The performance data should always be obtained from a single stereo detecting device, since multiple devices (spectrum analyzer, separate single channel detectors, etc.) could result in adjustments that are not representative of the actual end performance obtainable. Multiple devices may be useful during adjustments, but are not a correct source of performance data.

Even more important than laboratory performance data is the performance that can be obtained with actual operating hardware. The data shown in Figs. 3, 4, 5, 6, 7, and 8 are graphs of the performance of the PMX system in use with a popular current transmitter. The stereo exciter used is a Continental Electronics 302A and the stereo monitor used is a Continental Electronics PMX-SM1. Fig. 9 is a block diagram of the equipment interconnection used for the data.

The 315R-1 used here was a stock transmitter with two new convenience features: the third harmonic resonator and neutralizing controls are made adjustable through the rear of the transmitter. This permits adjustment while the transmitter is in operation. It is necessary to obtain adequate RF drive power to the final amplifier, and this was done by maintaining the RF driver supply voltage above 190Vdc. The transmitter was operated into a dummy load, and was adjusted for maximum efficiency and minimum incidental phase modulation at the plate current minimum (plate dip). There was no special compensation, correction, or filtering used in the transmitter for stereo operation.

The AM stereo equipment was initially adjusted to provide optimum performance under ideal laboratory conditions using a high linearity envelope modulator in place of the AM transmitter. The ideal modulator was removed, and the 315R-1 connected in its place. The only adjustments made to the stereo system were the use of the correct time delay compensation value for the 315R-1 and the correct L + R signal level to the audio input on the 315R-1.

The data shown in these graphs reflects the performance of a current transmitter operating correctly without any additional corrections within the AM stereo system for the specific properties of the transmitter. Better performance can usually be obtained by compensating the stereo system for the envelope modulation properties of the transmitter.

All the data was taken at 85% main channel modulation, with the transmitter operating at 5 kW into a dummy load. Fig. 3 shows the envelope modulation performance (response and total harmonic distortion) as measured with an envelope detector. The noise floor was measured at −63.4 dB relative to 100%, or −62 dB relative to 85% modulation. Fig. 4 presents the same information for the L − R transmission channel, measured with a linear phase modulation detector. The low frequency rolloff allows the measurements to be made with the pilot tone present, as would be the case for an actual broadcast transmission.

Figs. 5 and 6 present the same information for the left and right channels respectively. It is significant to note that these measurements were made at 85% envelope modulation. This corresponds to 170% left (or right) channel modulation by FM stereo standards, and represents an operating stress level that some am stereo systems cannot withstand. Figs. 7 and 8 show the separation as measured with the 85% L + R (envelope)

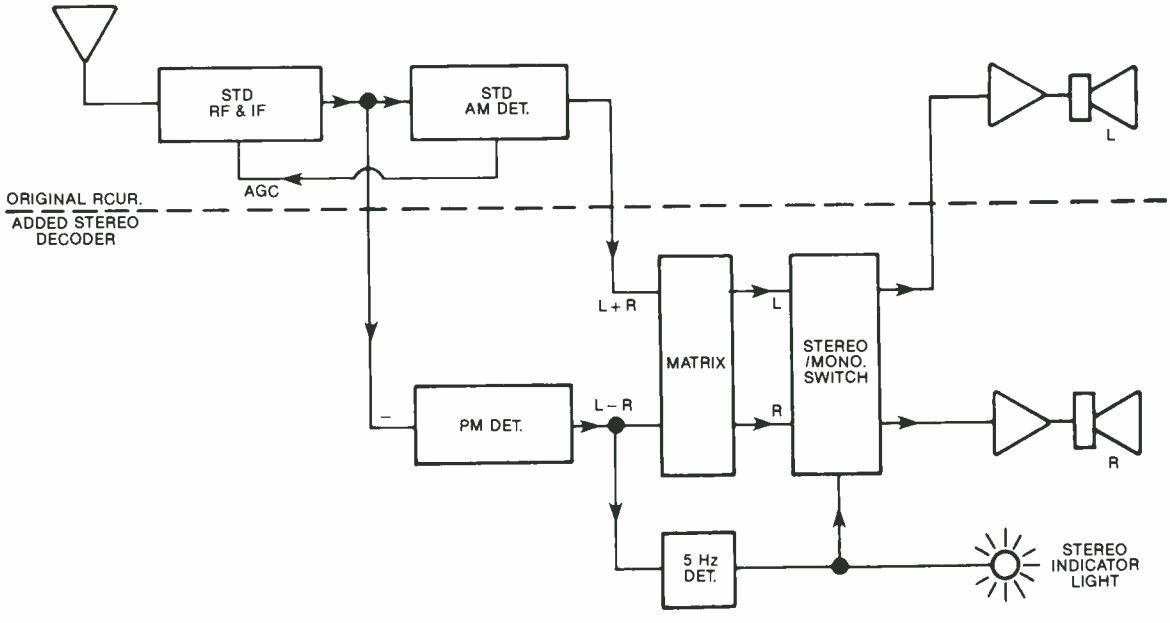


Fig. 2. Block diagram of the stereo receiver.

and L – R (phase) modulation levels used for the other stereo data.

MEASUREMENT METHODS AND TECHNIQUES

The above data presents an excellent indication of the actual performance that can be obtained with this system. The measurements are quite significant, but are not the only measurements significant to AM stereo transmissions.

The response and *THD* of an envelope detector for a left (and right) transmission will provide compatibility information, while an L – R transmission will provide cross-mode conversion (crosstalk) data. A L + R transmission with a L – R detection will measure the opposite cross-mode conversion, and is commonly used to evaluate the operating condition of the broadcast transmitter for AM stereo use. One of the most realistic tests of an AM stereo system is the simultaneous separate modulation of each channel with different test signals, as it simulates actual stereo programming conditions. It is important to evaluate both the left and right channels under the same conditions, as one channel can usually be "adjusted" for good performance at the expense of the performance in the opposite channel.

All AM stereo systems must have a common operating condition for the case where L = R, which is "center channel" stereo (which is identical to conventional monaural broadcasting). The differences between the AM stereo systems occur ONLY with stereo content in the signal, or L different than R.

OPERATING CHARACTERISTICS

Compatibility

The PMX system is perfectly compatible with conventional wideband envelope detectors. All am stereo systems have various degrees of imperfections with stereo using narrowband envelope detectors, as a result of crossmode conversions and RF filtering effects.

Coverage and Loudness

All stereo systems are equal with L = R modulation, and any differences are due to audio processing effects. With stereo program content, the ability to handle single channel modulation becomes important. The PMX system has no restrictions on single channel modulation, while all other active systems do. The PMX system offers the maximum available coverage and loudness because of this.

Occupied Bandwidth, Fidelity, Preemphasis, and Audio Processing

All of these items are interrelated, and must be considered together. Increased transmitted fidelity must result in increased occupied bandwidth for any system. The use of preemphasis must increase the high frequency sideband levels for any system. Audio processing effects will control the sideband density for any system. All systems are identical for the L = R condition, and any differences will be the result of the stereo content of the transmitted signal. The PMX system remains within the FCC occupied bandwidth restrictions without filtering for any reasonable operating condition, while providing full legal fidelity performance.

Synchronous Detection

All stereo systems operate correctly with synchronous detection for the L = R case. As the amount of stereo information increases, only a pure quadrature system retains maximum performance. Experience has shown that the PMX system delivers acceptable stereo performance with a synchronous detector, even though the system is not intended for such operation.

Soundfield Disturbances

Interference from co-channel and adjacent channel signals will influence the received signal characteristics, as will self-interference from reradiation. All stereo systems are affected by reradiation and the received audio signal will "move about" in a fashion that depends on each system. Adjacent channel interference will increase the effective modulation seen by the stereo detector, but the result will depend on the details of the detector operation as much as on the stereo system. There are differences in the co-channel interference performance, and the PMX system pilot tone tends to scramble the interfering phase structure and eliminate the undesired effects on the desired received stereo signal. The PMX system is thus relatively immune to co-channel interference.

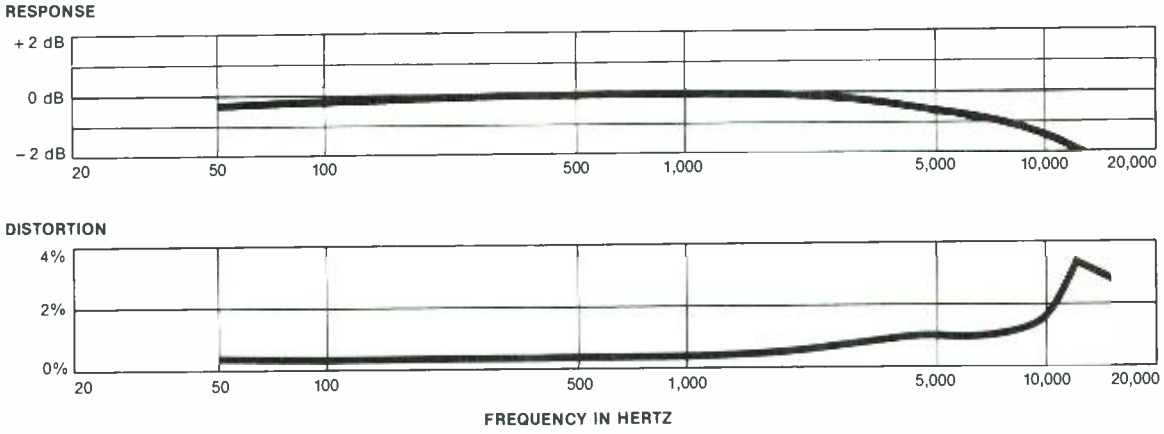


Fig. 3. L + R 85% envelope modulation. −62 dB noise floor/ref 85%. THD measured at constant envelope modulation 5 KW 315R-1 (828E-1) 1440 KHz.

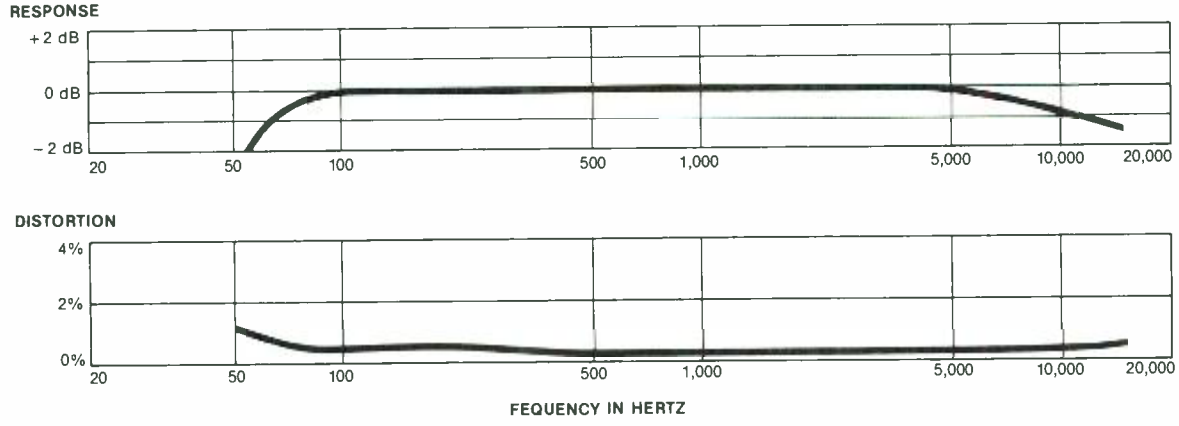


Fig. 4. L − R 85% modulation. −57 dB noise floor/85% modulation. Distortion measured at constant input due to L − R filtering in monitor 5 KS 315R−1.

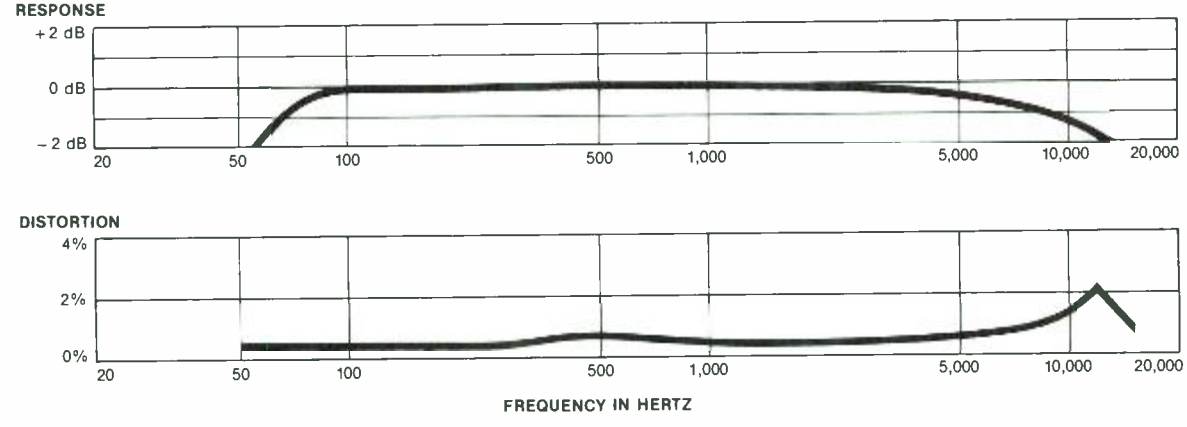


Fig. 5. Left channel 85% modulation (170% equiv. left mod). −60.5 dB noise floor/rel 85% modulation.

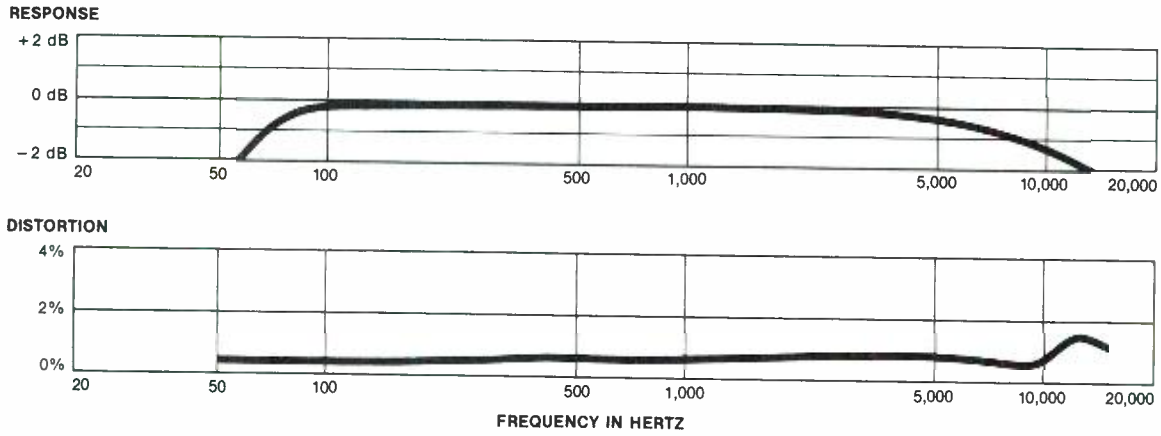


Fig. 6. Right channel 85% envelope modulation (170% equiv. right mod).

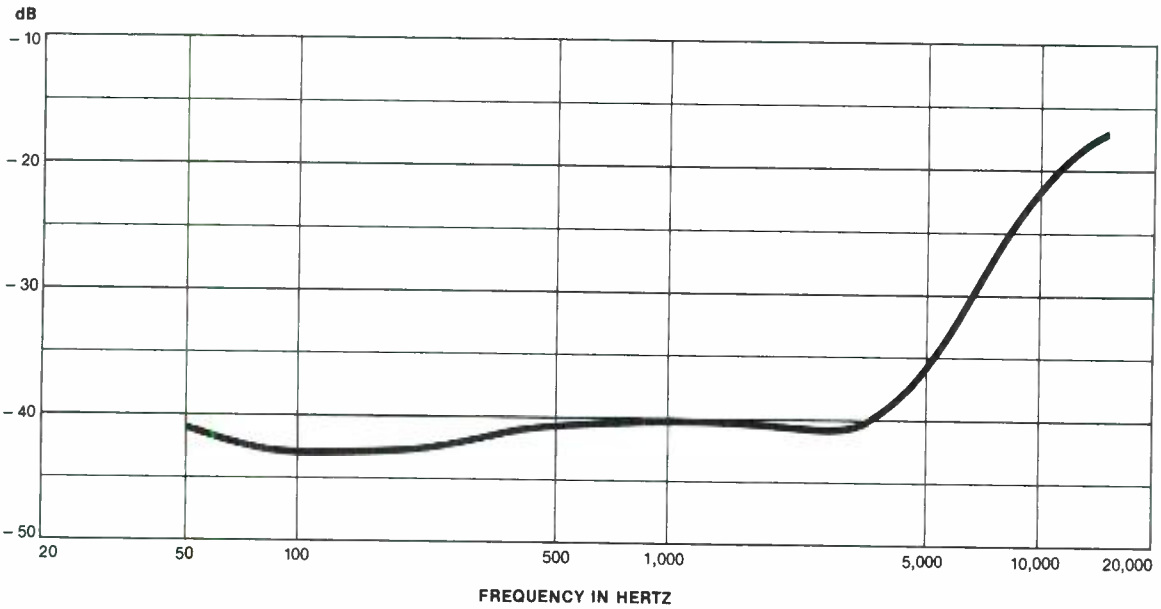


Fig. 7. Left channel detected, right channel transmitted at 85% envelope modulation (170% single channel).

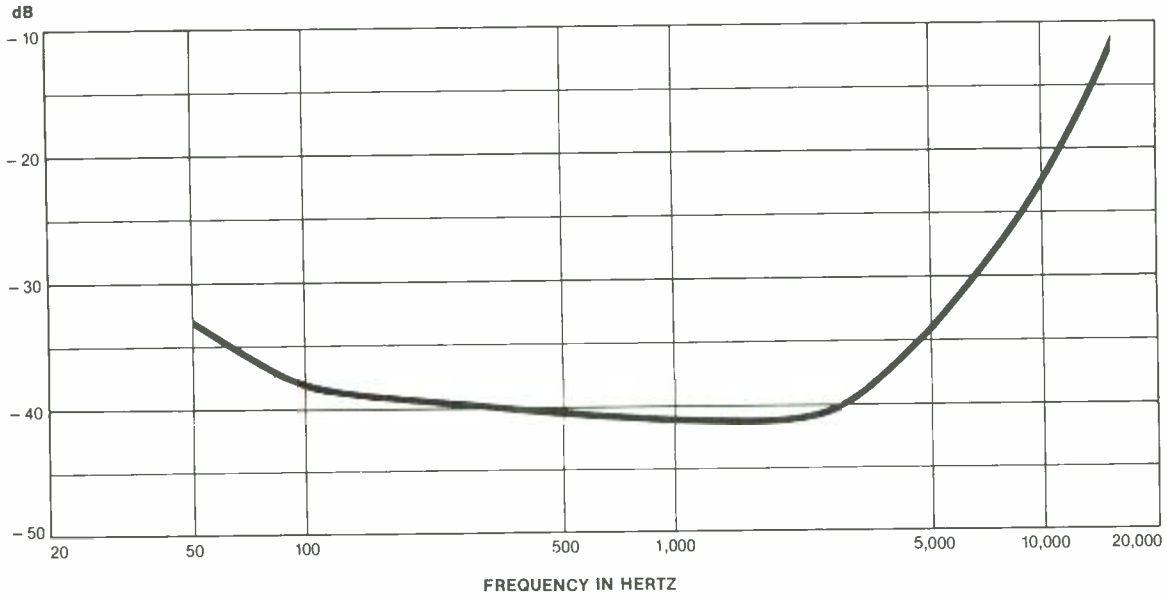


Fig. 8. Right channel detected, left channel transmitted at 85% envelope modulation (170% single channel).

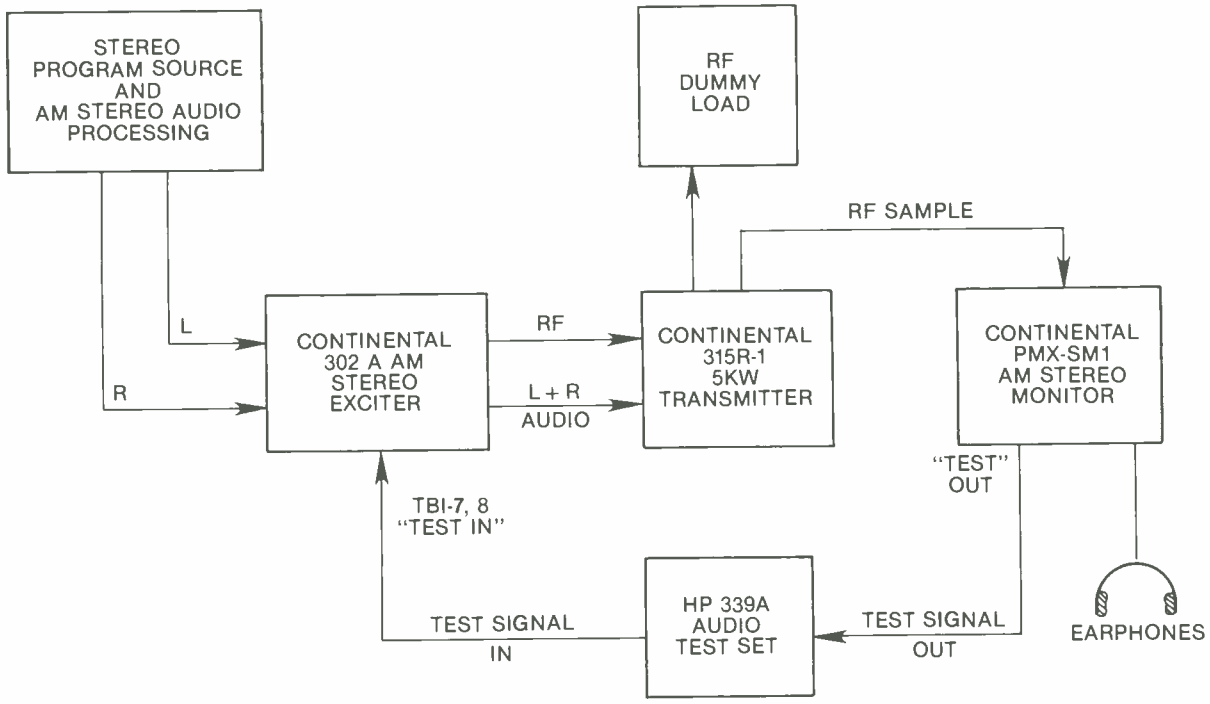


Fig. 9. PMX AM Stereo/315R-1 equipment interconnection.

3.3

FM Broadcast Transmitters

Geoffrey N. Mendenhall, P.E.
Vice President of Engineering
and
The Engineering Staff of Broadcast Electronics Inc.
Quincy, Illinois

With contributions by:
Warren B. Bruene, P.E.
Electrospace Systems Inc.
Richardson, Texas

HISTORY OF FM BROADCASTING

Although the mathematical principles explaining frequency modulation (FM) had been known for many years, the advantages and practical application to radio broadcasting were not realized until the 1930's, when Major Edwin H. Armstrong did extensive developmental work proving that FM radio transmissions were possible. Many theoreticians claimed to have proof that Armstrong's experiments were impossible based on mathematical models claiming that an infinite transmission bandwidth would be required. He never received proper credit for his many contributions to the radio communications industry during his lifetime. See reference (1) at the end of this chapter for more information about the career of Major Armstrong.

Among the advantages of FM are freedom from static, wide audio bandwidth, and the ability of an FM receiver to capture the stronger of two signals transmitted on the same carrier frequency.

In 1940, following extensive public hearings, the Commission established the FM Broadcast Service and set aside 40 channels in the 42 to 50 MHz band with commercial operation scheduled to begin January 1, 1941. Although World War II stopped all non-military radio construction, more than 40 FM stations continued to serve over 400,000 receivers. To eliminate the interference problems resulting from skywave reflection in the prewar FM band, the Commission moved the FM Broadcast Service to the 88 to 108 MHz band in 1945, thereby increasing the number of available channels to 100. However, the expected growth of FM broadcasting did not materialize. Since conversion of prewar FM receivers to the new band was not practical, purchase of a new receiver was the only way to receive the new FM stations. Television appeared to offer much more to the consumer than FM radio, since most FM stations merely duplicated the programming of an affiliated AM station. Despite the potential for a higher quality broadcast service, there was little public demand for new FM receivers and virtually no public reaction when FM stations dropped popular programs from their schedule or were off the air due to equipment failures. It is not surprising, therefore, that in May 1950, there had been only 16 new FM license applications during the previous 15 months in which 259 FM stations ceased operations. It was not until after the introduction of stereo multiplex FM broadcasting that public awareness of the FM band increased and then skyrocketed in the 1970's to make FM the dominant medium for musical programming.

CHARACTERISTICS OF FM COMPARED TO AM

Reduced Noise

The 88 to 108 MHz FM broadcast band is relatively free of atmospheric and other noise in-

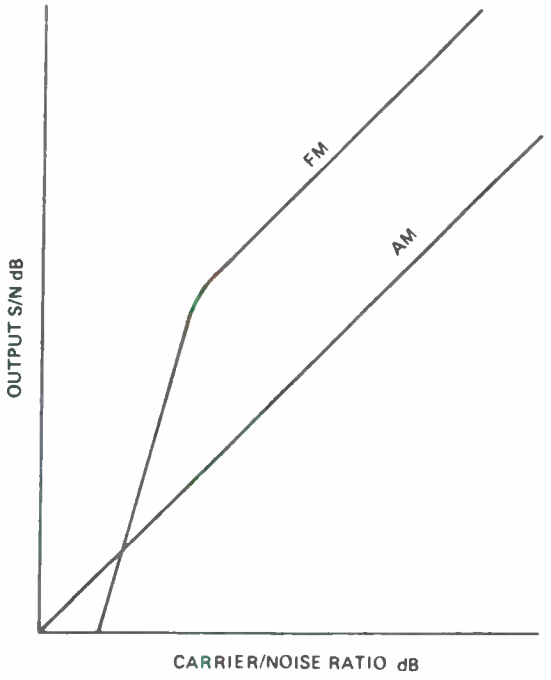


Fig. 1. FM improvement factor.

terference. Emission at these frequencies is not propagated great distances by the ionosphere as it is in the 535 to 1605 kHz AM broadcast band. Therefore, noise from lightning discharges is limited to line-of-sight distances and is almost negligible. Man-made noise is a far greater source of noise, particularly in urban areas. The level of man-made noise falls off at increasing higher frequencies so that the microvolts-per-meter noise level is about one-tenth as great in the FM band as it is in the AM band.

In addition, FM has an improved noise threshold characteristic when compared to AM. Limiting circuitry symmetrically clips the RF waveform in an FM receiver to remove any amplitude variations produced by static or impulse noise before they reach the demodulator which responds only to phase or frequency changes in the signal. The FM improvement factor is illustrated in Fig. 1. Note the sharp knee in the threshold curve above which noise and interference are suppressed, which results in an improved signal to noise (S/N) ratio. This same capture effect causes a weaker FM signal on the same channel to be suppressed, resulting in greatly reduced co-channel interference.

For even greater noise reduction, pre-emphasis (75 micro-second time constant) is employed in the transmitter whereby the audio frequency components above about 2.1 kHz are boosted in amplitude at the rate of 6 dB per octave before being applied to the modulator. Flat frequency response is restored in the receiver's de-emphasis network by attenuating the higher frequencies the same amount they were boosted in the transmitter. At the same time, the high frequency noise components which are characteristic to FM are also attenuated, resulting in greatly reduced background noise. Pre-emphasis is discussed in more detail in the FM theory and FM exciter sections of this chapter.

The net result of the above factors is a much better signal-to-noise ratio on FM than on AM and the ability to transmit much wider bandwidth information on FM. The lower background noise along with wider frequency response means that a signal of higher quality and wider dynamic range can be enjoyed.

Occupied Bandwidth

All the advantages of the FM broadcast medium over the AM broadcast medium do not come free of compromise. The primary compromise is that a standard FM broadcast channel occupies more than ten times the bandwidth of an AM broadcast channel. This is because the more complicated non-linear sideband structure of a frequency modulated carrier with wide deviation requires much more bandwidth than the simpler linear distribution of sidebands in an AM system. More details on the amplitude and spacing of FM sidebands are given in the section on FM modulation theory in this chapter. Fortunately, the FM broadcast band is located in the VHF portion of the frequency spectrum where more bandwidth is available than in the medium wave AM broadcast band.

High Fidelity

Fidelity is defined as the degree to which a system, or a portion of a system, accurately reproduces at its output the essential characteristics of the signal impressed upon its input. The large market for high-fidelity (HI-FI) equipment is evidence that the public recognizes and enjoys high quality reproduction. Many individuals spend a great deal of money to have high quality equipment in their homes.

Uniform frequency response over the audible range of at least 50 Hz to 15 kHz, very low amplitude distortion (harmonic and intermodulation), very low noise level, and good transient response (uniform time delay versus frequency) are necessary for HI-FI performance. The FM channel authorizations provide for adequate audio frequency response and a low-noise radio link to the listener. The rest of the performance is a matter of equipment design. The FCC has established minimum performance standards that assure HI-FI performance. Transmitter and receiver manufacturers strive to produce equipment

that exceed these minimum standards and broadcast stations strive to maintain the maximum performance capability of their equipment to provide truly HI-FI programs for the listener.

Stereophonic Transmission

A higher level of realism and listener enjoyment is provided by stereophonic transmission. Again, the wide channel allocations and ability of FM to compatibly multiplex several audio channels on one carrier permitted development of a practical stereo broadcasting system. This provides a means for the broadcast industry to provide the public with the same or better quality reproduction than is available on stereo records or tapes. The advent of the "compact disc" and other digital audio source equipment will continue to challenge equipment manufacturers and station engineers to further improve the performance of the entire FM broadcast chain. Detailed technical information about stereophonic transmission theory and standards is provided in the chapter about FM stereo and subcarriers.

Subcarrier Transmission

The wide channel bandwidth authorized for FM broadcasting also makes it feasible to multiplex several audio or data channels as subcarriers together with the stereo transmission. These channels commonly called SCAs, provide an important source of revenue to many stations as well as provide many useful audio and digital services to the community. Detailed technical information about subcarrier transmission theory and standards is provided in the chapter about FM stereo and subcarriers.

FCC Transmission Standards

The Federal Communications Commission regulates and enforces the technical standards that apply to radio broadcasting in the United States. In theory, this will assure that the public is provided with a consistently high standard of transmission quality from station to station. The rules and regulations covering transmitter technical performance are set forth in Part 73 of the FCC Rules and Regulations available from the U.S. Government Printing Office in Washington, D.C. The rules and regulations are changed from time to time to keep pace with new technology and changes within the broadcast industry. Every broadcast engineer should have access to a current copy of these rules and regulations so that the station's technical performance is maintained within the prescribed limits.

FM MODULATION THEORY

Angular modulation

Frequency modulation (FM) and phase modulation (PM) are both special cases of angular modulation. In any angular modulation system both the frequency and phase of the carrier vary with time as a function of the modulating signal.

The relationship between the frequency deviation of the carrier, the phase deviation of the carrier, and the sinusoidal modulating frequency is defined as the modulation index (m).

$$\text{Where: } m = \frac{\text{frequency deviation } (\pm \text{ Hertz})}{\text{modulating frequency (Hertz)}}$$

Since frequency modulation and phase modulation are both subsets of angular modulation they are virtually indistinguishable from one another except in the modulator characteristics.

In a PM system, the modulating signal causes the phase of the carrier wave to vary according to the instantaneous amplitude of the modulating signal. A phase modulator generates a constant amount of phase deviation of the carrier with a constant amplitude modulating signal independent of the frequency of the modulating signal. The frequency deviation of the carrier produced by a phase modulator does increase as the modulating frequency is increased even though the level of the modulating voltage is held constant. The net effect is that the phase modulator behaves as if it were a frequency modulator with a 6 dB/octave rising slope on the modulating signal input.

A frequency modulator generates a constant frequency deviation of the carrier with a constant amplitude modulating signal independent of the frequency of the modulating signal. The phase deviation of the carrier produced by a frequency modulator decreases as the modulating frequency is increased even though the level of the modulating voltage is held constant. The net effect is that the frequency modulator behaves as if it were a phase modulator with a 6 dB/octave falling slope on the modulating signal input.

In FM broadcasting, we desire a signal that has frequency deviation that is proportional the amplitude of the modulating signal, but independent of the frequency of the modulating signal as is produced by a frequency modulator.

The instantaneous frequency (rate of change of phase) of the RF output wave differs from the carrier frequency by an amount proportional to the instantaneous value of the modulating waveform. For example, consider a 100 MHz carrier wave FM modulated by a 1000 Hz audio tone and assume that a 1 volt input to the modulator

causes ±20 kHz of frequency deviation on the positive and negative peaks of this tone. If the audio input amplitude is increased to 2 volts, the peak deviation will become ±40 kHz varying in sine-wave fashion from one peak deviation to the other and back again at the 1000 Hz rate. In FM broadcasting, the FCC has established that a peak frequency deviation of ±75 kHz shall constitute 100 percent modulation.

It is interesting to note that when pre-emphasis is used ahead of the FM modulator, the system becomes a phase modulator at audio frequencies above the turnover point of the pre-emphasis network. This is because the frequency response of the pre-emphasis network rises at the rate of 6 dB/octave above this point. FM broadcasting with pre-emphasis really becomes a mixture of FM at low modulating frequencies and PM at high modulating frequencies.

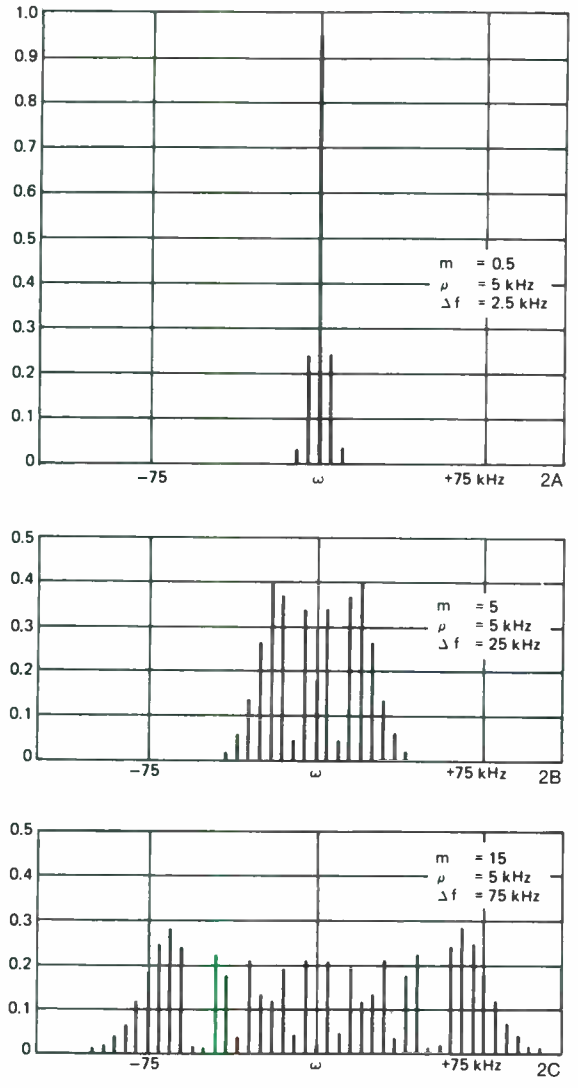


Fig. 2. RF spectrum with modulation indexes of 0.5, 5.0, and 15.

FM Sideband Structure

The frequency modulated RF output spectrum contains many sideband frequency components, theoretically an infinite number. They consist of pairs of sideband components spaced from the carrier frequency by multiples of the modulating frequency. When the modulation index is small ($m = 0.5$) the amplitude of the second and higher order sidebands is small so that the output consists mainly of the carrier and the pair of first-order sidebands, as illustrated in Fig. 2A. The total transmitter RF output power remains constant with modulation, but the distribution of that power into the sidebands varies with the modulation index so that power at the carrier frequency is reduced by the amount of power added to the sidebands.

As the modulation index is increased as in wide deviation FM broadcasting, the higher order sidebands become more prominent. The amplitude and phase of the carrier (J_0) as well as the sidebands (J_1 thru J_n) can be expressed mathematically by making the modulation index (m) the argument of a simplified Bessel function.

$E(t) =$	total RF output voltage
$A[J_0\ (m)\sin\ \omega c(t)]$	carrier amplitude
$+[J_1\ (m)\sin(\omega c+\omega m)t]$	first order upper sideband
$-[J_1\ (m)\sin(\omega c-\omega m)t]$	first order lower sideband
$+[J_2\ (m)\sin(\omega c+2\omega m)t]$	second order upper sideband
$+[J_2\ (m)\sin(\omega c-2\omega m)t]$	second order lower sideband
$+[J_3\ (m)\sin(\omega c+3\omega m)t]$	third order upper sideband
$-[J_3\ (m)\sin(\omega c-3\omega m)t]$	third order lower sideband
$\pm[J_n\ (m)\sin(\omega c\pm n\omega m)t]$	... higher order sidebands

Where:

- A = The unmodulated carrier amplitude constant
- J_0 = The modulated carrier amplitude
  $J_1, J_2, J_3 \ldots J_n$ are the amplitudes of the nth order sidebands
- m = The modulation index
- ωc = $2\ \pi\ F_c$ (The carrier frequency)
- ωm = $2\ \pi\ F_m$ (The modulating frequency)

The numeric values of the Bessel functions (J_0 thru J_n) which express the amplitudes of the various frequency components can be found in mathematical tables. Fig. 3 shows a graphical representation of how the Bessel function values for the carrier and the first eight pairs of sidebands vary with the modulation index.

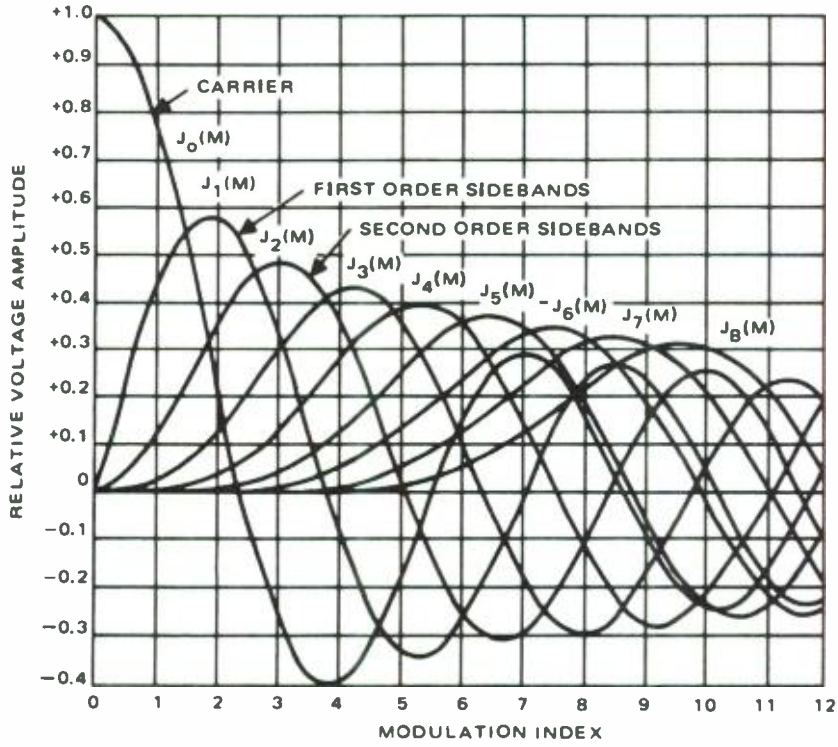


Fig. 3. Relationship of carrier and sideband amplitudes to modulation index.

In a monophonic FM broadcast transmitter, the modulation index can become very high at low modulating frequencies. With a 50 Hz audio input signal of sufficient amplitude to produce 75 kHz deviation (100 percent modulation), the modulation index is:

$$m = \frac{75000}{50} = 1500$$

With a 15,000 Hz input at the same deviation (also 100 percent modulation), the modulation index is only:

$$m = \frac{75000}{15000} = 5$$

Fig. 2B and 2C illustrate the frequency components present for modulation indices of 5 and of 15. Note that the number of significant sideband components becomes very large with a high modulation index. The total bandwidth occupied extends beyond ±75 kHz from the carrier depending upon the modulating frequency. This single tone modulating frequency analysis is useful in understanding the general nature of FM and for making tests and measurements. When program modulation is applied, there are many more sideband components present and they are varying so much that sideband energy becomes distributed over the entire occupied bandwidth rather than appearing at discrete frequencies.

Bessel Nulls

It is interesting to note that at certain modulation indices, the carrier amplitude goes to zero with all the transmitted power distributed at frequencies other than the carrier frequency. This carrier null phenomenon is useful as an extremely accurate method for measuring the frequency deviation and to check the calibration of modulation monitors. Referring again to Fig. 3, note that the carrier amplitude goes to zero and reverses sign at several values of modulation index including; 2.405, 5.520, and 8.654. Fig. 4 is a photograph taken from an RF spectrum analyzer showing the first Bessel null ($m = 2.405$) of a carrier at a frequency of 100 MHz.

If we want to determine the audio input level required to achieve 75 kHz deviation, we can apply an audio tone of exactly 8,667 Hz (75,000 divided by 8.654) and increase the audio level until the carrier disappears for the third time. At this audio level the deviation is exactly 75 kHz. The carrier amplitude (null) detector must have sufficient selectivity to separate the carrier from the sidebands and could be a spectrum analyzer or a receiver with a narrow IF bandwidth. The FM signal can even be heterodyned down to a convenient frequency for measurement. Heterodyning does not alter the modulation index while frequency division or multiplication does change the modulation index. When a frequency (or phase) modulated wave is multiplied or divided,

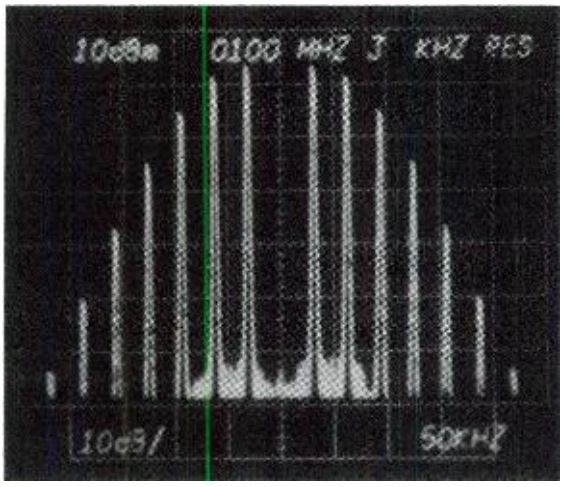


Fig. 4. FM RF spectrum showing occupied bandwidth and Bessel Null single tone @ ±75 KHz deviation.

this also multiplies or divides the frequency deviation and the modulation index by the same amount.

A listing of useful carrier and first order sideband nulls as function of the modulation index (m) and the modulating frequency (F_m) is given below.

Occupied Bandwidth

After examining the Bessel function and the resulting spectra, it becomes clear that the occupied bandwidth of an FM signal is far greater than the amount of deviation from the carrier that one might incorrectly assume as the bandwidth. In fact, the occupied bandwidth is infinite if all the sidebands are taken into account, so it is now clear that a frequency modulation system would require the transmission of an infinite number of sidebands for perfect demodulation of information. In practice, a signal of acceptable quality can be transmitted in the limited bandwidth assigned to an FM channel.

Effects of Bandwidth Limitation

Practical considerations in the transmitter RF circuitry make it necessary to restrict the RF bandwidth to less than infinity. As a result, the higher order sidebands will be altered in amplitude and phase. Bandwidth limitation will cause distortion in any FM system.

Consider the model shown in Fig. 5A, where a perfect FM modulator is connected to a perfect demodulator via an RF path of infinite bandwidth. The demodulated audio shown in Fig. 5B contains no distortion components.

In Fig. 6A, a passive LC bandpass filter is inserted between the modulator and demodulator in order to restrict the bandwidth. Audio distortion products now appear at the output of our perfect demodulator as shown in Fig. 6B. These distortion products are due solely to the bandwidth restriction (300 kHz bw_3) imposed by the passive bandpass filter.

Fig. 7A and 7B show the effects of a narrowband RF bandpass filter on the RF spectrum of a composite signal consisting of a stereophonic subcarrier modulated only on the left channel with 4.5 kHz plus a 67 kHz unmodulated SCA subcarrier. The only distortion evident on the RF spectrogram is the loss of some sidebands greater than 150 kHz from the center frequency and some amplitude differences between the upper and lower sideband pairs. Fig. 7B shows the corresponding effects observed on the demodulated baseband spectrum for the same signal. Note the creation of many undesired intermodulation terms which cause crosstalk into both the stereophonic and SCA subcarrier bands. The change in the RF spectrum is subtle, but the resulting spectrum after demodulation is clearly modified.

As one can see, the distortion in any practical FM system will depend on the amount of band-

NULL	MODULATION INDEX (m)		(F_m) IN Hz (FOR 75 kHz DEVIATION)	
	CARRIER	1st SIDEBANDS	CARRIER	1st SIDEBANDS
1st	2.405	3.852	31,185	19,470
2nd	5.520	7.016	13,587	10,690
3rd	8.654	10.173	8,667	7,372
4th	11.792	13.323	6,360	5,629
5th	14.931	16.470	5,023	4,554
6th	18.071	19.616	4,150	3,823
7th	21.212	22.760	3,536	3,295

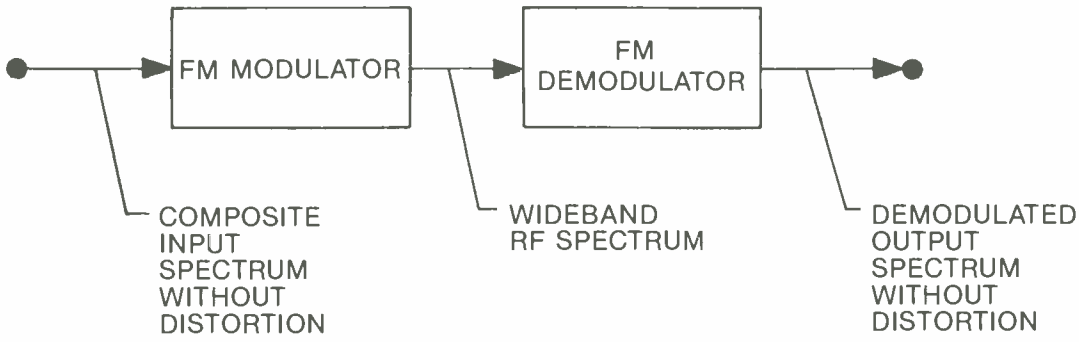
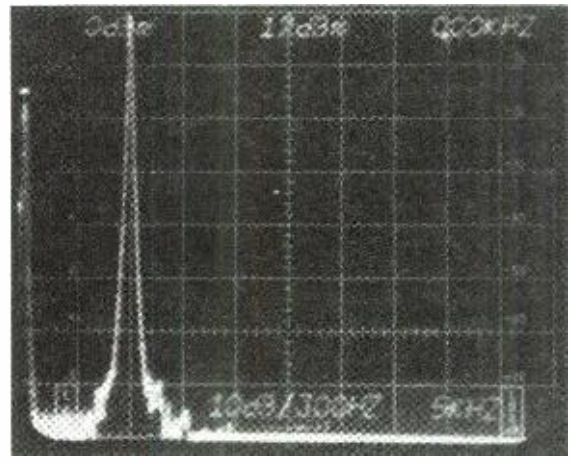
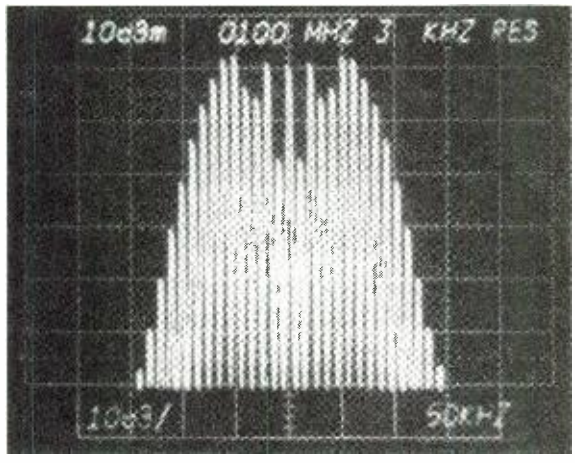


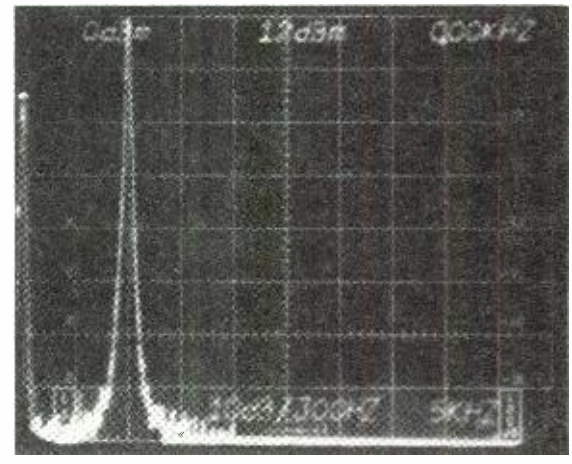
Fig. 5A. Wideband RF path.



BASEBAND SPECTRUM TO FM MODULATOR



RF SPECTRUM TO DEMODULATOR



DEMODULATED BASEBAND SPECTRUM

Fig. 5B. Single tone (10 KHz) modulation thru wideband RF path.

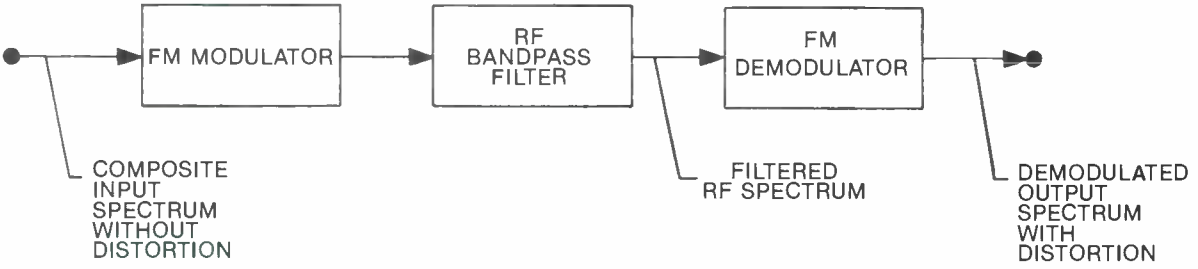
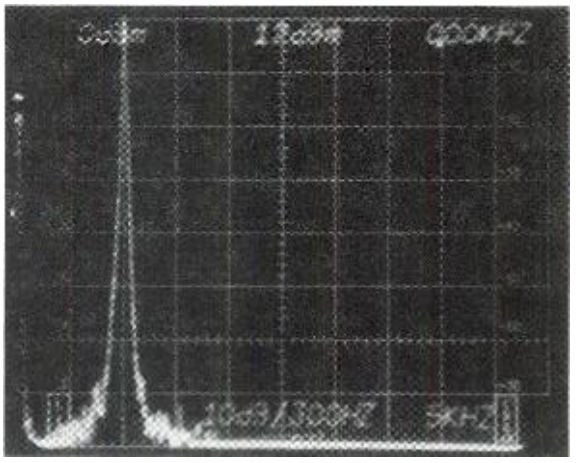
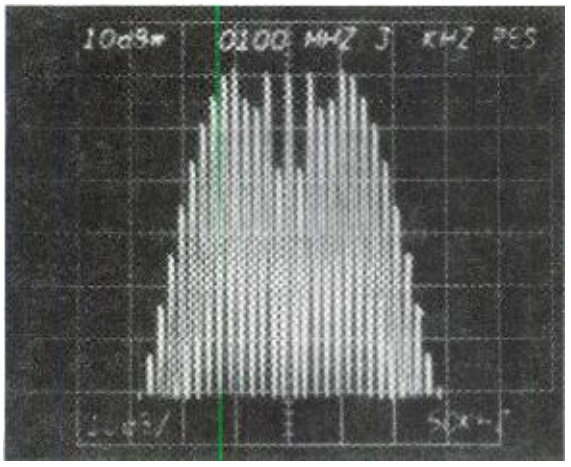


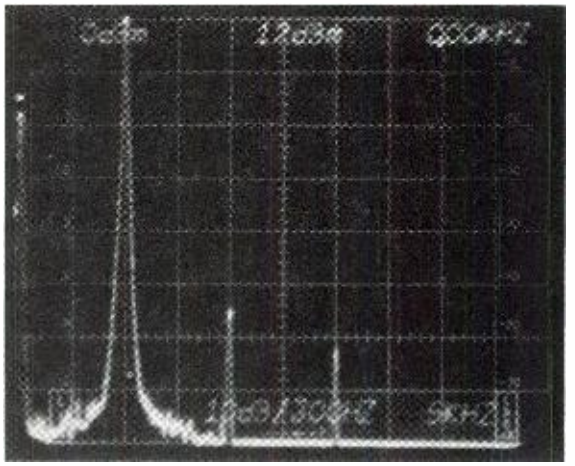
Fig. 6A. Bandwidth limited RF path.



BASEBAND SPECTRUM TO FM MODULATOR

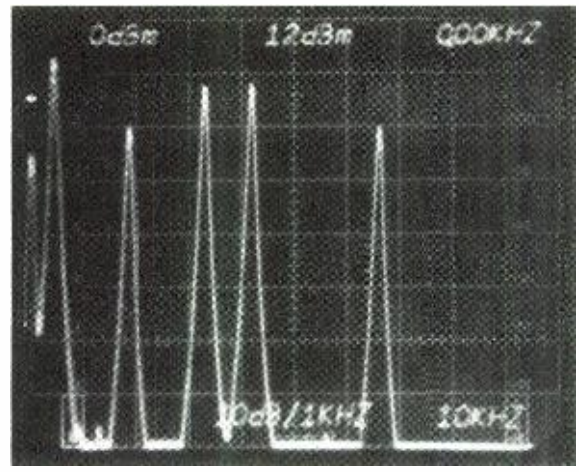


BANDWIDTH LIMITED RF SPECTRUM TO DEMODULATOR

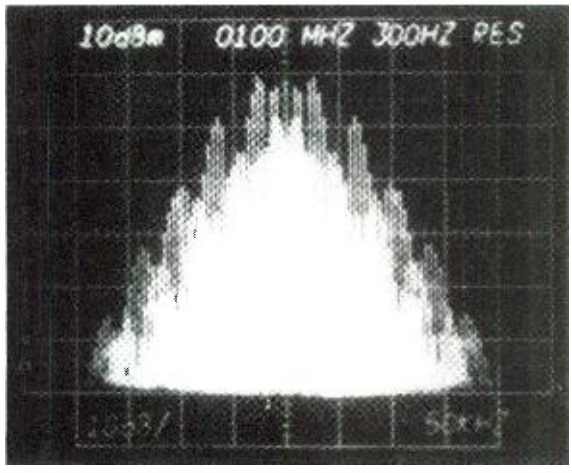


DEMODULATED BASEBAND SPECTRUM

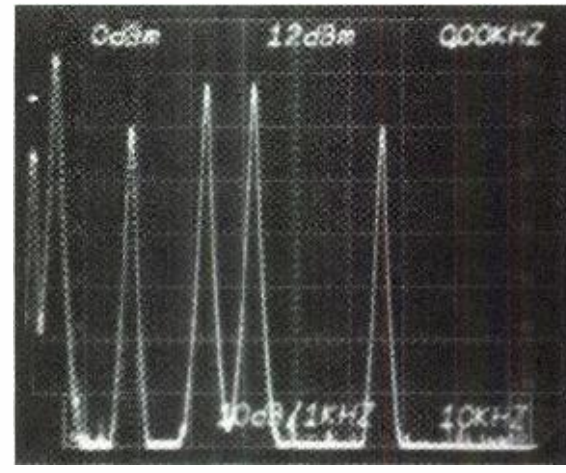
Fig. 6B. Singletone (10 KHz) modulation thru narrowband RF path.



BASEBAND SPECTRUM TO FM MODULATOR



RF SPECTRUM TO DEMODULATOR



DEMODULATED BASEBAND SPECTRUM

Fig. 7A. Stereo (L or R = 4.5 KHz) plus SCA (unmod.) modulation thru wideband RF path.

width available versus the modulation index being transmitted.

Limiting Factors Within An FM Transmitter

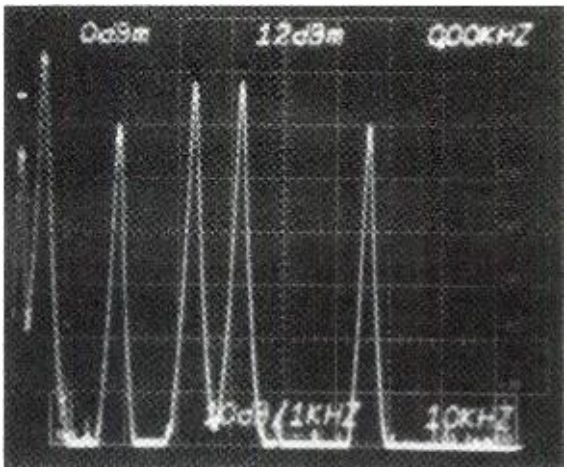
Relating the specific quantitative effect of the bandwidth limitations imposed by a particular transmitter to the actual distortion of the demodulated composite baseband is a complicated problem indeed. Some of the factors involved are:

1. Total number of tuned circuits involved.
2. Amplitude and phase response of the total combination of tuned circuits in the RF path.
3. Amount of drive (saturation effects) to each class "C" stage.
4. Non-linear transfer function within each amplifier stage.

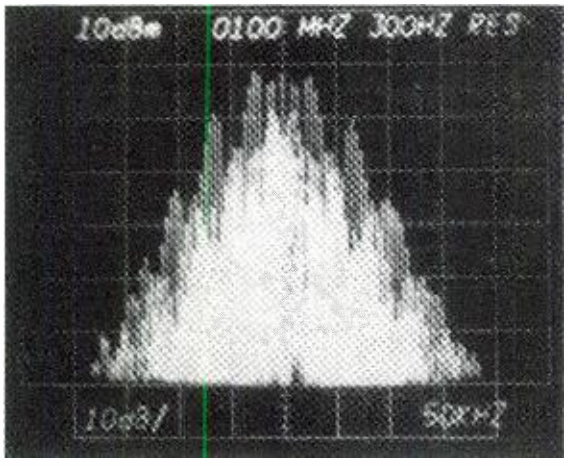
Improvement of The RF Path

The following design techniques can help improve the transmitter's bandwidth:

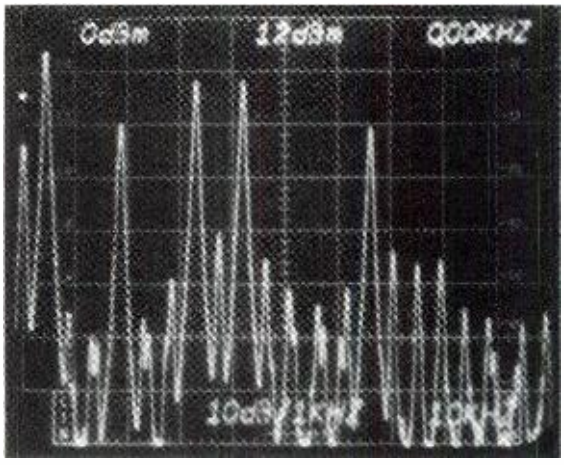
1. Maximize bandwidth by using a broadband exciter and a broadband IPA stage.
2. Use a single-tube design or a broadband, completely solid-state design where feasible.
3. Optimize both grid circuit and plate circuit of the tuned stage for the best possible bandwidth.
4. Minimize the number of interactive tuned networks.



BASEBAND SPECTRUM TO FM MODULATOR



BANDWIDTH LIMITED RF SPECTRUM TO SPECTRUM



DEMODULATED BASEBAND SPECTRUM

Fig. 7B. Stereo (L or R = 4.5 KHz) plus SCA (unmod.) modulation thru narrowband RF path.

5. Use a broadband antenna system with a low standing wave ratio on the transmission line.

For more detailed information about FM modulation theory, see references (2), (3), and (4) at the end of this chapter.

PRE-EMPHASIS

The standards adopted for FM broadcasting require the use of pre-emphasis. The standard pre-emphasis curve is defined as an ideal RC network with a time constant of 75 microseconds. The 3 dB point is at a frequency of:

$$f = \frac{1}{2\pi RC} = \frac{1}{2\pi 75 \times 10^{-6}} = 2{,}122 \text{ Hz.}$$

The 75 microsecond curve and the tolerance allowed by the FCC is shown in Fig. 8A.

The reduction in receiver output noise due to the use of pre-emphasis in monophonic transmission is illustrated in Fig. 9. The noise voltage in a narrow bandwidth (for example, 1 Hz) increases directly with frequency, therefore, the power spectral density increases as the square of frequency as shown. When de-emphasis is used, the noise voltage is attenuated above 2.1 kHz so that it remains constant with frequency. The power spectral density is also constant above 2.1 kHz. The area between these curves represents the noise power that is removed by the use of de-emphasis. This diagram indicates the importance of pre-emphasis for high-fidelity transmission because the high-frequency noise at the receiver would be very much greater without de-emphasis.

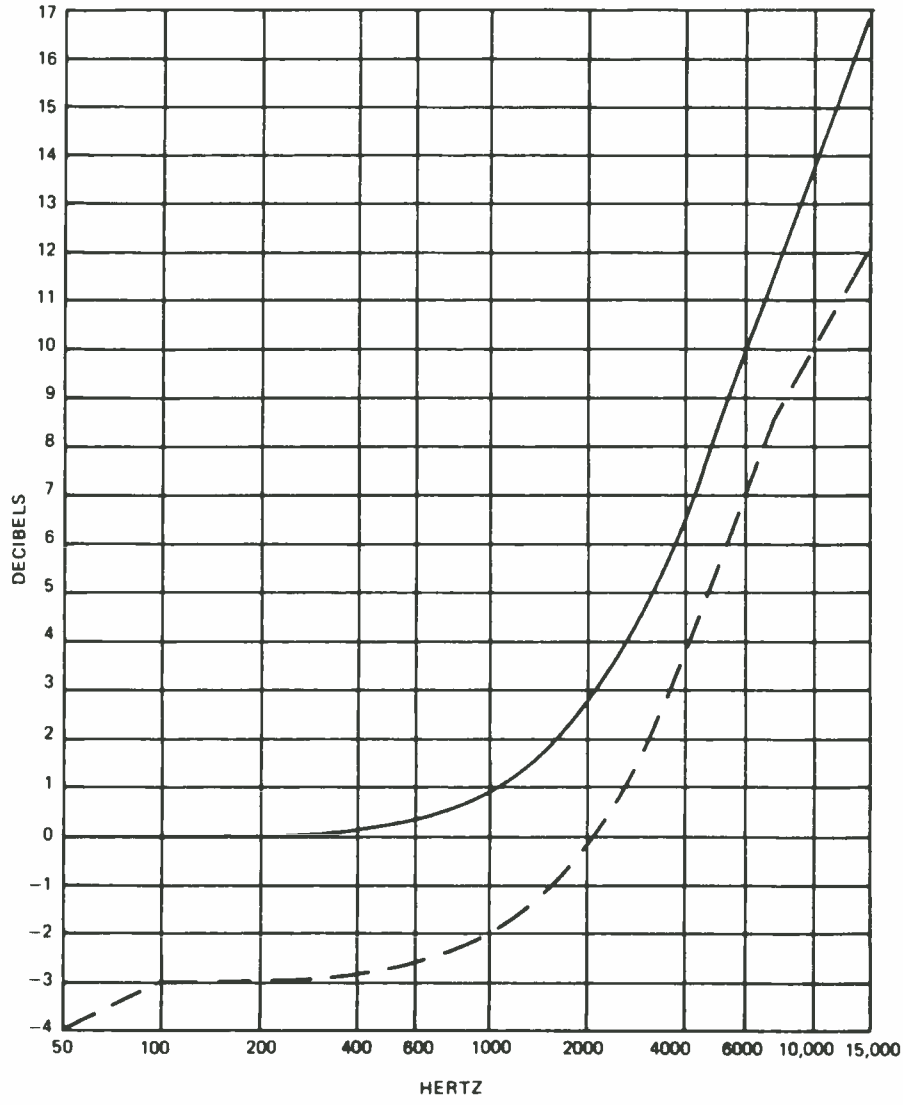


Fig. 8A. FCC Standard 75-microsecond pre-emphasis curve (solid line) and tolerance limits (solid and dashed lines).

Pre-emphasis is practical because program energy tends to peak at several kilohertz and then falls off fairly rapidly at the higher frequencies. For this reason, the higher frequencies can be boosted in amplitude without causing much increase in modulation level. There is some increase, however, so the net improvement due to pre-emphasis is the ratio of the areas under the two curves of the diagram less this reduction in audio input level required to keep within the 100 percent modulation limit. Modern audio processing equipment takes the pre-emphasis curve into account when controlling peak modulation levels.

In the section on FM modulation theory, it was mentioned that the use of pre-emphasis ahead of an FM modulator actually causes the system to behave like FM at low modulating frequencies and like PM at high modulating frequencies.

The location of the pre-emphasis network in the system depends on whether the station is operating in the monaural or stereo mode. In the case of monaural transmission, the pre-emphasis network is usually located in the FM exciter just ahead of the modulator stage. Stereo transmission requires that the FM modulator have a flat response to the composite baseband signal from the stereo generator, so the individual pre-emphasis networks for the left and right channels are located in the stereo generator before the left and right audio channels are multiplexed into the composite baseband signal. The pre-emphasis time constant may be reduced to 25 microseconds if Dolby type "B" noise reduction is being used by the station. This will assure reasonable compatibility at low modulation levels, with the standard 75 microsecond receiver de-emphasis.

FREQUENCY IN HERTZ	DECIBELS
400 HZ	0.15 dB
1,000	0.87
2,000	2.76
3,000	4.77
4,000	6.58
5,000	8.16
6,000	9.54
7,000	10.75
8,000	11.82
9,000	12.78
10,000	13.66
11,000	14.45
12,000	15.18
13,000	15.86
14,000	16.49
15,000	17.07

Fig. 8B. 75 Microsecond pre-emphasis response.

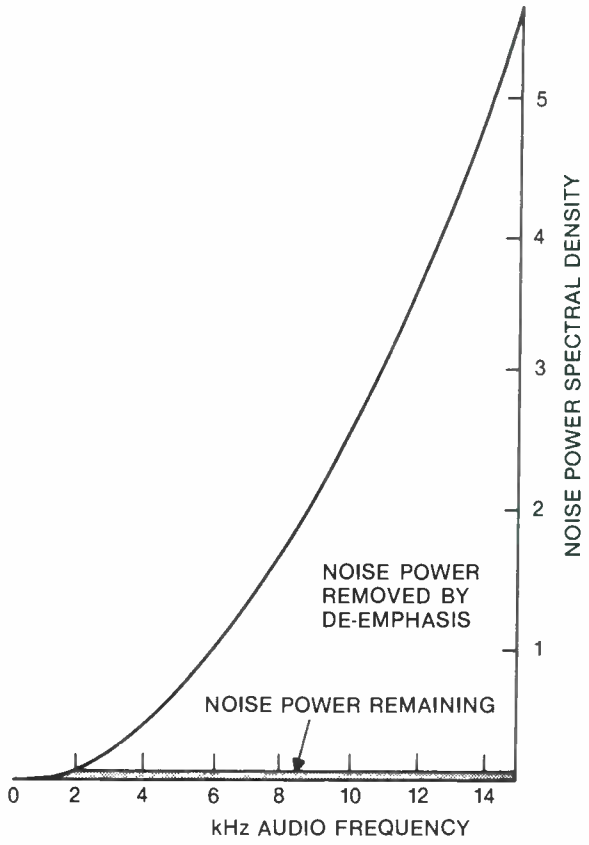


Fig. 9. Noise power spectral density before and after de-emphasis in receiver.

THE FM TRANSMITTER

The purpose of the FM transmitter is to convert one or more audio frequency (composite baseband) input signals into a frequency modulated, radio frequency signal at the desired power output level to feed into the radiating antenna system. In it's simplest form, it can be considered to be an FM modulator and an RF power amplifier packaged into one unit.

Actually the FM transmitter consists of a series of individual subsystems each having a specific function:

1. The FM exciter converts the audio/baseband into frequency modulated RF and determines the key qualities of the signal.
2. The intermediate power amplifier (IPA) is required in some transmitters to boost the RF power level up to a level sufficient to drive the final stage.
3. The final power amplifier further increases the signal level to the final value required to drive the antenna system.
4. The power supplies convert the input power from the ac line into the various dc or ac voltages and currents needed by each of these subsystems.
5. The transmitter control system monitors, protects, and provides commands to each of these subsystems so that they work together to provide the desired result.
6. The RF lowpass filter removes undesired harmonic frequencies from the transmitter's output, leaving only the fundamental output frequency.
7. The directional coupler provides an indication of the power being delivered to and reflected from the antenna system.

Fig. 10 shows a simplified block diagram of a typical FM transmitter.

FM EXCITERS

The heart of an FM broadcast transmitter is its exciter. The function of the exciter is to generate and modulate the carrier wave with one or more inputs (mono, stereo, SCA) in accordance with the FCC standards. The FM modulated carrier is then amplified by a wideband amplifier to the level required by the transmitter's following stage.

Stereo transmission places the most stringent performance requirements upon the exciter. Since the exciter is the origin of the transmitter's signal, it determines most of the signal's technical characteristics; including signal-to-noise-ratio, distortion, amplitude response, phase response, and frequency stability. Waveform linearity, amplitude bandwidth, and phase linearity must be maintained within acceptable limits throughout the baseband chain from the stereo and subcarrier generators to the FM exciter's modulated oscillator. From here, the FM carrier is usually amplified in a series of class "C" non-linear power amplifiers, where any amplitude variation is removed. The amplitude and phase responses of all the RF networks which follow the exciter must also be controlled to minimize degradation of the baseband.

Before the advent of stereo broadcasting, most of the FM exciters employed phase modulation techniques. Some of these were adapted to stereo but it was difficult to achieve and maintain the performance requirements for stereo transmission.

In the FM modulation theory section, the important relationship between PM and FM was discussed. If the audio frequency response is made to fall off at the rate of 6 dB/octave across the entire audio band at the input of a phase modulator, the resulting modulated output will be identical to that of a frequency modulated carrier. In 1948, James R. Day, an associate of Edwin H. Armstrong, demonstrated a "Serrasoid" phase modulator which used pulse circuits to achieve large phase shifts with low distortion. The "Serrasoid" modulation technique, in conjunction with the audio response shaping mentioned above, became the standard method of generating wide deviation FM with low distortion. This principle called "indirect FM" was used in many FM broadcast transmitters prior to the advent of stereo broadcasting. The advantage was that the carrier frequency could be generated by a stable crystal oscillator with the phase modulation occurring in later stages. The amount of phase deviation with low distortion was limited in most systems, so it was necessary to start with a low frequency oscillator and multiply it's frequency and modulation index many times to achieve 75 kHz deviation at low modulating frequencies. This technique has been abandoned in favor of direct FM systems.

Direct FM

Direct FM is a modulation technique where the frequency of an oscillator can be made to change in proportion to an applied voltage. Such an oscillator, called a voltage tuned oscillator (VTO), was made possible by the development of varactor tuning diodes which change capacitance as their reverse bias voltage is varied (also known as a voltage controlled oscillator or VCO).

If the composite baseband signal is applied to the tuning terminal of a VTO, the result is a "direct FM" modulated oscillator. Fig. 11 is a block diagram that fits most of the modern direct FM exciters on the market.

The signal-to-noise ratio of an FM exciter is dependent on the short-term stability of the modulated oscillator. That stability is determined by factors such as operating level, noise figure

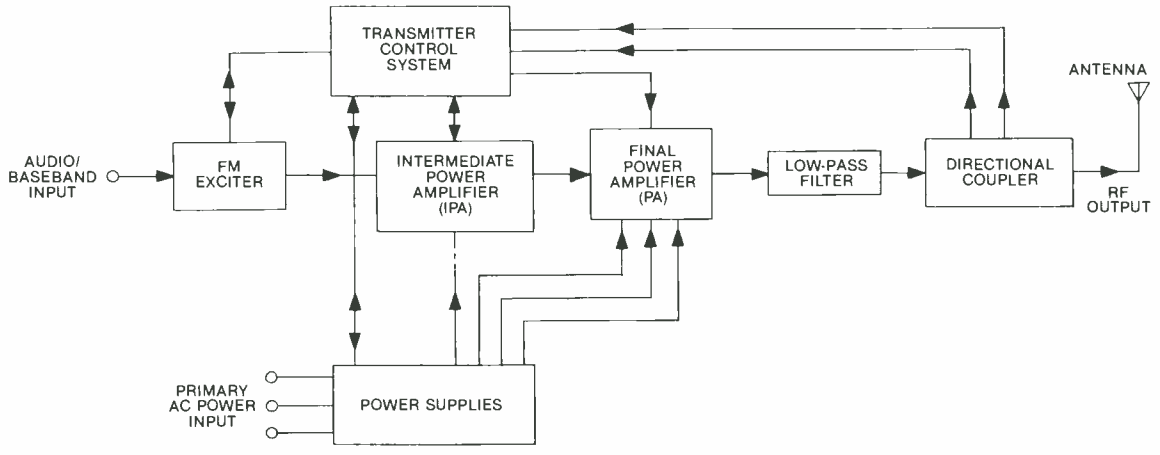


Fig. 10. Simplified block diagram of an FM broadcast transmitter.

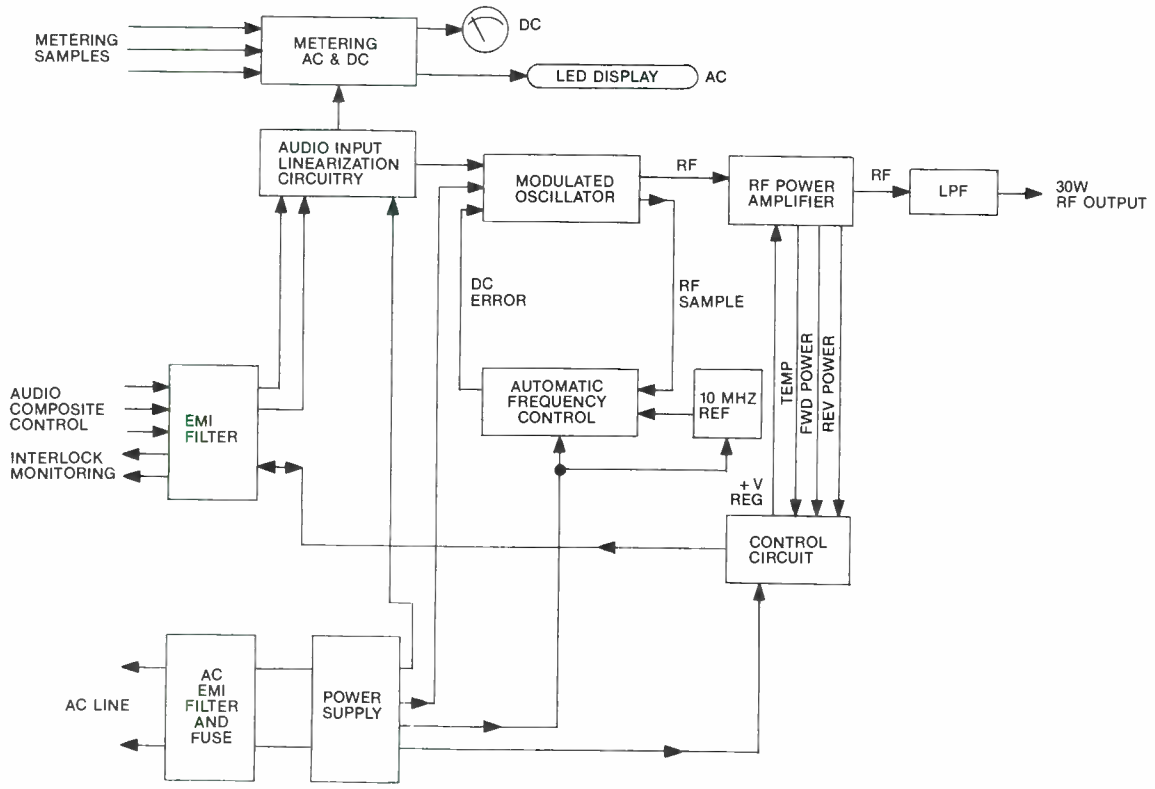


Fig. 11. FM exciter block diagram.

of the oscillator transistor, circuit configuration, method of amplitude limiting, loaded "Q" of the oscillator tank circuit, and the mechanical stability of components.

FM Modulator Linearity

Non-linearities in the FM oscillator can, by altering the waveform of the baseband signal, create distortion in the demodulated output at the receiver. A secondary effect of this distortion may include stereo crosstalk into the SCA.

The composite baseband signal is translated to a frequency modulated carrier frequency by the modulated oscillator. Frequency modulation is produced by applying the composite baseband signal to a voltage tunable RF oscillator. The modulated oscillator usually operates at the carrier frequency and is voltage tuned by varactor diodes, operating in a parallel LC circuit.

To have perfect modulation linearity, the RF output frequency (F_c) must change in direct proportion to the composite modulating voltage (V_m) applied to the varactor diodes (C_v). This requirement implies that the capacitance of the varactor diodes must change as nearly the square of the modulating voltage as shown in following relationships:

(F_c) is proportional to (V_m) (Desired linear voltage to frequency translation)

$$\text{if } F_c = \frac{1}{2\pi\sqrt{(L)(C_t)}}$$

$$\text{and: } C_v = \frac{K}{V_m^2} \text{ (If } C_{fixed} = 0)$$

Where: F_c = Instantaneous carrier frequency
L = Inductance of resonant circuit
C_t = Total capacitance across L (C fixed + C varactors)
C_v = Capacitance of varactor tuning diodes
K = Varactor constant
V_m = Baseband modulating voltage

Unfortunately, the voltage versus capacitance characteristic of practical varactor diodes is not the desired square law relationship. All varactor-tuned oscillators have an inherently non-linear modulating characteristic. This non-linearity is very predictable and repeatable for a given circuit configuration, making correction by complementary predistortion of the modulating signal feasible. Suitable predistortion can be applied to the composite baseband signal by using a piecewise linear approximation to produce the desired complementary transfer function. Fig. 12 shows a typical network of switching diodes and resistors used for complementary predistortion of the composite baseband. Fig. 13 shows how the predistor-

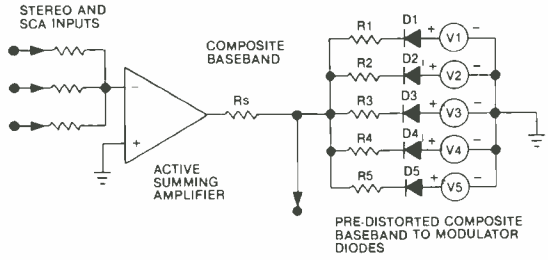


Fig. 12. Predistortion network.

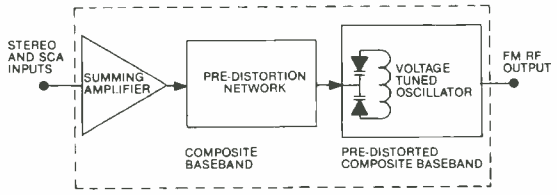


Fig. 13. Linearized FM modulator block diagram.

tion network is cascaded with a non-linear voltage-tuned oscillator to produce a linearized FM modulator.

It is also possible to improve both the linearity and signal to noise ratio of the modulated oscillator by demodulating its RF output to baseband and then feeding some of this baseband with the proper phase relationship back into the composite input of the modulator. This type of configuration places the entire modulated oscillator within a negative feedback loop and transfers the responsibility for maintaining linearity to the demodulator. Digital demodulation schemes can be made very linear, but the additional complexity and the potential problems with loop stability have limited the applications of this approach to linearization.

Modulator linearization has reduced harmonic and intermodulation distortion to less than .05% in the current generation of equipment. Any distortion of the baseband signal caused by the modulated oscillator will have secondary effects on stereo and SCA crosstalk, which are quite noticeable at the receiver in spite of the rather small amounts of distortion to the baseband. For example, if the harmonic distortion to the baseband is increased from .05% to 1.0%, as much as 26 dB additional crosstalk into the SCA can be expected.

For illustrative purposes, Fig. 14A, 14B, and 14C give representations of the fundamental and second order terms in the composite baseband spectrum with increasing amounts of harmonic distortion in the modulated oscillator. Fig. 14B shows this spectrum after 0.05% harmonic distortion has been added to each component. Note that the second order stereo (L-R) sidebands are 78 dB below 100% modulation or about 58 dB below a 67 kHz SCA with a 10% injection. With normal energy distribution in L-R and the SCA, crosstalk from stereo into the SCA will be more than 60 dB below the SCA subcarrier. Fig. 14C shows the same baseband spectrum with 1.0% harmonic distortion. The second order stereo sidebands are only 32 dB below the SCA. Crosstalk may now increase as much as 26 dB, depending on the respective energy distributions in (L-R) and the SCA.

Transient InterModulation (TIM) distortion is usually not a factor in varactor-tuned modulated oscillators. The modulation bandwidth capability is generally more than ten times the composite bandwidth and no negative feedback is used to maintain linearity.

Assuring that the composite baseband signal undergoes minimal distortion in the modulation process will suppress undesired harmonic and intermodulation products in the baseband, making the FM exciter transparent to the signals coupled into it. All exciter stages after the modulated oscillator operate as broadband amplifiers with minimal bandwidth limitations.

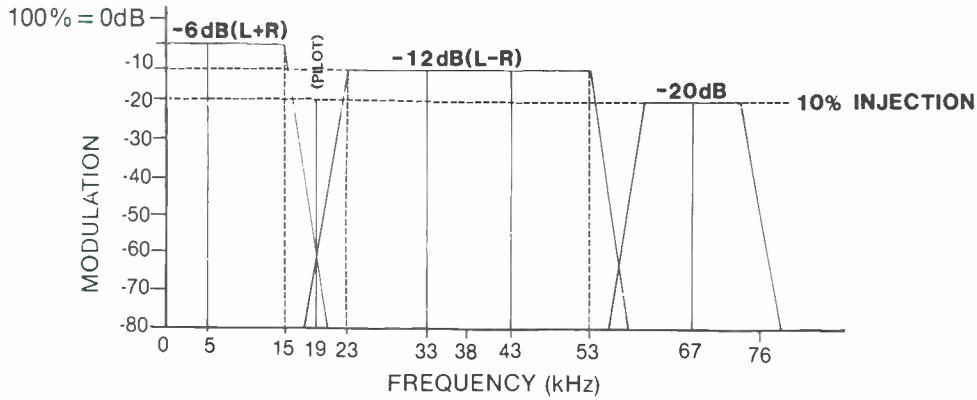
Automatic Frequency Control

The frequency stability of direct FM oscillators is not good enough to meet the FCC frequency tolerance of ±2,000 Hz. This requires an automatic frequency control system (AFC) that uses a stable crystal oscillator as the reference frequency.

The modulated oscillator need not have good long-term stability since the AFC feedback loop will correct for long-term drift to keep the average carrier frequency within limits. The modulated oscillator does need excellent short-term stability (less than 1 second) because the control loop time constant must be long enough so that the AFC circuit does not try to remove desired low frequency audio modulation. This means that the oscillator is essentially running open-loop at frequencies above a few Hertz so that the noise performance of the modulator will also be determined by the short term stability characteristics of the oscillator.

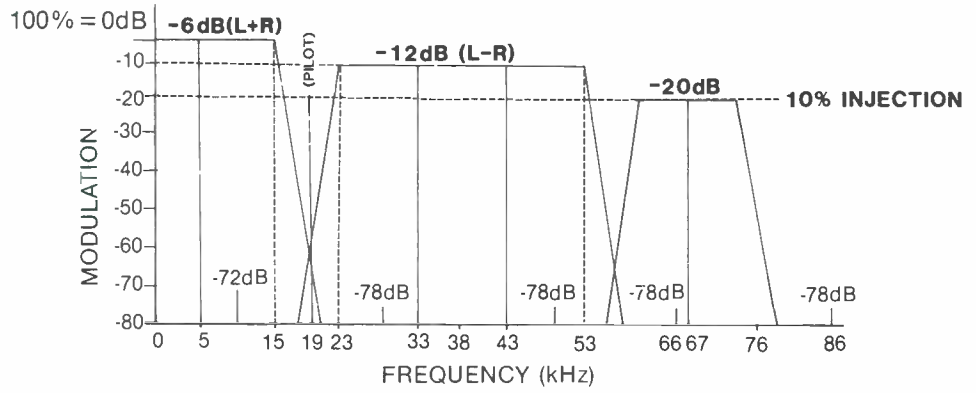
Phase-Locked-Loop Automatic Frequency Control

Phase-locked-loop (PLL) technology has provided a means of precisely controlling the carrier's average frequency while permitting wide deviation of the carrier frequency at baseband modulating frequencies. This implies that a PLL system behaves like an audio high-pass filter with higher modulating frequencies being ignored by



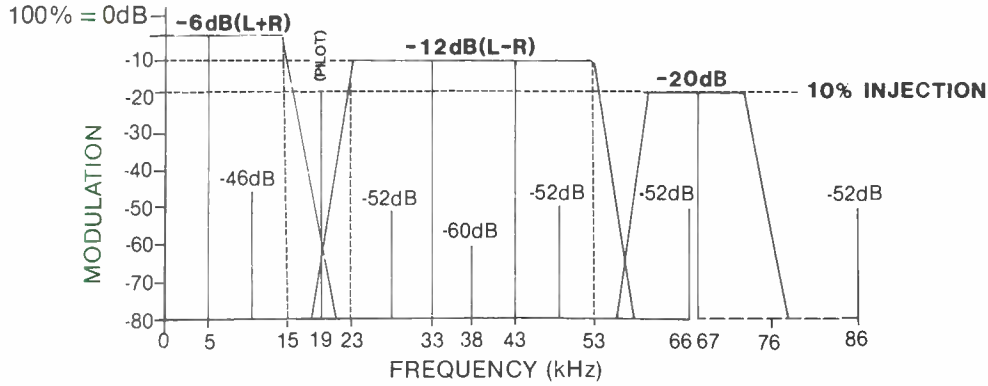
L OR R ONLY MODULATED 100% @ 5 kHz. UNMODULATED SCA @ 10% INJECTION

Fig. 14A. Ideal demodulated composite baseband spectrum with no modulator distortion.



L OR R ONLY MODULATED 100% @ 5 kHz. UNMODULATED SCA @ 10% INJECTION.
INTERFERING SECOND HARMONIC STEREO SIDEBANDS ARE 58 dB BELOW SCA.
ONLY FUNDAMENTAL AND SECOND HARMONIC TERMS ARE SHOWN.

Fig. 14B. Demodulated composite baseband spectrum with 0.05% harmonic distortion in modulator.



L OR R ONLY MODULATED 100% @ 5 kHz. UNMODULATED SCA @ 10% INJECTION.
INTERFERING SECOND HARMONIC STEREO SIDEBANDS ARE 32 dB BELOW SCA.
ONLY FUNDAMENTAL AND SECOND HARMONIC TERMS ARE SHOWN.

Fig. 14C. Demodulated composite baseband spectrum with 1.0 % harmonic distortion in modulator.

the control loop while lower frequencies are considered to be errors in the average frequency and are tracked out by the loop. An added advantage of the PLL is the ability to synthesize the desired frequency from a single reference oscillator, thereby eliminating the need to change crystals when changing the frequency of the exciter.

The block diagram shown in Fig. 15 includes the key elements in the PLL. The output of the modulated oscillator operating at the carrier frequency is digitally divided down to a frequency of a few kilohertz or even less, called the comparison frequency. Likewise, the reference crystal oscillator is also digitally divided down to the comparison frequency. The two frequencies are compared in a digital phase/frequency detector to develop an error voltage which corrects the carrier frequency of the modulated oscillator. The reason for dividing the modulated oscillator frequency so many times is to reduce the modulation index enough to limit the peak phase deviation at the comparison frequency to a value that will not exceed the linear range of the phase/frequency detector. If the linear range is exceeded, the loop will lose lock. This is why some exciters may lose AFC lock in the presence of low frequency modulation components.

The phase detector output is integrated and low-pass filtered to remove the comparison frequency and all other frequency components above a few Hertz so that the AFC circuit does not try to track-out low frequency modulation. Some FM exciters use a dual-speed PLL in order to keep the loop turn-over frequency low enough to maintain good amplitude and phase response at 30 Hz, while also providing quick lock-up time. The PLL error correction circuitry must respond quickly during the initial frequency scan of the FM band to achieve lock-up to the precision reference oscillator in a few seconds. The loop bandwidth is wide during acquisition and lock-up. After lock is achieved, the bandwidth is reduced to provide the optimum modulation characteristic.

The reference oscillator is usually temperature compensated and requires no warm-up to maintain ±3 PPM or better accuracy over the operating temperature range. 10 MHz is often selected as the reference frequency for convenient comparison to international frequency standards. For more information about PLL frequency synthesizers see reference (5) at the end of this chapter.

Exciter Metering

Metering of important operating parameters can be provided by a combination of analog metering and a digital LED display. Steady-state parameters are usually selected by multiposition

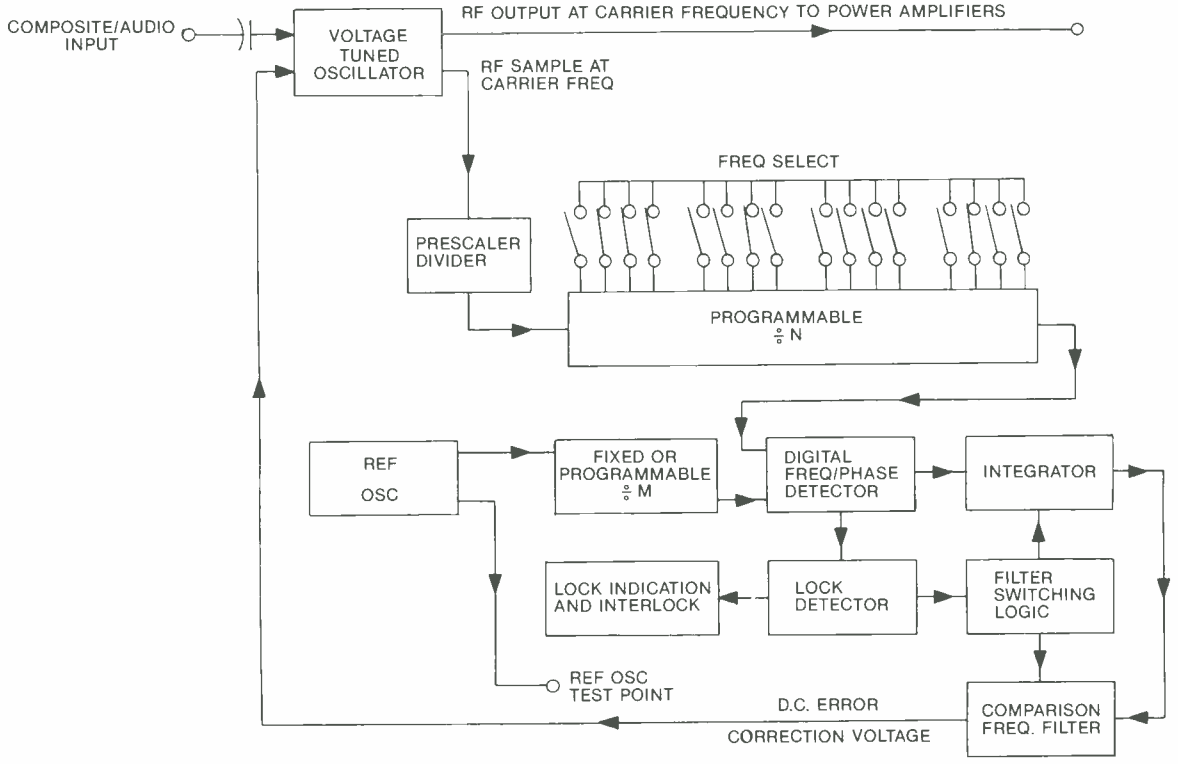


Fig. 15. Phase-locked-loop frequency synthesizer.

switch and displayed on a conventional analog multimeter. Typical steady-state functions include regulated, pre-regulated, and unregulated supply voltages; the AFC control voltage; RF power amplifier collector voltage and current; forward output power; and reflected power.

Either a color-coded LED display or a peak reading analog meter are usually provided to constantly monitor the time varying composite signal applied to the modulated oscillator. In either case, a high-speed peak detector gives accurate peak readings on signals from dc to 100 kHz. A one-shot multivibrator circuit provides a clear indication of short transient peaks exceeding 100 percent modulation.

Exciter Packaging

Protection of sensitive circuits within an FM exciter from external electromagnetic interference is important because the unit is often located in the near field of multiple broadcast antennas operating over a broad range of frequencies. The exciter should be protected from conducted EMI by use of RC and/or LC filters on all leads entering the cabinet, including the ac line. Additionally, the power transformer may have an electrostatic shield between the primary and secondary windings. The modulated oscillator is often shock mounted to prevent the transmission of mechanical vibrations from the transmitter's blower. This avoids microphonic pick-up by the modulator that would degrade the FM signal to noise ratio. Magnetic shielding of the modulator is also used to prevent hum pick-up from nearby transformers. In some cases, a hum-bucking circuit is provided to help cancel hum induced into the modulator.

The mechanical construction of most present day exciters is designed around a plug-in modular or semi-modular approach, which allows easy removal of sub-assemblies for repair or replacement.

The exciter chassis may be mounted on pull-out slides so that all sub-assemblies are accessible while the unit continues to operate. Front-panel test jacks are often provided to allow measurement of the composite signal without removing or opening the unit.

Exciter Output Stage

The broadband RF amplifier in the exciter amplifies the output of the modulated oscillator from a power level of a few milliwatts up to an output level in the range of 5 to 30 watts. The output stage should be protected against damage by an infinite VSWR at any phase angle.

The typical RF amplifier is designed to have a bandwidth of at least 20 MHz, using successive broadband impedance matching sections for each stage. Each group of matching sections consists of micro-strip or lumped elements.

The broadband performance of the RF amplifier eliminates the need for adjustments to any particular frequency within the FM band. The exciter output is transparent to the signal generated by the modulated oscillator and the amplifier stability is enhanced under varying load conditions.

A micro-strip directional coupler is often incorporated in the RF amplifier output network. This coupler supplies information to the exciter control circuitry which provides automatic control of power output level and provides protection against operation under high VSWR conditions.

All standard FM exciters will produce at least 10 watts output so they can be used as a complete transmitter for educational stations with the addition of a harmonic filter to the output. For higher power levels, the exciter is used to drive an external power amplifier.

RF POWER AMPLIFIERS

The remainder of the FM transmitter consists of a chain of power amplifiers, each having from 6 to 20 dB of power gain. Ideally, the transmitter should have as wide a bandwidth as practical with a minimum of tuned stages. Broadband solid-state amplifiers are preferred to eliminate tuned networks in the RF path. Higher powered transmitters in the multi-kilowatt range may use multiple tube stages each with fairly low gain such as in the grounded grid configuration or a single grid driven PA stage with high gain and efficiency. The dollars/watt economics of single-tube transmitters outweigh the bandwidth benefits of solid-state transmitters at the higher power levels with present technology. Design improvements in tube-type power amplifiers have concentrated on improving bandwidth, reliability, and cost effectiveness.

TRANSMITTER POWER OUTPUT REQUIREMENTS

The FCC regulates the power of FM broadcast stations in terms of effective radiated power (ERP). The authorized ERP applies only to the horizontally polarized component of radiation. Elliptical or circular polarization is also permitted where the ERP of the vertically polarized component may be as great as the authorized horizontal component. This means that twice as much total power may be radiated and twice as much transmitter power will be required.

The transmitter power requirement can be reduced by increasing the gain of the antenna. There is, of course, an economic trade off between the cost of a higher gain antenna versus the cost of a larger transmitter and the added primary power costs. For a high ERP, it is common to use antennas with up to 12 elements which provide a power gain of about 12.6 (or 6.3 in each polarization).

The long transmission lines associated with the tall towers commonly used are a source of considerable power loss. For example, the efficiency of 2000 ft. of 3-1/8 in. rigid coax at 100 MHz is only about 62 percent.

FM transmitters are designed to operate over a range of power outputs so that with a few basic sizes any required power output can be furnished. Popular maximum ratings range from 250 watts to 60 kilowatts. Most installations use a maximum transmitter power output (TPO) of thirty kilowatts because it is more economical to achieve the maximum 100 kilowatts ERP with circular polarization by means of sufficient antenna gain.

RF POWER AMPLIFIER PERFORMANCE REQUIREMENTS

The basic function of the power amplifier is to amplify the power of the exciter output to the authorized transmitter power output level. Most of the overall transmitter performance characteristics are determined by the exciter but a few are established or affected by the power amplifier characteristics:

1. The output at harmonics of the carrier frequency is almost completely a function of the attenuation provided by the output tank circuit and output low-pass/notch filters. The limit in decibels is [43 dB + 10(log watts) dB] or 80 dB whichever is less. (73 dB for 1 KW output or 80 dB for 5 KW and higher)
2. The major source of AM noise usually originates in the last power amplifier stage. The FCC limit is 50 dB below 100 percent equivalent AM modulation.
3. The RF power output control system which must keep the output within + 5 percent and -10 percent of authorized output is usually achieved in the final power amplifier.
4. Inadequate passband, particularly with respect to phase linearity across the signal bandwidth, can reduce stereo separation and cause SCA crosstalk.
5. The presence of standing waves on the transmission line to the antenna may also react with the power amplifier to cause degraded stereo separation and SCA crosstalk.

The power amplifiers should provide trouble-free service and be easy to maintain and repair. Good overall efficiency is also desirable to reduce the primary power consumption.

Power Amplifier Bandwidth Considerations

As mentioned earlier, the FM signal theoretically occupies infinite bandwidth. In practice, however, truncation of the insignificant sidebands (typically less than 1 percent of the carrier) makes the system practical by accepting a certain degree of signal degradation. The input and output tuned circuits of the PA limit the bandwidth of the FM signal. The degree of bandwidth reduction is a design constraint which affects the gain and efficiency in all tuned PA stages.

The bandwidth of an amplifier is determined by the load resistance across the tuned circuit and the output or input capacitance of the amplifier. For a single-tuned circuit, the bandwidth is proportional to the ratio of capacitive reactance to resistance:

$$BW = \frac{K}{2\pi f R_L(C)} \propto \frac{K(X_c)}{R_L}$$

Where: BW = bandwidth between half-power points (BW3)
K = proportionality constant
R_L = load resistance (appearing across tuned circuit)
C = total capacitance of tuned circuit (includes stray capacitances and output or input capacitances of the tube)
X_c = capacitive reactance of C
f = carrier frequency

The load resistance is directly related to the RF voltage swing on the tube element. For the same power and efficiency, the bandwidth can be increased if the capacitance is reduced.

INTERMEDIATE POWER AMPLIFIERS

The intermediate power amplifier (IPA) is located between the exciter and the final amplifier in higher power transmitters that require more than about 30 watts of drive to the final amplifier. The IPA may consist of one or more tubes or solid-state amplifier modules.

Interstage Coupling Circuits

The separate IPA output circuit and the final amplifier input circuit are often coupled together by a coaxial transmission line. Impedance matching is usually accomplished at either end by one of the configurations shown in Fig. 16A, 16-B, 16-C, and 16-D.

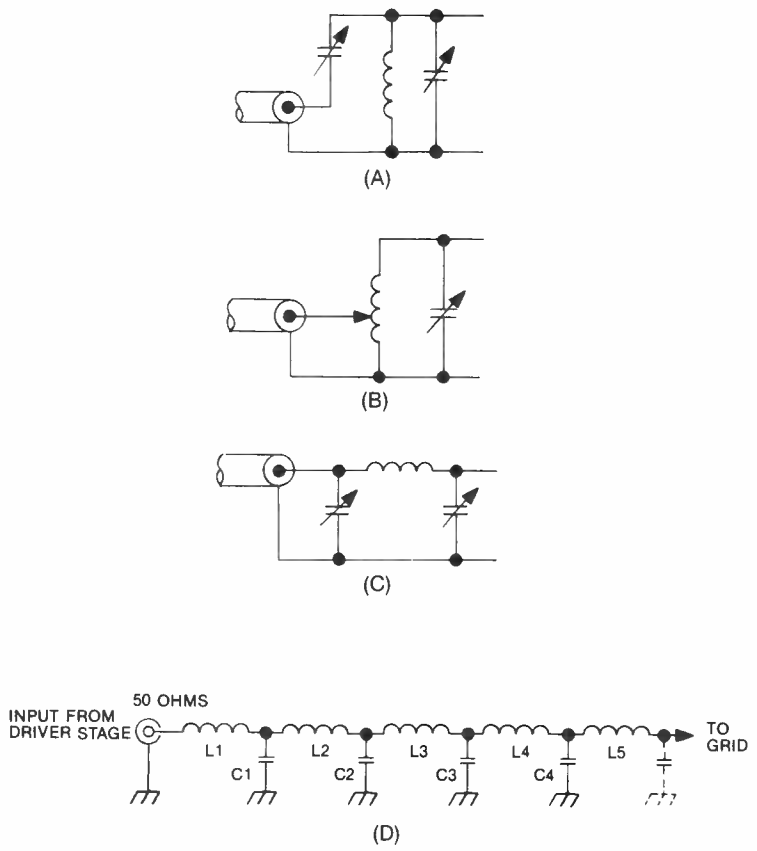


Fig. 16. Interstage RF coupling circuits.

All of the classical circuits shown in Fig. 16, except "D", require some interactive adjustment of the tuning and loading elements to provide a satisfactory impedance match for each operating frequency and RF drive level. The circuit in Fig. 16D utilizes multiple LC sections with each section providing a small step in the total impedance transformation. This technique provides a broadband impedance match without adjustment; thereby improving the transmitter's stability, ease of operation and maintainability. A single grid resonating control is sufficient to tune and match the 50 ohm driver impedance to the high input impedance of the grid over the entire 88-108 MHz FM broadcast band with a 4:1 range of RF power levels.

The interconnecting transmission line between the coupling circuits should be properly matched to avoid a high VSWR. Directional wattmeters are normally placed in the line to measure forward and reflected power from which standing wave ratio can be established. The VSWR is established by the match at the load end of the transmission line.

The transmission line matching problem is eliminated in some transmitters by integrating an IPA stage utilizing a tube(s) into the grid circuit of the final amplifier stage by having the plate of the IPA and the grid of the final tube share a common tuned circuit. This technique has the advantage of simplicity by not transforming the impedance down to 50 ohms and then back up to the grid impedance level, but does not allow the IPA to be connected directly to the antenna as a low power back-up system.

Solid-state RF power devices require a very low load impedance at the device output terminal, so that an impedance transformation that goes through the 50 ohm intermediate impedance level is required to couple these devices into the relatively high impedance of the final amplifier grid circuit. Therefore, virtually all solid-state IPA systems have a 50 ohm impedance point within the system that can be used to feed the antenna in an emergency.

High power transmitters utilizing a grounded-grid amplifier configuration in the output stage, require large amounts of drive power (typically greater than 1500 watts). The IPA may be a standard 3 KW transmitter that can also be used as a stand-by transmitter.

Most of the newer design high power transmitters only require between 150 and 600 watts of drive into a high gain final amplifier. This per-

mits the use of a system of solid-state, wideband modules to boost the exciter's power up to the level required to drive the grid of the final tube.

Solid-State IPA Systems

A solid-state IPA almost always consists of a system of individual amplifier modules that are combined to provide the desired power output. The advantages of using several lower power modules instead of a single high power amplifier are:

1. Redundancy is provided by isolating the input and output of each module, permitting uninterrupted operation at reduced power if one or more of the modules fails.
2. The ability to repair or replace failed modules without having to go "off-the-air".
3. More effective cooling of each power device junction by splitting the concentration of heat to be dissipated into several areas instead of one small area.
4. Better isolation between the amplifier modules and the input circuit of the final power amplifier is provided by the combiner/isolator.
5. Redundant power supplies for each module improve overall reliability.

Each RF power amplifier module consists of one or more solid-state devices with broadband impedance transformation networks for input and output matching. A new generation of class "C" BIPOLAR and MOSFET devices permit the design of broadband amplifier stages that exhibit both high efficiency and the wide bandwidth necessary to cover the FM broadcast band.

Regardless of which type of solid-state device is used, the input impedance is always lower than the desired 50 ohm input impedance, so a broadband impedance transformation scheme is required. This is usually accomplished by a combination of coaxial baluns and push-pull coaxial line sections that are cross-coupled to provide 4:1 or higher transformation ratios over the FM band.

By operating two devices in push-pull, the input impedance (differential) is double that of a single ended circuit and the suppression of even order harmonics is enhanced. Two devices fed in this manner also provide some degree of redundancy within the module itself since partial RF output can be obtained with one device failed. In a similar manner, the low output impedance of these solid-state devices can be transformed up to the desired 50 ohm module output impedance where combining occurs. Fig. 17 illustrates a simplified schematic of a broadband IPA module utilizing the push-pull configuration.

IPA Splitting and Combining

There are two types of splitting/combining schemes used:

1. 90 degree hybrid splitter or combiner ("N-1" hybrids required to split or combine "N" inputs). (see section on transmitter output combining)
2. Wilkinson "N-way" in-phase splitter or combiner.

Either type of splitter/combiner must provide isolation between the individual power amplifier modules and low loss splitting or combining of the total power. By choosing the proper lengths for the coaxial interconnecting cables, either of the above methods can be configured to operate the individual modules "in-phase" so that the loading on each of the modules tracks the other modules when the impedance at the output of the combiner is varied.

The cascaded 90 degree hybrid system shown in Fig. 18 provides double isolation between the IPA and the grid circuit by first combining the

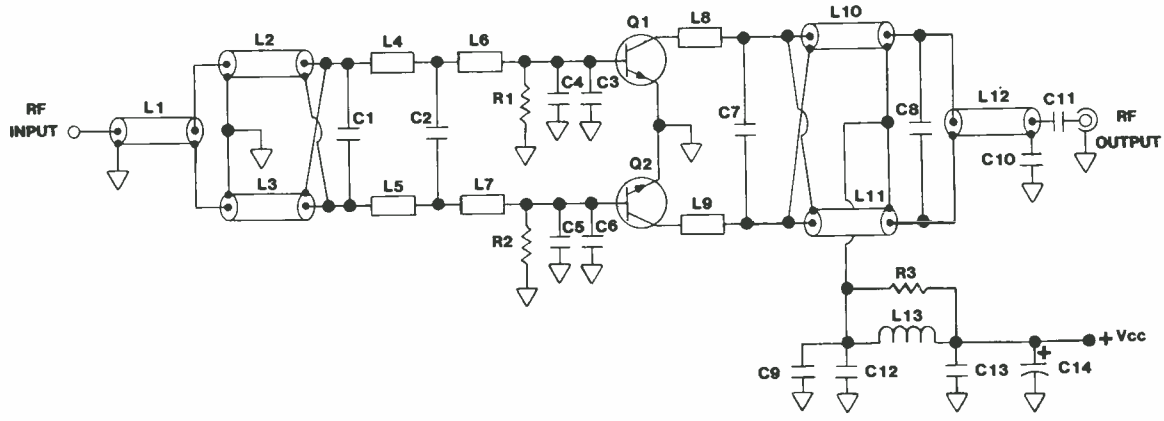


Fig. 17. Simplified schematic of a broadband intermediate power amplifier module.

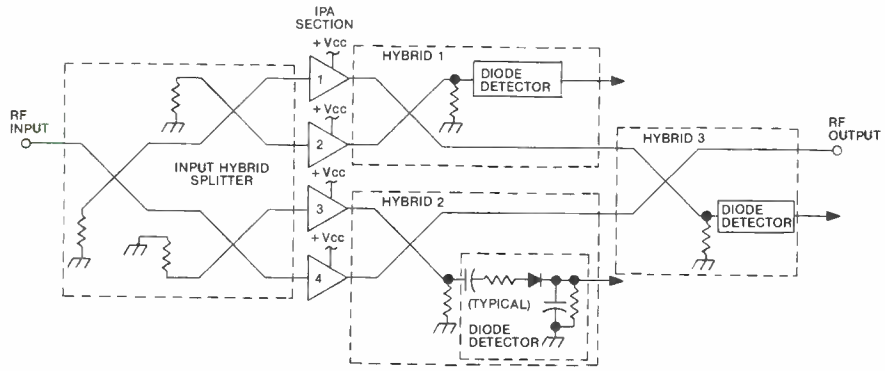


Fig. 18. Cascaded 90 degree hybrid splitting/combining system.

two pairs of amplifiers and then combining the outputs of the first two combiners. A portion of the reflected power, caused by a mismatch at the output, will be dissipated in the reject loads so that the IPA modules will operate into a lower VSWR than exists at the output. The unbalanced 50 ohm reject loads are accessible for monitoring of reject load power which is useful in determining the balance of the system. The coaxial interconnecting cables between module pairs must be offset in electrical length by one-quarter wavelength (90 degrees) at the operating frequency so that the modules operate in phase while the hybrids operate in quadrature.

The Wilkinson system shown in Fig. 19 is a simple and effective way to split and combine modules operating in phase, but usually requires a balanced reject load making reject power measurements more difficult. By adding additional coaxial balun sections to the Wilkinson/Gysel, e.g., it is possible to use unbalanced reject loads. Since the Wilkinson operates in phase, all of the coaxial interconnecting cables should be equal in length.

Since most IPA splitter/combiner systems are designed around a 50 ohm input and output impedance level, these systems can be easily used as a low power stand-by transmitter by routing the output to the antenna system. An RF low pass filter (LPF) is required only when directly feeding the antenna system. The harmonic suppression of the IPA is not as critical when driving a nonlinear power amplifier that also generates harmonics, because this stage will have its own LPF.

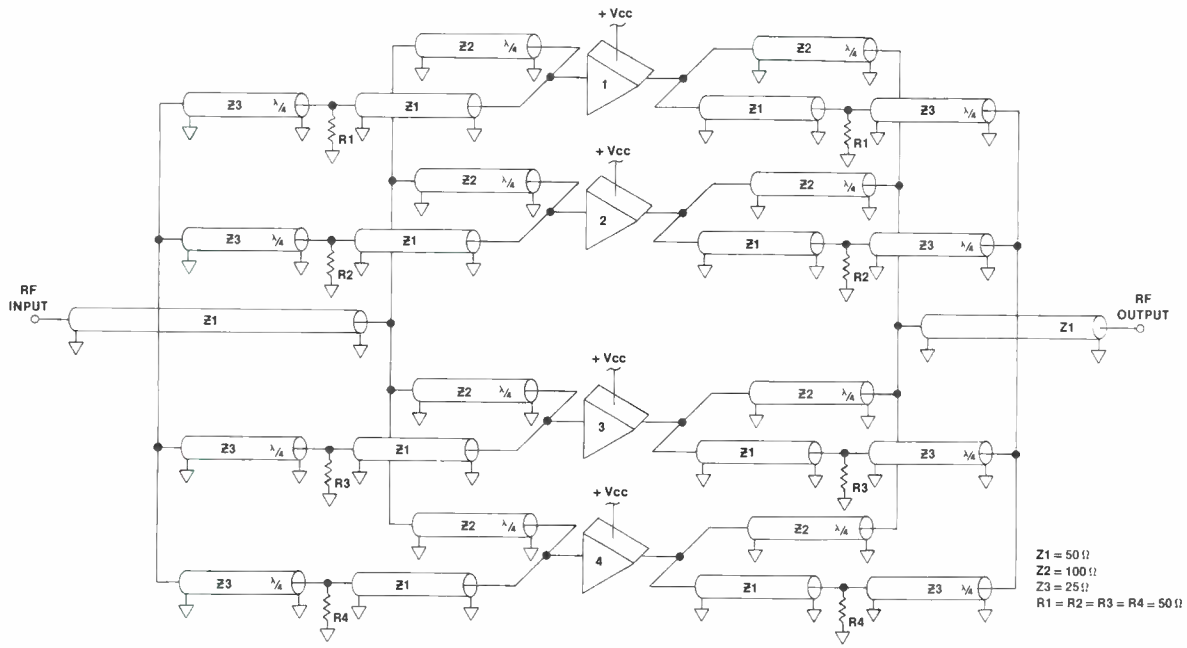


Fig. 19. Wilkinson/Gysel in-phase splitting/combining system with unbalanced reject loads.

Solid-State FM Broadcast Transmitters

The techniques used to construct IPA systems can also be used to construct a completely solid state transmitter using arrays of combined modules for the final output stage. An additional RF low pass filter is usually required to meet FCC emission requirements. Several manufacturers offer solid state FM broadcast transmitters with power outputs ranging from 100 watts up to several kilowatts, but present economic factors still favor the single tube FM transmitter for power levels above a few kilowatts. The primary advantages of a solid-state transmitter are the built-in amplifier redundancy and the ability to cover the entire FM band without the need for re-tuning. Even a tubeless transmitter is not entirely maintenance free, because high power solid-state RF devices do age and wear out like tubes, depending on the junction operating temperature and internal current density. The typical life of an RF transistor conservatively operated, is about ten years.

When broadband, solid state, amplifiers are combined for higher power, tuned output band-pass filters may still be necessary when operating in a dense RF environment in order to prevent RF intermodulation products from being generated in the PA modules.

For more information about solid state amplifiers and hybrid splitter/combiners, see references (6), (7), (8) and (9) at the end of this chapter.

VACUUM TUBE POWER AMPLIFIER CIRCUITS

The amplitude of an FM signal remains constant with modulation so that efficient Class "B" and "C" amplifiers can be used. Most exciters being manufactured at this time, provide 10 to 30 watts of output power. It is technically feasible to develop transistor amplifiers for any required power, but they are not yet economically competitive at high power levels. Additional circuitry is involved because it takes the combined output of many transistors to produce a few kilowatts of power output. For this reason, the following discussion will relate to vacuum tube amplifier circuits.

FM broadcast power amplifier circuits have evolved into two basic types. One type uses a tetrode or pentode tube in a grid-driven circuit while the other uses a high-mu triode in a cathode-driven (grounded grid) circuit.

Cathode-Driven Triode Amplifiers

The high-mu triodes being used in cathode-driven (grounded-grid) FM amplifiers were originally developed for linear SSB amplifiers. Their characteristics are well adapted to FM broadcast use because the circuit is very simple and no screen or grid bias power supplies are required. Fig. 20 shows the basic circuit configuration. In this case, the grid is connected directly to chassis ground. DC grid current is the difference between dc cathode current and dc plate current. The output tank circuit is a shorted coaxial cavity which is capacitively loaded by the tube output and stray circuit capacitance. A small capacitor is used for trimming the tuning and another small variable capacitor is used for adjusting the loading. A pi-network matches the 50 ohm input to the tube cathode.

The triodes are usually operated in the class "B" mode in order to achieve maximum power gain, which is on the order of 20 (13 dB). They can be driven into class "C" operation by providing grid bias. This increases the plate efficiency, but also requires increased drive power.

Most of the drive power into a grounded-grid amplifier is fed through the tube and appears in the stage's output. This increases the apparent efficiency so that the efficiency factor given by the manufacturer may be higher than the actual

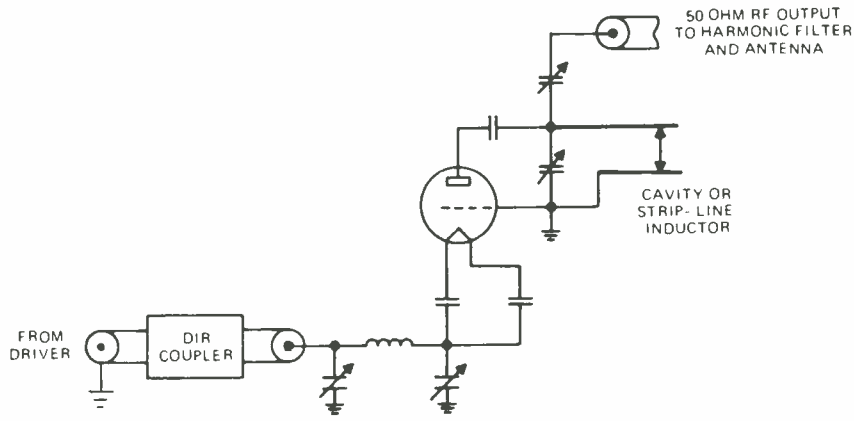


Fig. 20. Cathode-driven triode power amplifier.

plate efficiency of the tube. The true plate efficiency is determined by dividing the output power by the total input power, which includes both the dc plate input power ($I_p x E_p$) and the RF drive power. Since most of the drive power is fed through the tube, any changes in loading of the output circuit will also affect the input tuning and driver stage.

There is RF drive voltage on the cathode (filament) of the tube, so some means of de-coupling must be used to block it from the filament transformer. One method employs high current RF chokes since the inductance can be very low at this frequency range. The other commonly used method feeds the filament power through the input tank circuit inductor.

Cathode-driven stages are normally used only for the higher power stages. The first stage in a multi-tube transmitter is nearly always a tetrode because of its higher power gain.

Grounded-Grid Versus Grid-Driven Tetrode Operation

Tetrodes may also be operated in the grounded-grid configuration by placing both the control grid and the screen grid at RF ground. Higher efficiency and gain can be achieved by placing negative bias on the control grid while placing a positive voltage on the screen grid of a cathode-driven tetrode.

The input capacitance of a tetrode in a grounded-grid configuration is much less than a grid-driven configuration and the input impedance is lower providing better bandwidth.

Approximate input capacitances of some typical tubes are:

TUBE TYPE	Cin (PF)	
	Grounded Grid	Grounded Cathode
4CX 3,000A	67	140
4CX 3,500A	59	111
4CX 5,000A	53	115
4CX15,000A	67	161
4CX20,000A/8990	83	190

The typical drive power requirements, as a function of plate voltage, for a 5 kW power amplifier are:

CONFIGURATION	PLATE VOLTAGE/ DRIVE POWER	
	4500 VOLTS	5200 VOLTS
GROUNDED-GRID	340 WATTS	280 WATTS
GRID-DRIVEN	190 WATTS	140 WATTS

Television transmitters sometimes use a grounded-grid tetrode configuration to increase the input bandwidth of the amplifier. There are several trade-offs between the performance of grounded-grid and grid-driven operation of a tetrode PA with respect to gain, efficiency, amplitude bandwidth, phase bandwidth, and synchronous AM under equivalent operating conditions:

1. When driving the PA into saturation, the bandwidth of the PA is limited by the output cavity bandwidth in the grounded-grid amplifier. The PA bandwidth in the grid-driven amplifier is limited by the input circuit "Q", which is basically determined by the amount of swamping resistance.
2. Output bandwidth under saturation can be improved in either configuration by reducing the plate voltage. This involves a trade-off in efficiency with a smaller voltage swing. The bandwidth improvement can be obtained with a loss of PA gain and efficiency.
3. A grounded-grid saturated PA improves bandwidth over a grid-driven saturated PA at the expense of amplifier gain. Best performance for FM operation is obtained when the amplifier is driven into saturation where little change in output power occurs with increasing drive power. Maximum efficiency also occurs at this point.
4. The phase linearity in the 0.5 dB bandwidth is better in a grid-driven configuration. The class "C", grounded-grid, PA exhibits a more non-linear phase slope within the passband, yet has a wider amplitude bandwidth. This phenomenon is due to interaction of the input and output circuits because they are effectively connected in series in the grounded-grid configuration. The neutralized grid-driven PA provides more isolation between these networks, so they behave more like independent filters.

Grid-Driven Tetrode and Pentode Amplifiers

A small tetrode tube such as the 4CX250B is commonly used as the only amplifier stage in 250 watt transmitters and as the driver for higher power stages. The largest single stage transmitter presently available, uses a high gain 5CX1500A pentode to deliver 2.5 kW. Higher power levels require two stages (an IPA and the final PA).

Transmitters using tetrode amplifiers throughout usually have one less stage than those using triodes. Since tetrodes have higher power gain, they are driven into class "C" operation for high plate efficiency. Against these advantages is the requirement for neutralization, along with screen and bias power supplies.

Fig. 21 shows a schematic of a grid-driven tetrode amplifier. In this example, the screen is operated at dc ground potential and the cathode (filament) is operated below ground by the amount of screen voltage required. This is called grounded-screen operation. It has the advantage that stability problems due to undesired resonances in the screen bypass capacitors are eliminated. With directly heated tubes, it is necessary to use filament bypass capacitors. During grounded-screen operation, these bypass capacitors will need to have a higher breakdown voltage rating since they will have the dc screen voltage across them. The filament transformer must have additional insulation to withstand the dc screen voltage. The screen power supply provides a negative voltage in series with the cathode to ground and must have the additional capacity to handle the sume of the plate and screen currents. A coaxial cavity is used in the output circuit so that the circulating current is spread over large surfaces keeping the losses very low. This cavity is a shorted quarter-wavelength transmission line section which resonates the tube's output capacitance. The length is preset to the desired carrier frequency and then a small value variable capacitor is used to trim the system to resonance. Capacitive output coupling is used from the high RF voltage point to the 50 ohm transmission line. The 50 ohm input is capacitively coupled into the grid circuit inductor to provide the correct impedance match.

Pentode amplifiers have even higher gain than their tetrode counterparts. The circuit configuration and bias supply requirements for the pentode are similar to the tetrode since the third (suppressor) grid is tied directly to ground. The additional isolating effect of the (suppressor) grid eliminates the need for neutralization in the pentode amplifier.

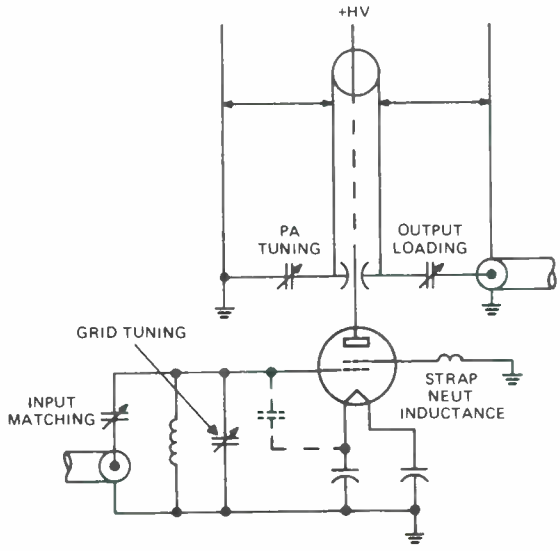


Fig. 21. Grid-driven grounded screen tetrode power amplifiers.

Impedance Matching into the Grid

The grid circuit is usually loaded (swamped) with added resistance. The purpose of this resistance is to broaden the bandwidth of the circuit by lowering the circuit "Q" and to provide a more constant load to the driver. It also makes neutralizing less critical so that the amplifier is less likely to become unstable with varying output circuit loading.

Cathode or filament lead inductance from inside the tube, through the socket and filament capacitors to ground, can heavily load the input circuit. This is caused by RF current flowing from grid to filament through the tube capacitance and then through the filament lead inductance to ground. An RF voltage is developed on the filament which in effect causes the tube to be partly cathode driven. This undesirable extra drive power requirement can be minimized by series resonating the cathode return path with the filament bypass capacitors or by minimizing the cathode to ground inductance by using a specially designed tube socket using thin-film dielectric "sandwich" capacitors for coupling and bypassing.

High power, grid driven, class "C", amplifiers require a swing of several hundred RF volts on the grid. To develop this high voltage swing, the input impedance of the grid must be increased by the grid input matching circuit. Since the capacitance between the grid and the other tube elements may be 100 picofarads or more, the capacitive reactance at 100 MHz will be very low unless the input capacitance is parallel resonated with an inductor. Bandwidth can be maximized by minimizing any additional circuit capacitance and utilizing a portion of the tube input capacitance as part of the impedance transformation network. Fig. 22A and 22B show two popular methods of resonating and matching into the grid of a high power tube. Both methods can be analyzed by recognizing that the desired impedance transformation is produced by an equivalent "L" network.

In Fig. 22A, a variable inductor (L_{in}) is used to raise the input reactance of the tube by bringing the tube input capacitance (C_{in}) almost to parallel resonance. Parallel resonance is not reached since a small amount of parallel capacitance (C_p) is required by the equivalent "L" network to transform the high impedance (Z_{in}) of the tube down to a lower value through the series matching inductor (L_s). This configuration has

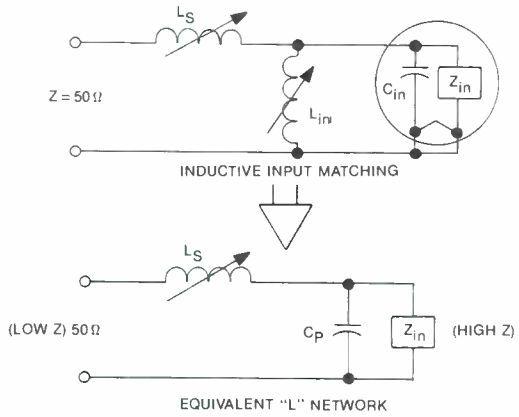


Fig. 22A. Inductive input matching.

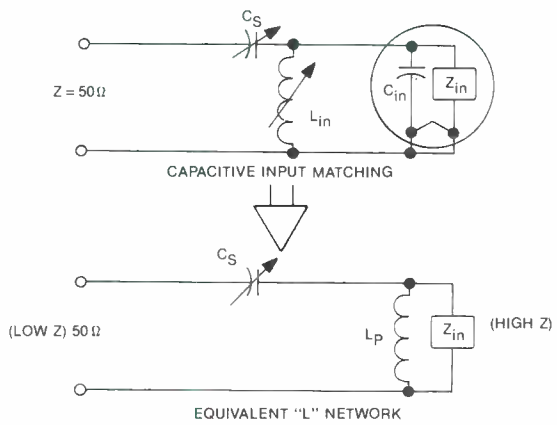


Fig. 22B. Capacitive input matching.

the advantage of providing a low-pass filter by using part of the tube's input capacitance to form (C_p), instead of an external bandwidth-reducing variable capacitor.

Fig. 22B uses variable inductor (L_{in}) to take the input capacitance (C_{in}) past parallel resonance so that the tube's input impedance becomes slightly inductive. The variable series matching capacitor (C_s) forms the rest of the equivalent "L" network. This configuration is a high-pass filter.

Neutralization

Apparently, none of the cathode-driven amplifiers utilizing triodes require neutralization. It is necessary that the grid-to-ground inductance, both internal and external to the tube, be kept very low to maintain this advantage. Omission of neutralization will allow a small amount of interaction between the output circuit and the input circuit through the plate-to-filament capacitance. This effect is not very noticeable because of the large coupling between the input and output circuits through the electron beam of the tube. Cathode-driven tetrodes have higher gain and may require some form of neutralization.

Grid-driven, high gain tetrodes need accurate neutralization for best stability and performance. Self-neutralization can be accomplished very simply by placing a small amount of inductance between the tube screen grid and ground. This inductance is usually in the form of several short, adjustable-length straps. The RF current flowing from plate to screen in the tube also flows through this screen lead inductance. This develops a small RF voltage on the screen, of the opposite phase, which cancels the voltage fed-back through the plate-to-grid capacitance. This method of lowering the self-neutralizing frequency of the tube works only if the self-neutralizing frequency of the tube/socket combination is above the desired operating frequency before the inductance is added. Special attention must be given to minimizing the inductances in the tube socket by integrating distributed bypass capacitors into the socket and cavity deck assembly. Pentodes normally do not require neutralization because the suppressor grid effectively isolates the plate from the grid.

POWER AMPLIFIER OUTPUT CIRCUITS

Usually, the output circuit consists of a "high-Q" (low loss) transmission line cavity, strip line, or a lumped inductor that resonates the tube output capacitance. A means of trimming the tuning and a means of adjusting the coupling to the output transmission line must also be provided by the output circuit. The tank circuit loaded "Q" is kept as low as practical to minimize circuit loss and to maintain as wide an RF bandwidth as possible.

The Power Amplifier Cavity

The vacuum tube power amplifier is constructed in an enclosure containing distributed tank circuit elements for minimum loss. The efficiency of the PA depends on the RF plate voltage swing, the plate current conduction angle, and the cavity efficiency. The cavity efficiency is related to the ratio of loaded to unloaded "Q" as follows:

$$N = 1 - \left(\frac{Q_L}{Q_u}\right) \times 100$$

Where: N = efficiency in percent
Q_L = loaded "Q" of cavity
Q_u = unloaded "Q" of cavity

The loaded "Q" depends on the plate load impedance and output circuit capacitance. Unloaded "Q" depends on the cavity volume and the RF resistivity of the conductors due to skin effects. A high unloaded "Q" is desirable, as is a low loaded "Q", for best efficiency. As the loaded "Q" goes up, the bandwidth decreases. For a given tube output capacitance and power level, loaded "Q" decreases with decreasing plate voltage or with increasing plate current. The increase in bandwidth at reduced plate voltage occurs because the load resistance is directly related to the RF voltage swing on the tube element. For the same power and efficiency, the bandwidth can also be increased if the output capacitance is reduced. Power tube selection and minimization of stray capacitance are areas of prime concern when designing for maximum bandwidth.

The methods used to improve the bandwidth of PA output circuits include minimizing added tuning capacitance. The ideal case would be to resonate the plate capacitance alone with a "perfect" inductor, but practical quarter-wave cavities require either the addition of a variable capacitor or a variable inductor using sliding contacts for tuning. The inherent mechanical and electrical compromises are the requirement for a plate dc blocking capacitor and the presence of maximum RF current at the grounded end of the line where the conductor may be non-homogeneous.

The Quarter-Wavelength Cavity

The quarter-wavelength coaxial cavity is the compact and popular output circuit illustrated in Fig. 23. The tube anode is coupled through a dc blocking capacitor to a shortened quarter-wave length transmission line. The tube's output capacitance is brought to resonance by the inductive component of the transmission line that is physically less than a quarter-wavelength long. Plate tuning can be accomplished either by adding end-loading capacitance at the high impedance end of the line with a variable capacitor or by sliding the ground plane at the low impedance end of the line. The plate tuning capacitor may be a sliding or rotating plate near the anode of the tube. The center conductor of the transmission line (chimney) is at dc ground while the anode of the tube operates at a high RF and dc potential. DC voltage is fed through an isolated quarter-wavelength de-coupling network inside the chimney to the anode of the tube, while the plate blocking capacitor prevents dc current flow from the anode into the chimney.

The Folded-Half-Wavelength Cavity

Another approach to VHF power amplification uses the re-entrant, folded-half-wave cavity design illustrated in Fig. 24. The dc anode voltage is applied to the lower portion of the plate line through a choke at the RF voltage null point.

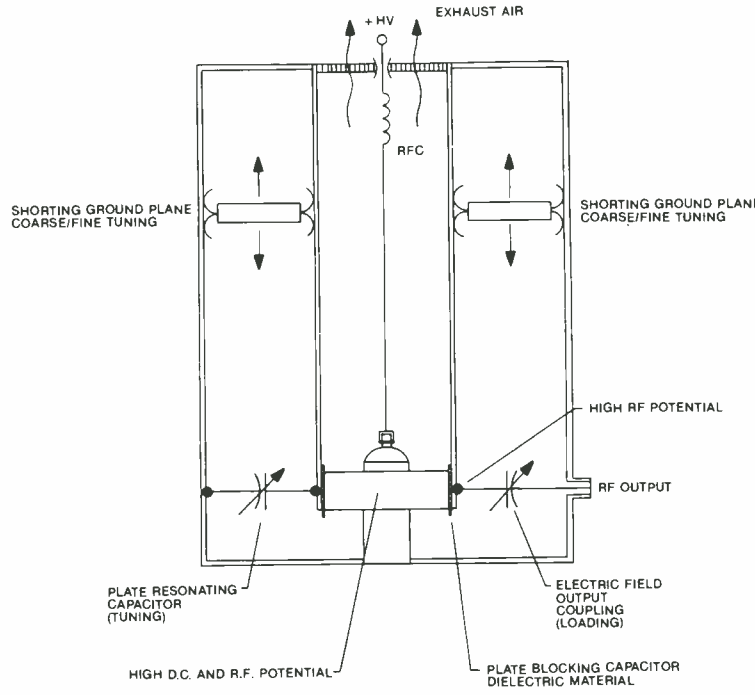


Fig. 23. The quarter-wavelength cavity.

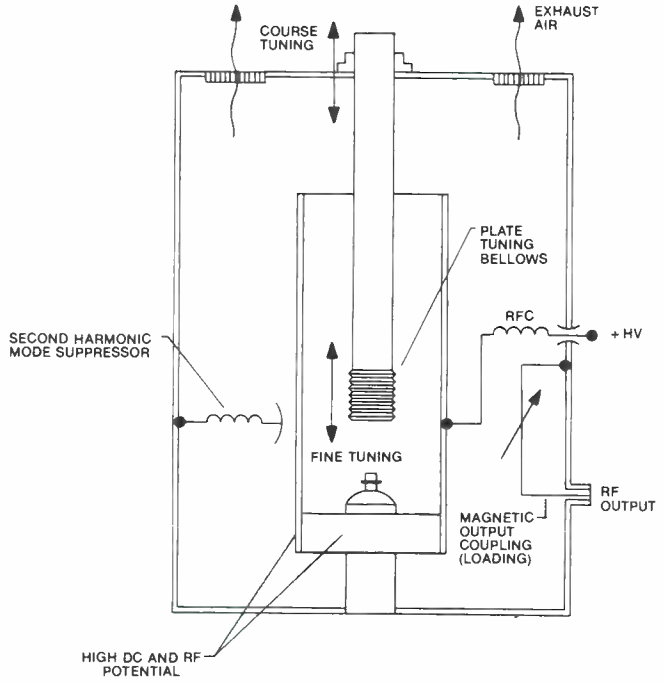


Fig. 24. The folded-half-wavelength cavity.

This RF voltage null point is reasonably consistent through the entire commercial FM broadcast band. The second harmonic voltage loop, which is located at this same point, exhibits a high source impedance and high voltage, allowing suppression with a simple series LC arrangement. This method provides about 50 dB of suppression to the second harmonic with little power loss at the fundamental frequency. The half-wave line is tuned by mechanically expanding or contracting the physical length of a flexible extension (bellows) on the end of the secondary transmission line stub, which is located concentrically within the primary transmission line (chimney). The bellows assembly is constructed of beryllium copper, providing high conductivity and long flex life.

Coarse frequency adjustment is accomplished by presetting the depth of the top secondary section of plate line into the tank cavity. A plate blocking capacitor is unnecessary since an air gap is provided between the primary line carrying the dc plate voltage and the secondary line at dc ground potential. Ohmic losses are minimized because the high RF current point is located in the central area of the homogeneous primary line where no joints, fasteners, or obstructions occur. Due to the folded nature, this configuration requires only slightly more physical space than the quarter-wave design.

Other power amplifier configurations may use lumped components or hybrid combinations with distributed transmission line elements to achieve similar results. The discrete circuit elements are chosen for their individual inductance or capacitance, instead of being operated in a purely quarter-wave or half-wave mode. Stray inductance and capacitance add to the component values resulting in the hybrid nature of these circuits.

The RF voltage and current distributions for the quarter-wavelength and the folded-half-wavelength cavities are shown in Fig. 25.

Regardless of the specific configuration, the output circuit must transform the high resonant plate impedance down to the output transmission line impedance of 50 ohms.

The bandwidth of either a quarter-wave or half-wave transmission line cavity is optimized by choosing the highest characteristic impedance mechanically allowable. The center conductor is sized for minimum impedance discontinuity and is clamped to the outer surface of the anode fins for better heat transfer. In the folded half-wave cavity, the secondary tuning line (with adjustable bellows) is sized to maintain a similar characteristic impedance without appreciable end-loading capacitance.

References (10) and (16) at the end of this chapter give detailed information about the design of tube type RF power amplifiers.

Output Coupling

Power may be coupled from a quarter-wavelength cavity to the transmission line by a capacitive probe located at the high RF voltage point

located at the anode end of the quarter-wave line as shown in Fig. 23. The loaded "Q" of this circuit varies with the degree capacitive coupling. Another method of coupling power from the quarter-wavelength cavity uses a tuned loop located near the grounded (high current) end of the line.

Power may be coupled from the half-wave line by an inductive loop located in the strong fundamental magnetic field near the center of the cavity as shown in Fig. 24. One end of the output loop that couples energy to the transmission line is electrically grounded to the cavity wall. Output loading is mechanically controlled by changing the position of the loop in the magnetic field generated at the null point of the primary line structure. Multiple phosphor-bronze leaves provide the connections to the loop allowing mechanical movement without sliding contacts. The coupling to the cavity varies as the square of the effective loop area and inversely as the square of the distance of the loop center from the cavity center axis. As this loop is positioned so that it links more or less magnetic field, it determines the output loading of the transmitter.

Power Amplifier Source Impedance

At the milliwatt levels used in RF test equipment, it is customary to provide both 50 ohm source and load impedances at both ends of a coaxial transmission line. This approach minimizes any reflections on the line since both the transmitter (source) and the termination (load) will absorb reflected energy. A 50 ohm source impedance is usually provided by placing a 50 ohm build-out resistor in series with a low impedance voltage source (Thevenin equivalent). The closed circuit voltage with this configuration is exactly one-half of the open circuit voltage, meaning that half of the total available RF power is dissipated in the source resistance.

It becomes obvious that while an FM transmitter is designed to drive a 50 ohm load, it does not itself have an output source impedance of 50 ohms. In order to achieve high efficiency, the output stage is driven into voltage saturation which provides a low output source impedance. Since the low source impedance of the transmitter provides a mismatch to reflected power from the load, this power is almost totally reflected back from the transmitter output stage toward the load again.

POWER SUPPLIES

Power supplies provide the appropriate dc or ac voltages to the various subsystems with the transmitter. The range of voltages and currents provided can be from less than 5 volts at a few milliamperes, to over 10,000 volts at several amperes in a typical FM transmitter. Safety must be a prime consideration when working around potentially lethal power supplies. Power supplies must be designed with adequate bleeder resistors and interlocks to discharge high voltages before an operator can come in contact with these circuits. The degree to which the ac components are filtered out of the dc outputs of the power supplies will, in large part, determine the "asynchronous" (without FM modulation) AM noise of the FM transmitter.

FM transmitters usually contain multiple power supplies for each of the functional blocks within the system. These power supplies fall into two general categories:

1. Single-phase supplies (single input winding on the transformer).

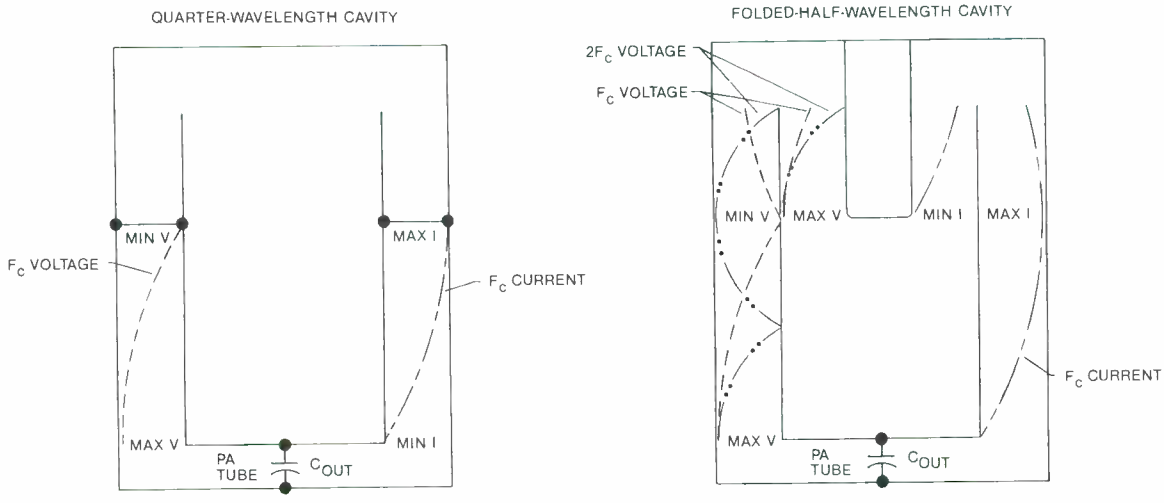


Fig. 25. Cavity RF voltage and current distributions.

2. Polyphase supplies (3 or more input windings on the transformer).

Single Phase Power Supplies

Single-phase power supplies with conventional full-wave rectification and filtering are most often used for the FM exciter, the control system, bias supplies, and the intermediate power amplifier (IPA). The filament transformer is also a single-phase transformer. A single-phase supply requires a larger filter choke to achieve the "critical inductance" requirement and a greater value of filter capacitance to maintain acceptably low ripple content compared to a polyphase supply. Large value filter components also mean that the greater stored energy in these components can have a more destructive effect if an arc-over occurs. Choke-input filter sections are normally used to help limit the in-rush current while the shunt capacitor is charging during turn-on. This also maximizes utilization of the transformer and rectifiers by keeping the charging current nearly constant, providing the best filtering action. Choke-input filters have the undesirable characteristic of poor voltage regulation over a wide range of loads. The output voltage will "soar" above the nominal value with no load unless there is enough current through the "bleeder" resistor to keep the choke in the constant current range. Fortunately, in a FM transmitter application, the load on the power supply is fairly constant since the power output of the transmitter does not vary significantly with FM modulation. In higher power transmitters where the main power source is three phase, care must be taken to balance each of the individual single phase loads among the three phases so that the total load on each of the individual phases is equal.

Polyphase Power Supplies

Polyphase power supplies are used for the final power amplifier high voltage supply in high power transmitters. Sometimes they are also used for tube or solid state IPA supplies. Large blowers used to cool transmitters are usually operated from a three phase power source. Care must be taken to make the three line connections to the blower motor in the proper sequence so that the motor will turn in proper direction.

The most common type of polyphase supply is three phase with full-wave rectification and LC filtering. Other polyphase systems encountered in broadcast equipment are usually multiples of the three phases with twelve phase rectifiers becoming more popular. The main advantages of a polyphase power supply are:

1. Division of the load current between three or more lines to reduce line losses and the size of each of the lines.
2. Greatly reduced filtering requirements after rectification due to the low ripple at the output of a polyphase full-wave rectifier.
3. Better voltage regulation with a choke input filter with typically 6% or less "soaring" from no load to full load.
4. Greater choice of output voltages from a given transformer by selection of either a DELTA or WYE configuration.

The main disadvantage of polyphase systems is their susceptibility to phase imbalance which causes degraded performance of the power supply. If significant imbalance exists in a polyphase system ripple rejection will be reduced in the polyphase rectifier with a resulting increase in AM noise.

The broadcast engineer should be particularly careful to be sure that the local utility does in fact, provide true three-phase power to the transmitter site. This can usually be verified by making sure that there are three transformers on the utility pole feeding the transmitter site. In many rural areas, the utilities are still synthesizing pseudo-three-phase service by providing the so called "open-delta" (V-V) or "Scott" (T-T) connection with two transformers instead of true three phase service. Operation on an "open-delta" service will degrade the transmitter's performance and increase the susceptibility of the transmitter to damage from transients on the line. Most transmitter manufacturers state that their warranty is void if the transmitter is connected to an "open-delta" system.

Special Power Supplies

Trends toward completely solid-state power amplification demand lower voltages at much higher currents. Voltage regulation of these high current supplies is necessary to suppress ripple, but the design of these specialized regulators is different from the typical high voltage power supply. Linear regulators are used at the lower power levels because they are low in efficiency, but they are simple and provide excellent ripple rejection without the need for suppression of switching transients. The linear regulators use series or shunt devices which change resistance dynamically to provide regulation with changes in load and therefore dissipate some of the power within the dynamic resistance.

Switch-mode regulators are used at higher power levels because they are high in efficiency, but they are more complicated and require additional suppression of the switching transients. The high efficiency comes from the digital "on" or

"off" nature of the switching regulator which reduces resistive losses by using low loss reactive components to store energy during switching.

In some cases, phase control switching regulation is applied to the high voltage power supply feeding the final output tube. The regulation is accomplished by switching thyristors in the ac mains ahead of the primary winding of the transformer. As the switching duty cycle is reduced, the plate voltage is also reduced. Care must be taken to protect solid-state devices connected to the main power line from lightning transients. Heavy duty transient suppressors are available for this purpose.

Low voltage/high current power supplies contain extremely large amounts of stored energy that can be dangerous due to the high peak currents that can occur during a short circuit across a component with high stored energy. For this reason, special attention must be paid to methods of safely discharging these circuits without damage to components or injury to the operator. The voltage regulator should provide short-circuit protection with some type of current limiting. The main danger to the operator from this type of power supply is burns due to the nearly instantaneous heating of metallic tools or other conductors that accidentally get into a high current path such as a short across the filter capacitor.

For more detailed information on power supply theory, see references (2), (12), and (13) at the end of this chapter.

Step-Start

Step-start is often used in large power supplies where peak in-rush currents become high when the power supply is first turned on. These peak currents are caused by the need to overcome the hysteresis effect to initially magnetize the core of the transformer when ac power is first applied and to charge the filter capacitor. Step-start systems temporarily insert a resistance or reactance in series with the power lines to limit the current to a reasonable value until initial magnetization of the core and filter charging are completed. The system should be designed so that failure of the step-start mechanism will not prevent getting "on-the-air" without step-start. This is accomplished by using "fail-safe" systems where the current limiting components are only in series with the line during the starting interval until the main circuit is closed in parallel with the step-start circuit, then the connection to the current limiting components is opened.

TRANSMITTER CONTROL SYSTEMS

Transmitter control systems are often overlooked or given little priority in the selection and maintenance of a broadcast transmitter. The transmitter's control system does however, serve several important purposes:

1. Must provide basic on/off control of the transmitter.
2. Must provide overload protection to protect the transmitter from damage.
3. Must provide safety interlock protection to prevent injury to people and accessory equipment such as RF switching equipment or RF loads.
4. Must provide a means for controlling the transmitter output power.
5. Must provide remote control capability and interfacing at installations where the transmitter is not at the same location as the control operator.
6. Must provide warm-up and cool-down timing sequences of filaments or other time sensitive operations.
7. May provide status indications of overloads or other critical parameters.
8. May provide automatic regulation of the transmitter output power.
9. May provide diagnostic indications to aid in adjustment and maintenance.
10. May provide totally automatic operation of the transmitter plant (ATS).

The transmitter's ability to stay "on-the-air" will only be as good as the reliability of the control system, so it is easy to recognize the importance of the selection and correct operation of the transmitter control system.

Early transmitter technology relied on simple relay logic combined with electromechanical contactors to control the transmitter. The speed and variety of overload protection was limited and diagnostics were not available. While these systems had the virtue of being simple and immune to RFI, the relay logic required continuing maintenance in order to keep the contacts clean and adjusted.

Later, the transmitter control logic relays were replaced by solid-state digital logic. This provided much more flexibility and reliability, but also raised concerns about the ruggedness and ability of solid-state logic to survive lightning strikes. Although this concern is valid, modern solid-state logic systems are well protected against damage by optical isolation, shunt protection techniques, and RFI filtering. Operating experience with the current generation of transmitters has proven that a properly designed solid-state control system is far more reliable than its relay predecessors.

Automatic Power Control

Many transmitters also provide automatic power control (APC) circuitry to maintain the transmitter's power output within preset limits by correcting for changes in line voltage, component aging, or small amounts of drift in operating parameters. The APC circuitry compares a sample of the transmitter output power against a reference and then adjusts the RF drive or other voltages within the transmitter to bring the output power within tolerance. Some of the more sophisticated APC circuits also provide proportional VSWR fold-back of the transmitter output power. If a sample of the reflected power on the transmission line exceeds a safe limit, the transmitter output power is proportionally reduced to a safe level until the problem is resolved. This feature prevents lost air time during antenna icing or other limited VSWR situations. All standard APC circuits should provide fast-acting shutdown of the transmitter during a catastrophic failure of the antenna system such as a short or open circuit. A well designed APC system should operate like a damped analog feedback system with fast response and low overshoot.

Microprocessor Control Systems

Recently, microprocessor technology has been applied to broadcast transmitter control systems. Microprocessor based control systems can expand the functions of the transmitter controller from basic housekeeping duties into powerful self diagnostics, controller redundancy, integrated remote control, user customization, and even self-correction of operational problems.

Microprocessor technology lends itself well to industrial control applications like broadcast transmitters because the hardware can be made just as reliable as hard-wired digital logic, but has the advantage of allowing changes and growth in the operational features by simple changes in software instructions without requiring a complete redesign of the hardware.

Several transmitter manufacturers are marketing transmitters with microprocessor based control systems. Some of the typical features that distinguish these control systems from non-microprocessor systems are:

1. Built-in trouble tree with fault location and diagnostic readouts often using plain English messages (user-friendly).
2. Simultaneous readouts of all operating parameters.
3. Real time calculation of efficiency, dissipation, VSWR, and other parameters requiring mathematical operations.
4. Built-in clock/calendar for logging changes in operating status, power failures, and overloads.
5. Tolerance flagging on key operating parameters as warnings for logging and for preventive maintenance.
6. The ability to communicate with the outside world for remote control or logging purposes through a standard serial interface.
7. The customer has the ability to customize the system features to the individual requirements of the station through the use of software menus.
8. Tuning aids which will allow the operator to adjust the system for peak efficiency, minimum dissipation, and minimum VSWR by means of a real time display of these calculated parameters.

The method of communicating information to the operator varies from one system to another, but most use LED or LCD readouts with codes or alphanumeric messages. Some microprocessor controllers use CRT displays so that a large amount of information can be displayed in several different formats.

Controller Back-Up Systems

A certain degree of redundancy is desirable in the transmitter control system so that the transmitter can stay "on-the-air" even if a portion of the system fails. There are several approaches being used in present equipment to provide back-up systems. A multi-level hierarchy can be used which automatically hands over basic control functions to a primary controller in the event of a problem in the microprocessor hardware or software. Good system design separates diagnostic and supervisory functions from basic control functions so that a failure in a higher level function will not affect the ability of the system to remain "on-the-air" without interruption. Watchdog circuits and software are embedded within the control system to detect failures and initiate corrective action before an interruption in service occurs.

It is also possible to have two entirely independent microprocessor systems operating in parallel with only one system in charge at one time. Sophisticated software is required to determine if the two systems agree and if they don't agree, an algorithm must be used to decide which one is right so that control can be delegated to the properly functioning system.

The ability to quickly substitute another replacement control system or a simplified controller bypass unit is useful in the event of total failure of the control system.

Remote Control Interfacing

Regardless of the type of control system used, the ability to interface easily with standard remote control systems is very important. Most modern systems interface with parallel control lines for each individual function requiring a momentary contact closure of 24 volts or less at a current of 50 milliamperes or less. These levels are compatible with relay logic or optically isolated solid state logic. Analog levels output from the transmitter for remote meter readings generally are fully buffered and fall into the range of 0-10 volts dc for a full scale reading at an impedance level of less than 10K ohms.

With the advent of microprocessor-based control systems there is a trend toward using standard computer asynchronous serial interfacing instead of parallel interfacing. Serial interfacing reduces the number of connections to the transmitter and can carry both control functions and digitized meter readings through the same interface. By converting analog information into digital information before transmission to the remote control point, the need for calibration and re-calibration of the remote metering point is reduced. Microprocessor based control systems also allow the remote control system functions to be integrated directly into the transmitter itself giving the remote control point access to more in-depth information about the transmitter than is possible by interfacing with an external remote control system.

For more specific information, see the chapter on remote control systems.

RF OUTPUT LOW-PASS FILTERS

The high efficiency, non-linear RF power amplifiers used in FM broadcast transmitters generate significant amounts of energy on frequencies that are integer multiples (harmonics) of the desired fundamental frequency. The output circuit alone does not provide enough harmonic attenuation to meet FCC Regulations. To comply with Part 73 of the FCC Rules and Regulations and to prevent interference to other services, a low-pass filter must be installed in the transmission line at the output of the transmitter. The FM band is narrow enough that one low-pass filter design can be used for any FM channel carrier frequency. These filters usually consist of multiple LC sections arranged so that frequencies within the FM band are passed with little attenuation (typically 0.1 dB or less) while frequencies above the FM band are highly attenuated (60 dB or more).

The most common type of filter used in this application is called a "reflective" filter, meaning that the frequency components outside the passband are reflected back out of the filter toward the source because it provides a mismatch at these undesired frequencies. The filter can be constructed using either "lumped" inductors and capacitors or by using a section of non-constant impedance transmission line to form "distributed" inductors and capacitors. The filters designed for low power transmitters often employ "lumped" elements (coils and capacitors) because they are compact and can be integrated into the transmitter cabinet. The distributed type of filter is most often used with high power FM broadcast transmitters because of its simplicity, extreme ruggedness, and ability to handle higher power levels. The distributed filter does have the disadvantage of having larger physical dimensions than a similar lumped filter, which may necessitate mounting the filter external to the transmitter cabinet. Fig. 26 shows a cut-away view of a typical distributed low-pass filter. Note that the areas where the center conductor of the transmission line is smaller than that required for the input Z_0 are inductive, while the areas where the center conductor is larger in diameter are capacitive.

When two filters (such as the output cavity and the harmonic filter) are connected together by a transmission line, the total harmonic attenuation will vary with interconnecting line length. The attenuation characteristics of the harmonic filter are specified for the condition where both the source and load impedances are equal to the desired transmission line impedance.

In actual use, the source impedance at the output of the tank circuit is much less than the 50 ohm load impedance presented by a properly terminated filter. If an unfortunate length of line is selected, the harmonic attenuation may be insufficient and the transmitter tuning may be affected. This undesirable condition can be corrected by changing the line length by approximately one-quarter wavelength. The line length between the tank circuit and harmonic filter is

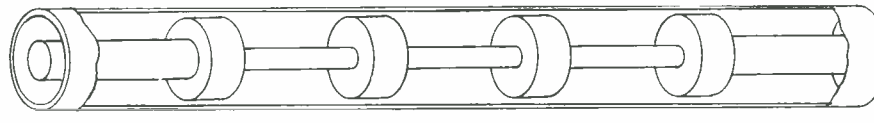


Fig. 26. Cut away view of a distributed low-pass filter.

usually supplied pre-cut to a value known to be satisfactory by the transmitter manufacturer.

Notch Filters

In some cases, a second harmonic notch filter is required in addition to the low-pass filter because the second harmonic component from amplifier is high and the cut-off slope of the low-pass filter is not steep enough to provide sufficient second harmonic attenuation. The additional attenuation required (typically 30 dB) can be provided by an absorptive notch filter which places a short circuit across the transmission line at the second harmonic while providing a high impedance at the fundamental. A one-quarter wavelength (at the fundamental frequency) shorted coaxial stub is often used for this function.

Some types of transmitters, including those using the folded half-wavelength cavity, have internal second harmonic mode suppressors which eliminate the need for an external notch filter.

TRANSMISSION LINE POWER AND SWR MEASUREMENTS

Directional wattmeters are instruments that measure the forward power (P_f) and reflected power (P_r) in a transmission line. The net power delivered to the load (antenna) is (P_f-P_r). If the transmission line is perfectly matched all the forward power will be absorbed by the load and there will be no reflected power. The peak voltage at each point along the line will be the same value and similarly the current at each point along the line will also have a uniform value. If the transmission line is mismatched, there will be reflected power with a resulting "standing wave" on the line. This means that the voltage and current distributions along the line will no longer be uniform with high values at certain points on the line and low values at points on the line that are one quarter wavelength away. The ratio of high value to the low value is called the standing wave ratio (SWR).

Standing Wave Ratio

The standing wave ratio (SWR) on the transmission line is related to the ratio of the forward to reflected power by the following formula:

$$SWR = \frac{1 + \sqrt{\frac{P_r}{P_f}}}{1 - \sqrt{\frac{P_r}{P_f}}}$$

This relationship is shown graphically in Fig. 27 so the approximate SWR can be obtained without computation.

The standing wave is due to the presence of two components of power, one traveling toward the load and the other reflected by the load mismatch, traveling back toward the generator.

These components are defined as:

$$P_f = \frac{(E_f)^2}{Z_o} = (I_f)^2(Z_o)$$

$$P_r = \frac{(E_r)^2}{Z_o} = (I_r)^2(Z_o)$$

$$P_n = (P_f - P_r)$$

The subscripts (f) and (r) are used to denote the forward and reflected values of power, voltage, and current; while Z_o is the characteristic impedance of the transmission line. (P_n) is the net power absorbed by the load (transmission line loss and antenna radiation).

Since the forward and reflected voltage and currents are traveling in opposite directions, they will add in phase at some point along the line length to produce a voltage maximum. One-quarter wave length along the line in either direction from this maximum, the forward and reflected components are out of phase and produce a voltage minimum. The forward and reflected components of current also add vectorially to produce a current standing wave. The magnitude of the standing wave is defined as:

$$SWR = \frac{E_{max}}{E_{min}} = \frac{I_{max}}{I_{min}}$$

The ratio of the highest voltage point on the line to the lowest voltage point on the line is a commonly used measure of system performance defined as the voltage standing wave ratio (VSWR). A VSWR of 1.0:1 means that a perfect match has been achieved while a VSWR of 2.0:1 means that a mismatch is causing approximately 11% of the power to be reflected.

At the point of reflection (the load mismatch), the phase of the reflected current is reversed 180 degrees from the forward current. The reflected voltage does not have this phase reversal. This displaces the voltage and current standing waves by 90 degrees along the line so that the (E_{max}) and (I_{min}) occur at the same points while (E_{min}) and (I_{max}) occur 90 degrees (one-quarter wavelength) away, in either direction from (E_{max}) and (I_{min}).

The fact that the reflected current is reversed in phase makes it possible to measure forward and reflected power separately using a device called

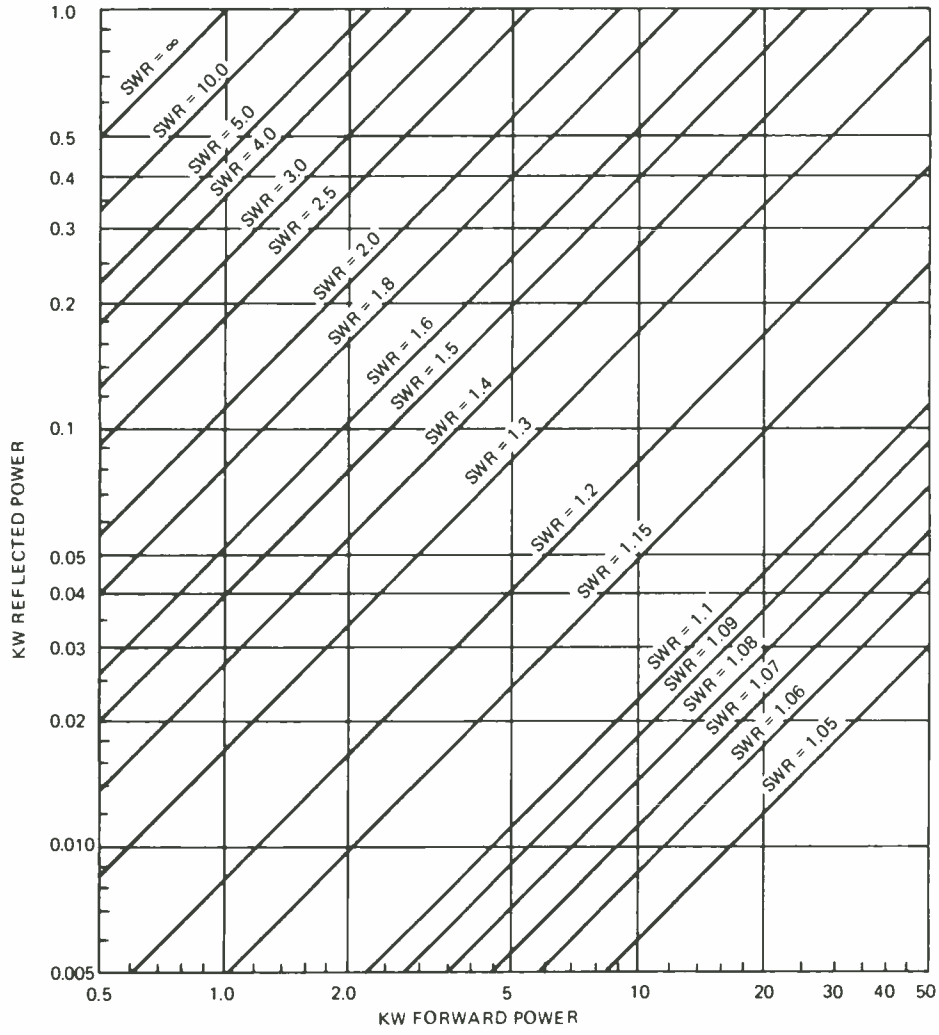


Fig. 27. Chart of SWR versus forward and reflected power.

a directional coupler. A small voltage is obtained by inductive coupling which represents the current in the transmission line. To this is added a sample of the voltage across the line that is simultaneously obtained by capacitive coupling. These two samples are adjusted to be exactly equal when the line is terminated with its characteristic impedance (no standing waves and no reflected components). The two RF samples are added, which gives a resultant RF voltage proportional to the forward components of voltage and current as illustrated in Fig. 28A.

The forward components of the samples are equal and in phase but the reflected components of voltage and current balance out. By having a second coupling section physically turned around in the opposite direction, the phase of the current sample is reversed and the reflected components add while the forward components balance out as illustrated by the vector diagram in Fig. 28B. These voltages output by the directional coupler representing the forward and reflected powers are usually rectified and buffered to feed the automatic power controller and a power indicating meter. Since power is proportional to the square of the voltage on the transmission line, the meter scale is calibrated to read the square of its input along with a diode correction factor so that forward and reflected power are read out directly.

VSWR Measurement

Although some FM transmitters can operate into a VSWR of greater than 1.8:1, the VSWR on an FM antenna transmission line should normally be kept to a value of 1.1:1 or less for good stereo performance. It takes very little reflected power to produce substantial VSWR as shown in Fig. 27. For this reason, the reflected power is usually read on a more sensitive meter position. Problems in the antenna system such as loose connections or icing may cause excessive VSWR. Instruments external to the transmitter

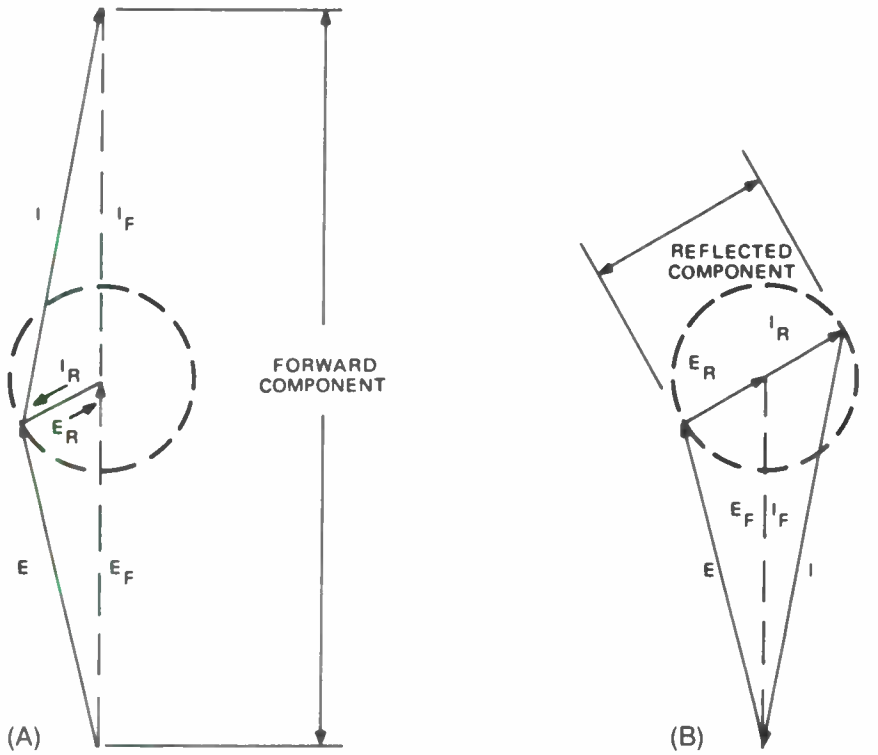


Fig. 28. Phasor addition of voltage and current samples to separate forward and reflected components.

are available that monitor reflected power and energize an alarm if it becomes excessive. As long as the transmitter power output is fairly constant, the use of reflected power to indicate excessive VSWR is simple and adequate.

COMBINED TRANSMITTERS

It is possible to combine the output of two RF power amplifiers for higher power levels. The important advantage is that the broadcast transmission is not interrupted if one amplifier fails. The radiated signal strength merely drops 6 dB until the failed amplifier is repaired and put back on the air. A dual amplifier system costs more than a single amplifier for a given total power output, but there are the economic advantages of reducing lost air time and eliminating the need for a separate standby transmitter. Automatic or manual output switching can be used to route the full power of the remaining amplifier directly to the antenna. Some stations go one step further and also install dual exciters with automatic switching so that if one exciter fails, the other unit is quickly switched into service.

Hybrid Couplers

Hybrid couplers are reciprocal 4-port devices that can be used either for splitting or combining RF sources over a wide frequency range. Fig. 29 shows an exploded view of a typical 3 dB, 90 degree hybrid coupler. The coupler consists of two identical parallel transmission lines that are coupled over a distance of approximately one-quarter wavelength and are enclosed within a single outer conductor. Ports at the same end of the coupler are in-phase while ports at opposite ends of the coupler are in quadrature (90 degree phase shift) with respect to each other.

The phase-shift between the two inputs or outputs is always 90 degrees and is almost independent of frequency. If the coupler is being used

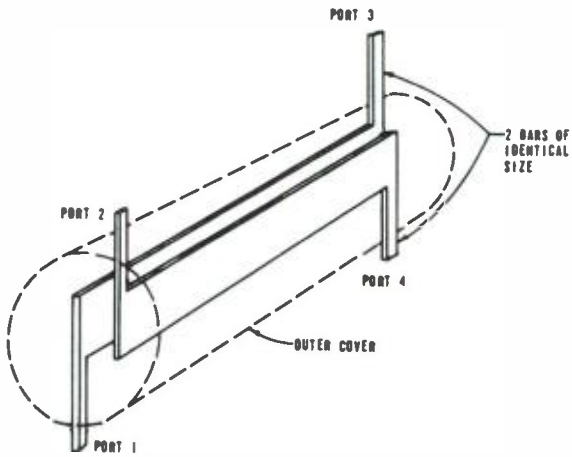


Fig. 29. Physical Model of 90° hybrid coupler.

to combine two signals into one output, these two signals must be fed to the hybrid coupler in phase quadrature. The reason this type of coupler is also called a 3 dB coupler is that when used as a power splitter, the split is equal or half-power (3 dB) between the two outputs.

Hybrid Combiners

The output hybrid combiner effectively isolates the two amplifiers from each other. Tuning adjustments can be made on one amplifier including turning it on and off without appreciably affecting the operation of the other amplifier. Good isolation is necessary so that if one transmitter fails, the other will continue to operate normally instead of in a mistuned condition.

Two of the ports on the hybrid coupler are the inputs from the power amplifiers, the sum port is the antenna output terminal, and the difference port goes to a resistive dummy load called the "reject load" since only the rejected power due to imbalance appears here. When the power fed to each of the two inputs is equal in amplitude with a phase difference of 90 degrees, the total power is delivered to the sum port (antenna). Very little of the power appears at the reject load if the phase relationship and power balance is correct. If the phase relationship is reversed between the two amplifiers, all the power is delivered to the reject load, so care must be taken to be sure that the proper one of the two possible 90 degree phase relationships is used. When all the ports on the hybrid combiner are properly terminated, isolation of 30 dB or more can be achieved between the power amplifiers. For perfect isolation between the amplifiers, the load impedance on the sum and difference ports must be exactly the same. This is approached in practice by providing a 1.0:1 VSWR with a resistive 50 ohm load for the termination (reject load) on the difference port and then reducing the VSWR on the antenna transmission line as low as possible by trimming the antenna match. This will keep the input port impedances from changing very much when one amplifier is not operating.

The input ports will present a load to each transmitter with a VSWR that is lower than the VSWR on the output transmission line. This is because part of the reflected power coming into the output port will be directed to the reject load and only a portion will be fed back into the transmitters. Fig. 30 shows the effect of output port VSWR on the input port VSWR and on the isolation between ports.

If the two inputs from the separate amplifiers are not equal in amplitude or exactly in phase quadrature, some of the power will be dissipated in the difference port reject load. The match in input power and phase is not extremely critical

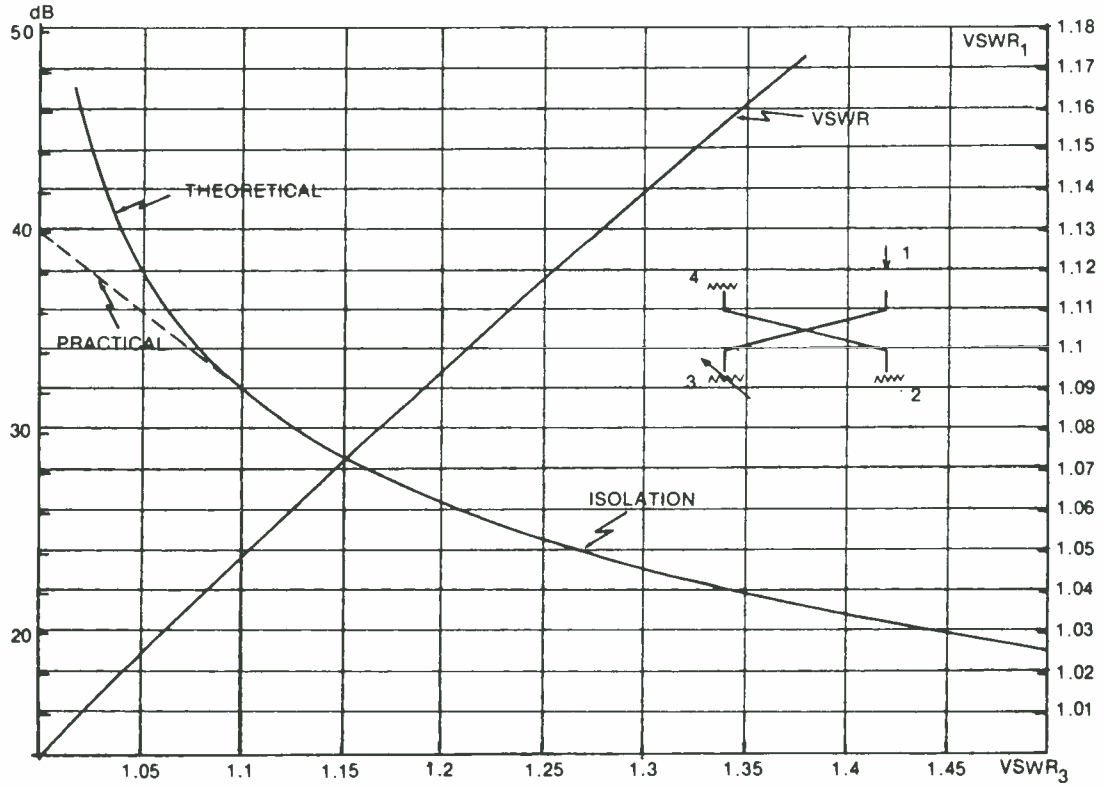


Fig. 30. Isolation of hybrid coupler.

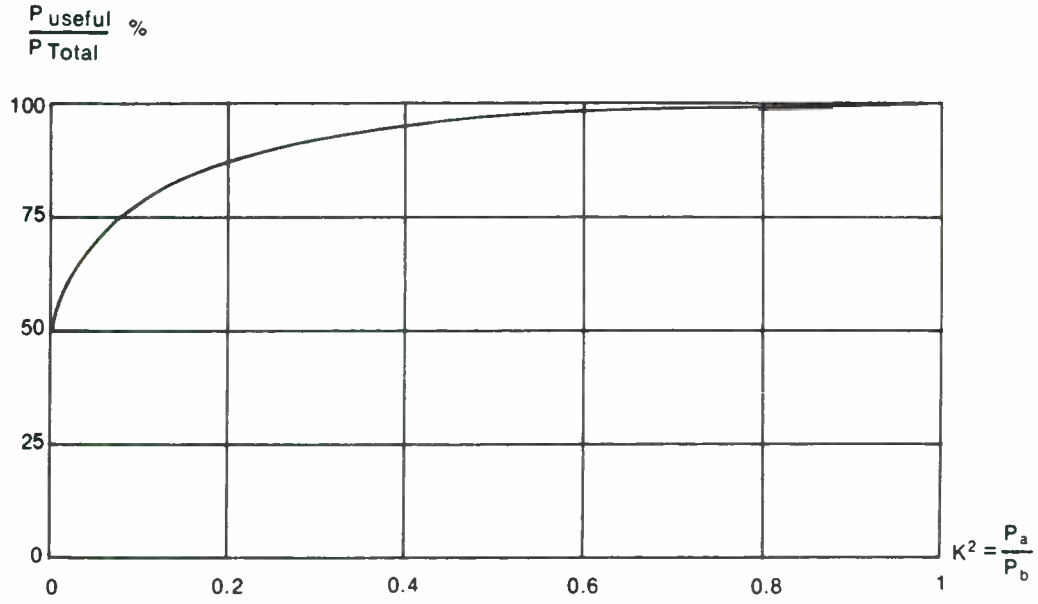


Fig. 31. Power imbalance in hybrid couplers.

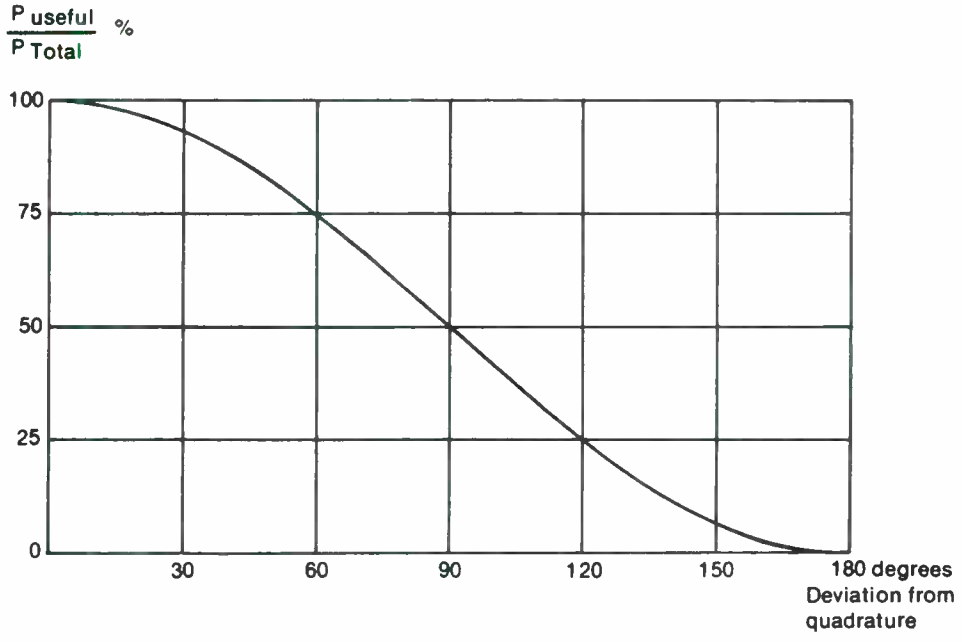


Fig. 32. Phase sensitivity, hybrid coupler.

as shown in Fig. 31 and Fig. 32. The power lost in the difference port reject load can be easily reduced to a negligible value by touching up the amplifier tuning and by adjusting the phase shift. For example, if one amplifier is delivering only half the power of the other amplifier, only about 3% of the total available power will be dissipated in the reject load and 97% is still fed to the output transmission line.

If one transmitter fails completely, half of the working amplifier's output goes to the antenna and the other half is dissipated in the difference port reject load. This is why the radiated output drops by 6 dB or to one-fourth of the original combined power. The reject load must be rated to handle a minimum of one-fourth of the total combined power, but often the reject load is rated to handle one-half the total power so that it can

also be used a test load for one of the transmitters.

Hybrid Splitting of Exciter Power

Fig. 33 shows a block diagram of a pair of combined amplifiers with dual exciters. The exciters cannot be operated in parallel like the amplifiers because their RF outputs would have to be on exactly the same carrier frequency and almost exactly in phase under all modulation conditions. An automatic or manual exciter switcher is used to direct the output of the desired exciter to the combined transmitter while the other standby exciter is routed to a dummy load. The one exciter in use, feeds a hybrid splitter/phase shifter which transforms one 50 ohm input into two isolated 50 ohm outputs that have a 90 degree phase shift between them with half the power going to each output. The operation of this hybrid splitter is the reciprocal of the hybrid combiner described above. The exciter must have enough power output capability to drive both power amplifiers. In some cases an additional IPA is required between the exciter and the splitter to boost the drive level. The length of coax from the power splitter to each amplifier input must be cut to a precise length so that the amplifiers will be fed in the proper phase relationship.

Each of the power amplifiers is assumed to have equal gain and phase shift. In practice, it may be difficult to get the amplifiers tuned so that their gains and phase shifts are equal at the same time. For this reason, a line stretcher or variable phase shift network is usually included with the exciter splitter so that the station engineer will have the ability to adjust phasing independent of amplifier tuning.

For more detailed information on the theory of hybrid couplers, see the chapter on television transmitters or reference (7) at the end of this chapter.

FILTERPLEXING

The practice of having several FM stations share a single broadband antenna system is becoming more popular in recent years. In order to connect several transmitters on different frequencies together onto one antenna system, a special device called a filterplexer is required. The purpose of the filterplexer is to provide isolation between the various transmitters while efficiently combining their power into a single transmission line. This is usually accomplished by a system of band-pass filters, band-reject filters, and hybrid combiners. The isolation is required to prevent power from one transmitter from entering another transmitter with resulting spurious emissions, as well as to keep the rest of the system running in the event of the failure of one or more transmitters.

An important consideration in the design of a filterplexing system is the effect on the phase response (group delay characteristic in the passband) of each of the signals passing through the system due to individual bandwidth limitations on each of the inputs.

RF Intermodulation Between FM Broadcast Transmitters

Interference to other stations within the FM broadcast band, as well as to other services outside the broadcast band, can be caused by RF intermodulation between two or more FM broadcast transmitters. Transmitter manufacturers have begun to characterize the susceptibility of their equipment to RF intermodulation so this information will be available to the designers of filterplexing equipment.

The degree of intermodulation interference generated within a given system can be accurately predicted before the system is built if the actual mixing loss of the transmitters is available when the system is designed. Accurate data on "Mixing Loss" or "Turn-Around-Loss" not only speeds the design of filterplexing equipment, but also results in higher performance and more cost effective designs because the exact degree of isolation required is known before the system is designed. Filterplexer characteristics, as well as antenna isolation requirements, can be tailored to the specific requirements of the transmitters be-

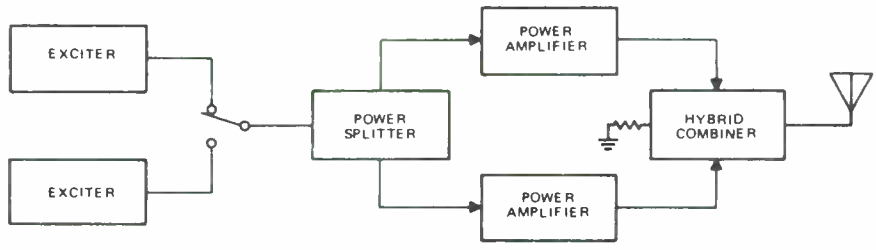


Fig. 33. Block diagram of transmitter with two power amplifiers, a hybrid combiner and dual exciters.

$$f_1 = 100.3\ Mhz. \qquad f_2 = 101.1\ Mhz.$$

$$2f_1 - f_2 = [2(100.3) - (101.1)\ ] = [200.6 - 101.1] = \ 99.5\ Mhz.$$

$$2f_2 - f_1 = [2(101.1) - (100.3)\ ] = [202.2 - 100.3] = 101.9\ Mhz.$$

OR

$$[f_1 - (f_2 - f_1)] = [100.3 - (101.1 - 100.3)] = [100.3 - 0.8] = \ 99.5\ Mhz.$$

$$[f_2 + (f_2 - f_1)] = [101.1 + (101.1 - 100.3)] = [101.1 + 0.8] = 101.9\ Mhz.$$

Fig. 34. 3rd order intermodulation products.

ing used. The end user is assured in advance of construction that the system will perform to specification without fear of overdesign or underdesign of the components within the system.

Mechanisms Which Generate RF Intermodulation Products

When two or more transmitters are coupled to each other, new spectral components are produced by mixing of the fundamental and harmonic terms of each of the desired output frequencies. For example, if only two transmitters are involved, the third order intermodulation (IM_3) terms could be generated in the following way. The output of the first transmitter (f_1) is coupled into the non-linear output stage of the second transmitter (f_2) because there is not complete isolation between the two output stages. (f_1) will mix with the second harmonic of (f_2) producing an in-band 3rd order term with a frequency of [$2(f_2)$-(f_1)]. In a similar fashion the other 3rd order term will be produced at a frequency of [$2(f_1)$-(f_2)]. This implies that the second harmonic content within each transmitter's output stage along with the specific non-linear characteristics of the output stage will have an effect on the value of the mixing loss.

It is possible, however, to generate these same 3rd order terms in another way. If the difference frequency between the two transmitters [(f_2)-(f_1)], which is an out-of-band frequency, re-mixes with either (f_1) or (f_2), the same 3rd order intermodulation frequencies are produced.

Empirical measurements indicate that the [$2(f_2)$-(f_1)] type of mechanism is the dominant mode generating 3rd order (IM) products in modern transmitters using a tuned cavity for the output network.

Fig. 34 shows an example of how the intermodulation product frequencies may be calculated. Fig. 35 and Fig. 36 show the resulting frequency spectra.

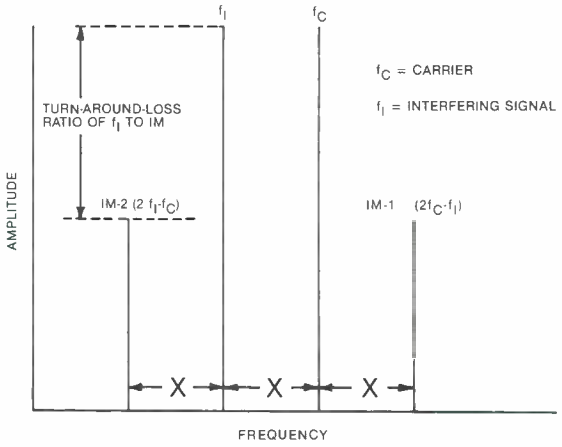


Fig. 35. Frequency spectrum of third order IM with the interfering level equal to the carrier level.

Intermodulation As A Function of "Turn-Around-Loss"

"Turn-Around-Loss" or "Mixing Loss" describes the phenomenon whereby the interfering signal mixes with the fundamental and its harmonics within the non-linear output device. This mixing occurs with a net conversion loss, hence the term "Turn-Around-Loss" has become widely used to quantify the ratio of the interfering level to the resulting (IM_3) level. A "Turn-Around-Loss" of 10 db means that the (IM_3) product fed back to the antenna system will be 10 db below the interfering signal fed into the transmitter's output stage.

"Turn-Around-Loss" will increase if the interfering signal falls outside the passband of the transmitter's output circuit, varying with the frequency separation of the desired signal and the interfering signal. This is because the interfering signal is first attenuated by the selectivity going into the non-linear device and then the (IM_3) product is further attenuated as it comes back out through the frequency selective circuit.

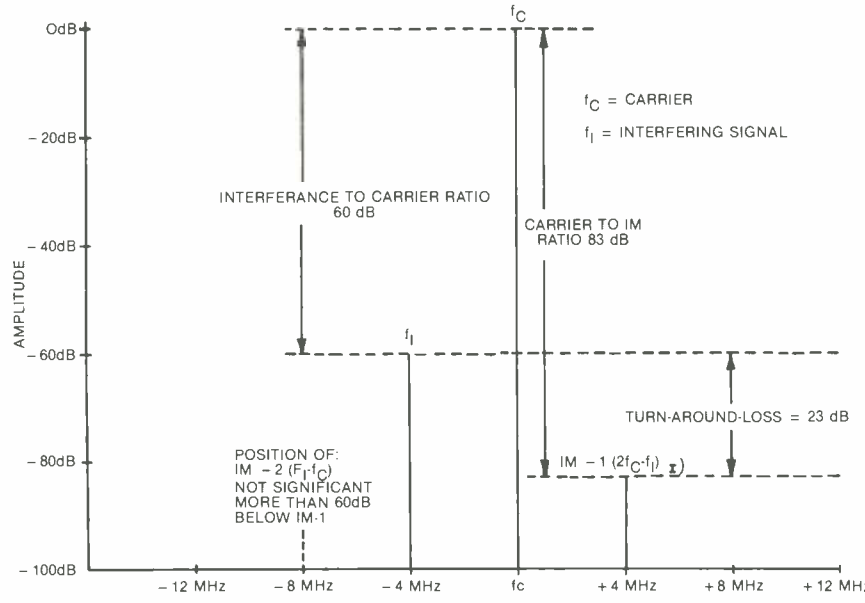


Fig. 36. Typical frequency spectrum of third order IM of a broadcast FM transmitter.

"Turn-Around-Loss" can actually be broken down into three individual parts:

1. The basic in-band conversion loss of the non-linear device.
2. The attenuation of the out-of-band interfering signal due to the selectivity of the output stage.
3. The attenuation of the resulting out-of-band (IM_3) products due to the selectivity of the output stage.

As the "Turn-Around-Loss" increases, the level of undesirable intermodulation products is reduced and the amount of isolation required between transmitters is also reduced.

The transmitter output circuit loading control directly affects the source impedance and therefore affects the efficiency of coupling the interfering signal into the output circuit where it mixes with the other frequencies present to produce (IM_3) products. Light loading reduces the amount of interference that enters the output circuit with a resulting increase in "Turn-Around-Loss". In addition, the output loading control setting will change the output circuit bandwidth (loaded "Q") and therefore also affect the amount of attenuation that out-of-band signals will encounter passing "into" and "out of" the output circuit.

Second harmonic traps or low-pass filters in the transmission line of either transmitter have little effect on the generation of intermodulation products. This is because the harmonic content of the interfering signal entering the output circuit of the transmitter has much less effect on (IM_3) generation than the harmonic content within the non-linear device itself. The resulting (IM_3) products fall within the passband of the low-pass filters and outside the reject band of the second harmonic traps, so these devices offer no attenuation to RF intermodulation products.

For more detailed information about RF intermodulation between transmitters, see the chapters on FM and TV antenna systems and reference (14) at the end of this chapter.

OPERATIONAL MEASUREMENTS

Certain operating parameters are important enough to justify regular observation. Especially important are: modulation level, carrier frequency, and output power level. The FCC requires that these operating parameters be observed as often as required to assure proper operation and to avoid causing interference to other broadcast services.

FM Modulation Measurement

The measurement of FM modulation can be accomplished with a broadcast type modulation monitor or with one of the newer modulation analyzers. Some FM exciters have built-in peak modulation displays for convenience in set-up and adjustment. Once the initial levels are correctly

set, modern audio processing equipment will usually hold the modulation levels within the desired window.

Much interest and concern has developed throughout the broadcasting industry as to the best method for the determination of modulation percentage for complex program material. The ability of meter movements to follow short-duration, non-repetitive peaks accurately has received special attention. Standard modulation meter movements cannot follow modulation peaks with the required accuracy. For this reason, modulation monitors have a peak-indicating device that can be preset to flash at the particular level of interest. This device should be used instead of the meter to determine peak modulation conditions of the transmitter.

The reason for setting a peak deviation limit is so that the related occupied bandwidth does not increase to the point of interfering with stations on adjacent channels. The FCC presently enforces the modulation limit by monitoring the instantaneous peak deviation of the station as displayed on an oscilloscope. This method of measurement does not exactly correlate with the station's occupied bandwidth because the duty-cycle of the modulation peaks is not taken into account. As a result, many sophisticated "peak limiting" and "overshoot control" devices have appeared on the market to maximize loudness without exceeding the peak deviation limit, by removing the low energy peaks that would extend beyond 100% modulation. The use of these devices does cause some degradation of the audio quality and they would no longer be used if the method of modulation measurement were changed to one based on occupied bandwidth.

Carrier Frequency Measurement

The average carrier frequency must be measured and maintained to within ± 2 kHz of the assigned channel with an accurate frequency monitor. These monitors fall into two categories; analog display of the frequency error from the nominal carrier frequency and digital display of the absolute carrier frequency. The trend is toward the digital counter because of its inherent accuracy and ease of use.

The requirement that a station utilize type-approved modulation and frequency monitors has been eliminated by the FCC. Each station is still required to maintain its frequency, modulation, and audio performance within the FCC limits defined in Part 73 of the Rules and Regulations, but the responsibility for selecting the method of measurement and type of measuring equipment is now up to the station operator. Every quality conscious station will want to have the necessary equipment to accurately evaluate the signal being broadcast. There are new options available in high performance yet general purpose test equipment, now that monitor type-approval is no longer required. For instance, modern modulation analyzers provide frequency agility as well as greater measurement capability than the more specialized modulation monitors. General purpose frequency counters are now available with sufficient accuracy to measure the carrier, subcarrier, and stereo pilot frequencies directly. Spectrum analyzers provide a wide range of capability including; the measurement of harmonic and spurious frequencies at the carrier frequency, composite baseband, Bessel nulls, occupied bandwidth, stereophonic and SCA crosstalk, and AM noise.

Measurement of RF Power Output

The methods for determining RF output power are specified in Part 73 of the FCC Rules and Regulations. An accurately calibrated directional wattmeter provides an excellent means of making direct measurement of RF output power. The directional wattmeter is seldom used as the primary RF power determining method because of the requirement for recalibration to a traceable standard at regular intervals. Use of the indirect method of power measurement avoids this requirement. The FCC now permits the use of the transmitter power output meter directly, if it is periodically calibrated by comparison with the indirect method, instead of with a dummy load and standard wattmeter.

Using the indirect method, the output power is calculated from a measurement of the dc input power multiplied by the efficiency factor of the final amplifier stage. The efficiency factor is provided by the transmitter manufacturer on the final test data sheet or in the instruction manual and must be applicable to the particular frequency and power level in use. The power input to the final amplifier stage is normally defined as the product of plate voltage and plate current to this stage. Multiple output stages which are combined for the total power, must have their individual dc power inputs arithmetically summed to obtain the total power input.

The directional wattmeter can be used as a check when compared to the power output calculated by the indirect method to determine if the efficiency factor has changed due to incorrect tuning, changing antenna conditions, or a weak output device.

Logging of Transmitter Operating Parameters

FM stations may wish to log certain transmitter parameters at regular intervals in order to

track equipment performance trends. The typical entries are:

1. Final amplifier plate voltage.
2. Final amplifier plate current.
3. RF transmission line current, voltage, or power.
4. Key tube parameters (grids, filament).
5. Carrier frequency.
6. Stereo pilot frequency.
7. Subcarrier(s) frequency.
8. Settings of tuning controls.

Microprocessor based control systems often provide automatic logging of all transmitter parameters including overloads and tolerance flagging.

Audio Performance Measurements

Most stations measure the performance of the entire audio system at regular intervals in order to verify the transmission quality and to locate any problem areas within the audio chain. Audio performance measurements are normally made from the audio console input to the output of the "off-air" de-modulator and include the following:

1. Audio frequency response.
2. Audio frequency harmonic distortion.
3. FM signal-to-noise ratio.
4. AM noise level.

Fig. 37 is a block diagram of a typical test set-up for audio performance measurements. All measurements are made on the composite system from microphone terminals of the console to the demodulated transmitter output. All normal program circuits, with the exception of audio limiting and compression amplifiers, must be included in the measurements. If the compression and limiting amplifiers have switches that convert them to linear, fixed-gain operation, the measurements can be made with the limiters and compression amplifiers in the linear fixed-gain mode of operation.

Measurement of Audio Frequency Response

The audio frequency response of the system is measured in reverse, that is, a constant percentage of modulation is maintained for all modulating frequencies by adjusting the amount of attenuation between the audio generator and the microphone input terminals. This is necessary because of the rising response due to pre-emphasis. Frequency response data is taken at three levels of modulation: 25 percent, 50 percent, and 100 percent. The audio voltmeter which measures the audio generator output voltage is used to maintain a constant voltage level versus frequency at the generator output terminals. The precision attenuator dials are adjusted for each modulating frequency to maintain the desired modulating level and the attenuator readings, in decibels, are recorded. Readings should be taken for the following modulating frequencies: 50, 100, 400, 1,000, 5,000, 7,500, 10,000, and 15,000 Hz.

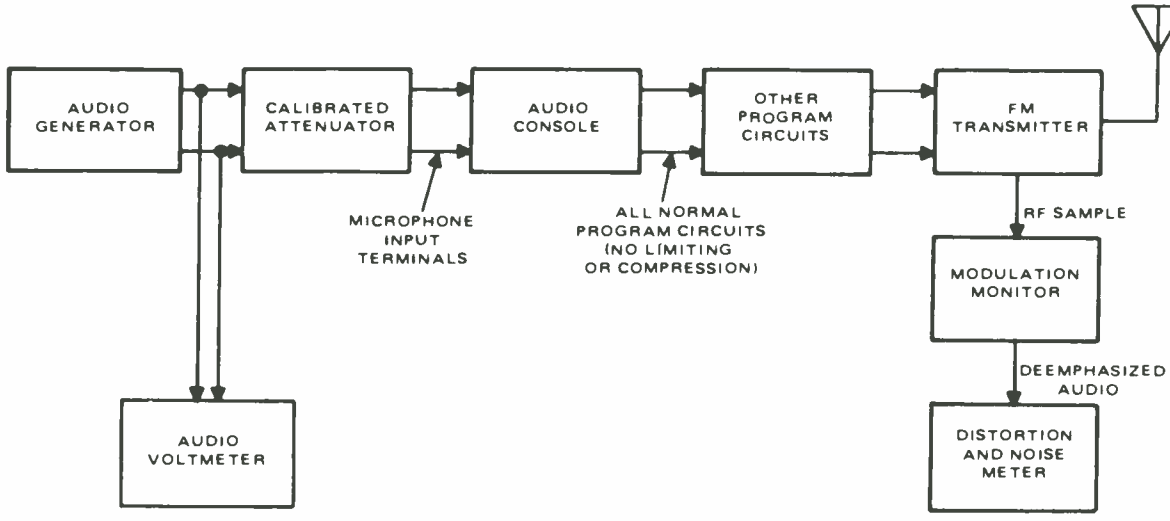


Fig. 37. Block diagram of test set-up for audio performance measurements.

When the attenuation, in decibels, is plotted versus frequency, the 75 microsecond pre-emphasis curve is obtained if the system frequency response is perfect. Deviations from the ideal response are permitted to an extent which allows the measured curve to be fitted between the upper and lower limit curves shown in Fig. 8A. The procedure for doing this is to offset the measured curve by subtracting or adding the same number of decibels from each of the measured values. This process may be repeated until a fit is obtained. If it is impossible to obtain a fit within the limits by subtracting or adding the same value of attenuation from all measured values, the system frequency response is inadequate and corrections must be made.

Measurement of Audio Harmonic Distortion

Total harmonic distortion (THD) of the system from microphone input terminals to transmitter output is measured by modulating the transmitter with sinusoidal modulating signals having low distortion and observing the harmonic content at the output of the modulation monitor. For this measurement, pre-emphasis is used in the transmitter and de-emphasis is used in the monitor. The distortion analyzer must respond to de-emphasized harmonics through 30 kHz.

The type of distortion meter normally used in this test reads not only harmonic distortion but also noise in the audio passband. For this reason, THD measurements above 5 kHz may be noise limited due to the effect of de-emphasis. If the total harmonic distortion and noise together are within the harmonic distortion limits, the system is assumed to meet its harmonic distortion requirements. A more accurate method of distortion measurement in the presence of noise is to use an audio frequency spectrum analyzer to determine the total RMS value of the individual distortion products.

The THD should be measured under the following conditions:

1. For modulating frequencies of 50, 100, 400, 1,000 and 5,000 Hz at modulating levels of 25, 50, and 100 percent modulation.
2. For modulating frequencies of 10 kHz and 15 kHz at a modulating level of 100 percent.

The preceding measurements should show that the system THD is less than 3.5 percent for modulating frequencies between 50 and 100 Hz, less than 2.5 percent for modulating frequencies between 100 and 7,500 Hz, and less than 3.0 percent for modulating frequencies between 7,500 and 15,000 Hz. Most modern equipment will pass these tests by a wide margin. If distortion levels greater than these are measured, the system requires adjustment or repair.

Measurement of Two-Tone Intermodulation Distortion

Audio intermodulation distortion (IMD) measurements are a quick and accurate way to evaluate the system performance before a complete set of THD measurements are made. If the system will pass a single 60 Hz/7 kHz, 4:1 (SMPTE-IMD) measurement at 100% modulation, it will probably pass all of the THD measurements.

Other types of difference-tone, swept two-tone, and sinewave/squarewave IMD measurements can reveal more subtle problems in the system such as transient IMD due to insufficient audio feedback bandwidth in the audio amplifier stages.

Measurement of FM Signal To Noise Ratio

The FM signal-to-noise ratio of the system is also measured from the microphone input terminals to the transmitter output. The residual noise level at the monitor output is measured with an audio voltmeter. For this measurement, pre-emphasis is employed in the transmitter and de-emphasis in the monitor. The residual audio noise level is referenced to the signal level produced by 400 Hz (L + R, mono) modulation at the 100 percent level (75 kHz deviation).

The procedure for making the FM signal-to-noise ratio measurement is as follows:

1. Modulate the transmitter with a 400 Hz sine wave applied at the microphone input terminals of the console and set the level for 100 percent modulation.
2. Read and record the audio signal level appearing at the modulation monitor output terminals. If the monitor has audio metering capability, the meter gain should be set for a 0.0 dB reference level according to the manufacturer's instructions.
3. Remove the modulation and terminate the console audio input terminals with a resistor equal to the normal microphone output impedance.
4. Read and record the residual audio noise voltage in decibels below the 400 Hz reference signal level. The measured signal-to-noise ratio should be at least 60 dB in a properly operating FM transmitter.

Measurement of AM Signal to Noise Ratios

The perfect FM transmitter will have a absolutely constant output, regardless of FM

modulation or power supply variations. In practice, there is always some residual amplitude modulation of the FM transmitter. There are two types of AM signal to noise ratio that are of interest to the FM broadcast engineer:

1. Asynchronous AM signal to noise ratio measured without FM modulation is primarily related to power supply ripple.
2. Synchronous AM signal to noise ratio (incidental AM) measured with FM modulation is related to the tuning and overall bandwidth of the system.

Asynchronous AM

Residual amplitude modulation of the transmitter output, due primarily to power supply ripple, is measured with an AM envelope detector. Most FM modulation monitors include an AM detector for this purpose. The detector must include 75 microsecond de-emphasis of its output. AM noise measurements must be made directly at the transmitter output (or an accurate sample of its output). No amplifying or limiting equipment may be used between the transmitter output and the AM detector since this equipment would modify the residual AM noise level present. The residual AM noise in a properly operating FM transmitter will be 50 dB below the level which would represent 100 percent amplitude modulation of the carrier. Since the transmitter cannot be amplitude modulated, this reference must be established indirectly by a measurement of the RF carrier voltage. Refer to the instructions of the detector manufacturer to determine the reference level. Generally, the reference level is determined by setting a carrier level meter to a specified reading. If the transmitter is unable to meet the 50 dB requirement, the problem can usually be traced to a power supply component or to line imbalance in a three phase system.

Synchronous AM

Synchronous AM is a measure of the amount of incidental amplitude modulation introduced onto the carrier by the presence of FM modulation. This measurement is very useful for determining the proper tuning of the transmitter. Since all transmitters have limited bandwidth, there will be a slight drop-off in power output as the carrier frequency is swept to either side of the center frequency. This slight change in RF output level follows the waveform of the signal being applied to the FM modulator causing AM modulation in synchronization with the FM modulation. Minimizing synchronous AM will assure that the transmitter passband is centered on the FM channel. Care must be taken when making these measurements that the test set-up does not introduce synchronous AM and give erroneous readings which would cause the operator to mistune the transmitter to compensate for errors in the measuring equipment. The input impedance of the envelope detector must provide a nearly perfect match so that there is a very low VSWR on the sampling line. Any significant VSWR on the sampling line will produce synchronous AM at the detector because the position of the voltage peak caused by the standing wave moves along this line with FM modulation.

Unfortunately the AM detectors supplied with some modulation monitors do not provide a good enough match to be useful for this measurement. Precision envelope detectors are available that present a good match (30 dB return loss) to the sampling line.

TUNING THE TRANSMITTER FOR BEST PERFORMANCE

The modern power amplifiers which have been discussed in the preceding sections, can operate with high reliability and power efficiency without compromising subcarrier performance, if they are properly adjusted.

All optimization should be done with the transmitter connected to the normal antenna system rather than to a dummy load. This is because the resistance and reactance of the antenna will be different from the dummy load and the optimum tuning point of the transmitter will shift between the two different loads. The tuning sequence is:

1. The transmitter is first tuned for normal output power and proper efficiency according to the manufacturer's instruction manual. The meter readings should closely agree with those listed on the manufacturer's final test data sheet if the transmitter is being operated at the same frequency and power level into an acceptable load.
2. A simple method for centering the transmitter passband on the carrier frequency involves adjustment for minimum synchronous AM. If the bandpass is narrow or skewed, increasing synchronous amplitude modulation of the carrier will result. A typical adjustment procedure is to FM modulate 100% at 400 Hz and fine-adjust the transmitter's grid tuning and output tuning controls for minimum 400 Hz AM modulation as detected by a wideband envelope detector (diode and line probe). It is helpful to display the demodulated output from the AM detector on an oscilloscope while

making this adjustment. Note that as the minimum point of synchronous AM is reached, the demodulated output from the AM detector will double in frequency to 800 Hz, because the fall-off in output power is symmetrical about the center frequency causing the amplitude variations to go through two complete cycles for every one FM sweep cycle. This effect is illustrated in Fig. 38. It should be possible to minimize synchronous AM while maintaining output power and efficiency in a properly designed power amplifier.

3. A more sensitive test is to tune for minimum intermodulation distortion in left-only or right-only stereo transmissions. Stereo separation will also vary with tuning.
4. For stations employing a 67 kHz SCA, transmitter tuning becomes very critical to minimizing crosstalk into the SCA. Modulate one channel only on the stereo generator to 100% with a 4.5 kHz tone. This will place the lower second harmonic (L-R) stereo sideband on top of 67 kHz SCA. Activate the SCA at normal injection level without modulation on the SCA. Tune the transmitter for minimum output from the SCA demodulator. This adjustment can also be made by listening to the residual SCA audio while normal stereo programming is being broadcast.

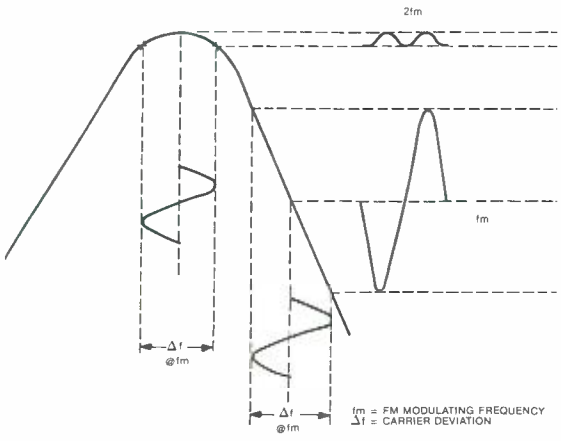


Fig. 38. Synchronous AM waveforms.

The new generation of power amplifiers have been designed to operate without compromising subcarrier performance. By providing broadband matching circuits, adjustment of these transmitters for optimal subcarrier performance (minimum crosstalk, maximum separation, etc.) is very repeatable and stable.

The field adjustment techniques are listed below in ascending order of sensitivity:

1. Tune for minimum synchronous AM noise.
2. Tune for minimum IMD in the left or right channel only.
3. Tune for minimum crosstalk into the unmodulated SCA subcarrier.

In any of these tests, the grid tuning is frequently more critical than the plate tuning. This is because the impedance match into the input capacitance of the grid becomes the bandwidth limiting factor. Even though the amplitude response appears flattened when the grid is heavily driven, the phase response has a serious effect on the higher order FM sidebands. For more information about tuning an FM transmitter for optimum performance, see references (15) and (16) at the end of this chapter.

INSTALLATION CONSIDERATIONS

Adequate planning and care in the installation of an FM broadcast transmitter and associated equipment will help avoid many problems that may be difficult and expensive to correct later. For example, poor grounds and ground loops may cause high noise levels.

Wiring the Transmitter Plant

Separate metalically shielded conduits or troughs should be provided for the audio and the ac wiring. A third conduit should be used if computer logic levels are employed for equipment control. These conduits or wiring troughs may be either overhead or below the cabinets. The ac wiring should be well separated from the audio pairs to prevent the induction of unwanted hum and noise into the audio circuits.

All audio shields should be grounded at only one point to prevent ground loops in the shields. This point may have to be found experimentally to give the lowest noise pickup. The equipment racks and transmitter should be connected together by copper straps at least 2 inches wide, tied to a good earth ground at one point. If a good ground screen is not available, a satisfactory ground can be provided by driving four or five copper ground rods 8 to 10 ft. long into the ground with a spacing of about 3 ft. These ground rods should be tied together with a wide copper strap. The straps connecting the equipment to the earth ground should be as short and direct as practical. It is often difficult to remove VHF-RF from the equipment by grounding because at FM carrier frequencies, nearly any connection to an earth ground has an appreciable impedance. The best way to keep RF out of sensitive low level circuits is by keeping them enclosed within an RF shield and by filtering leads that enter the shielded unit when necessary. Filters in

the audio lines may be made up of small bi-filar RF chokes and disc capacitors.

For stereo transmission, it is necessary to keep the L and R audio lines phased properly. To insure proper monaural compatibility, correct audio phasing polarity must be maintained throughout the station from the microphones, tape machines, and turntables through all of the audio equipment to the stereo generator audio input terminals. Stereo phone line pairs or separate RF studio to transmitter links (STL) should also be checked for proper polarity and equal phase delay.

The equipment should be located and arranged to provide sufficient room around the front, sides, and rear for easy access during servicing and maintenance. Servicing of certain components may be easier by removing a side panel from the transmitter.

Transmitter Cooling

Almost all FM broadcast transmitters require forced air cooling to remove heat from the output stage and other assemblies within the cabinet. A very important consideration in locating the transmitter is the provision for adequate cooling air. As a rough approximation, it can be assumed that the overall efficiency of the transmitter is about 50 percent. In other words, it will generate about the same number of kilowatts of heat as it does RF power output.

Fig. 39A shows a transmitter located in an air conditioned room. This type of closed-loop system requires no special ducting and has the advantage that the transmitter intake air is usually much cleaner than outside air. The transmitter exhaust air places a substantial heat load on the air conditioner during the summer, but it becomes a source of heat in the winter. The transmitter manufacturer can usually supply data on the number of cooling BTU's required, so that the proper size air conditioner can be selected. This method is used frequently with the lower power transmitters. A protective system should be provided to prevent over-heating of the transmitter if the air conditioner fails.

Fig. 39B shows a transmitter located in a wall separating an air conditioned room and a ventilated, but not air conditioned room. A large exhaust fan is provided in the ceiling to remove the rising hot air while an adequate cool air intake is provided in the lower portion of an outside wall. Adequate air filtering is required to keep the transmitter interior clean.

Fig. 39C shows a transmitter located in an air conditioned room with intake and exhaust air ducts to the outside. An auxiliary blower or fan is normally required to overcome pressure drop in the ducting. This type of system requires

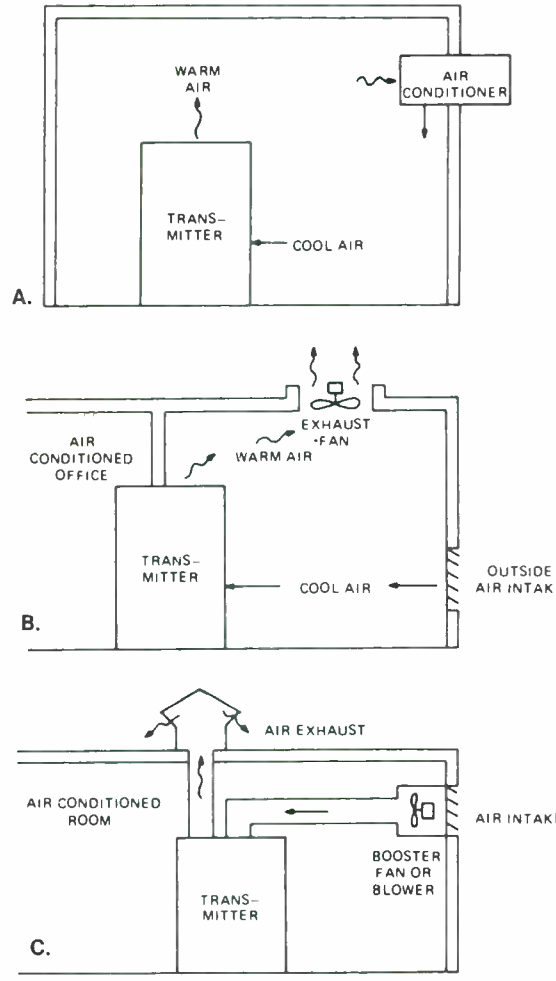


Fig. 39. Three methods of providing cooling air for the transmitter.

careful design to make sure that the air flow through the transmitter is not impeded by the duct work. Additional air interlocks may be required to protect the transmitter from a failure of the external fan. The air intake and exhaust openings to the outside should be provided with rain shields, insect screens, and dust filters as dictated by the environment. The location of the air intake and exhaust openings should be arranged so that wind pressure will not impede the air flow.

Air filters should be periodically cleaned or replaced according to the transmitter manufacturer's instructions. This is very important because dust or insect clogged air filters may reduce the cooling air flow enough to cause overheating of some of the components. The probability of component failure increases very rapidly when cooling is insufficient. Particular attention should be paid to removing dirt and dust from high voltage components during regular maintenance after all power is removed and all components are discharged.

Dust should be cleaned from the transmitter by means of a suitable brush and vacuum cleaner or as otherwise recommended by the transmitter manufacturer. Usually weekly cleaning is sufficient.

FM TRANSMITTER PLANT MAINTENANCE

Care of Power Tubes

The operating life of high power vacuum tubes can be extended by proper care. Most high power tubes utilize a directly heated cathode composed of a thoriated tungsten filament structure.

The key points to extending the life of RF power tubes are:

1. Store tubes upright (upside-down or right-side-up) along the axis of symmetry, not on their side. This will help to keep the internal elements concentrically aligned.
2. Use care when handling tubes to prevent mechanical shocks to the delicate internal structure. Don't set a tube on a hard surface without padding.
3. Keep the tube seals and anode cooler free of dust and dirt by cleaning once each week even in a clean environment.
4. Keep a spare tube on hand and rotate the tubes every few months to help keep the chemical "gas-getter" active so that the tubes remain gas free.
5. Keep a regular record of all tube operating parameters so that any trend of changes will be noticeable. In the event of a tube failure during the warranty period, this data will be essential to receiving credit on a replacement tube.
6. Monitor the filament voltage on a true RMS responding instrument and log any changes for future reference. The sampling point for this voltage measurement should be located as close to the tube's filament contacts as possible to minimize errors due to voltage drops in the filament wiring.

A tube that has been properly operated should gradually lose emission from the cathode until it is no longer useful because the emissive material is gradually consumed. The carcass of the tube can then be rebuilt with a new cathode and recycled back into service. Tube life is not directly related to plate dissipation (within the ratings), but is directly related to the current density (milliamperes per heater watt) emitted by a given size filament. This means that operating a given tube type at a lower plate current will proportionately increase the life of the tube.

Normally a new tube will deliver full output at a slightly reduced filament voltage. By operating the tube at the optimum filament voltage, the filament life can be significantly extended. The optimum value may be found by slowly reducing the filament voltage from the manufacturer's rated value until the RF power output drops about 2 percent and then increasing the voltage until the RF power increases back up 1 percent. In no case, should the filament voltage be reduced more than 5 percent below the manufacturer's rating. A brand new tube should be operated at the full rated filament voltage for the first 300 hours before the voltage is reduced to the optimum value for long life. This will assure that the "gas-getter" is properly activated. As the tube ages, the filament voltage will have to be increased to stay at the optimum value, until RF output power cannot be maintained at or above the rated value of filament voltage. At this point, the tube's useful life comes to an end. Check the manufacturer's data sheets and application notes for detailed information. An excellent guide to the proper care of power tubes is listed in reference (10) at the end of this chapter. Reference (17) gives detailed information about how to specify a proper forced-air cooling system for power tubes.

Preventive Maintenance

Preventive maintenance is equipment inspection and maintenance performed at regular intervals before an operational problem develops. The long term benefits are great because potential problems are discovered and solved while they are still easily manageable. A check-list of a few typical preventive maintenance items for an FM transmitter plant might include:

1. Weekly overall internal and external cleaning and inspection for damage or excessive wear.
2. Lubricate motors, tuning gears, and other moving parts at intervals recommended by the manufacturer.
3. Check and log all meter readings daily. Then compare these readings with the previous set of readings as an aid to diagnosing a developing problem.
4. Regularly exercise the automatic power control and any other servo systems.
5. Check the antenna lighting and de-icer systems.
6. Check the transmission line pressurization and VSWR.
7. Check all air filters in the transmitter plant and clean or replace as required.
8. Check the proper operation of all monitoring and remote control equipment.

9. Good overall housekeeping will pay big dividends in the long run by keeping the equipment clean and free of problems that would otherwise be caused by dirt build-up.

Maintenance Systems

The key to making any maintenance program work is to set up formal check-list, logging, parts inventory management, and repair scheduling systems. These systems provide the conscience and discipline required to keep the maintenance routine accurate and complete. Each station should develop a system suited for the particular physical plant involved. Often there will be more maintenance and repair work needing attention than there is time to do it all. In this case, the maintenance system should set the priorities for completing each item and assure that no item gets forgotten. Accurate notebooks describing all installation and maintenance work are a very helpful part of any maintenance system when working on the equipment years later after the human memory has faded.

REFERENCES

1. Lessing, Lawrence, *Man of High Fidelity: Edwin Howard Armstrong,* Bantam Publishing, 1959, The Armstrong Foundation, Columbia University, New York, N.Y.
2. *Reference Data for Radio Engineers,* ITT—Howard W. Sams and Co., Inc., New York, N.Y., Fifth Edition, 1970.
3. Terman, Frederick E., *Electronic and Radio Engineering,* McGraw-Hill Book Company, New York, N.Y., Fourth Edition, 1955.
4. Clarke, Kenneth K. and Hess, Donald T., *Communications Circuits: Analysis and Design,* Addison-Wesley Publishing Company, Reading, Massachusetts, Second Printing, 1978.
5. Rohde, Ulrich L., *Digital PLL Synthesizers-Theory and Design,* Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1983.
6. Krauss, Herbert L., Bostian, Charles W., and Raab, Frederick H., *Solid State Radio Engineering,* John Wiley and Sons, New York, N.Y., 1980.
7. Uyttendaele, Antoon G., "Design Requirements and Operational Features of the Gates Dualtran RF Switching System", Broadcast Products Division of Harris Corporation, Quincy, Illinois.
8. Johnson, Joseph, "Solid Circuits", Acrian/Communications Transistor Company, Cupertino, California, 1973.
9. Howe, Harlan Jr., "Simplified Design of High Power, N-Way, In-Phase Power Divider/Combiners", Microwave Journal, December, 1979.
10. Eimac, *Care and Feeding of Power Grid Tubes,* Eimac Division of Varian Corporation, San Carlos, California, 1967.
11. Hershberger, David and Weirather, Robert, "Amplitude Bandwidth, Phase Bandwidth, Incidental AM, and Saturation Characteristics of Power Tube Cavity Amplifiers for FM", Harris Corporation, Quincy, Illinois, 1982.
12. Motorola Silicon Rectifier Manual, Semiconductor Group-Motorola Inc., Phoenix, Arizona, 1980.
13. Hnatek, Eugene R., Design of Solid-State Power Supplies, Van Nostrand Reinhold Company, New York, N.Y., Second Edition, 1981.
14. Mendenhall, Geoffrey N., "A Study of RF Intermodulation Between FM Broadcast Transmitters Sharing Filterplexed or Co-located Antenna Systems", Broadcast Electronics Inc., Quincy, Illinois, 1983.
15. Mendenhall, Geoffrey N., "The Composite Signal—Key to Quality FM Broadcasting", Broadcast Electronics Inc., Quincy, Illinois, 1981.
16. Lyles, John T.M. and Shrestha, Mukunda B., "Transmitter Performance Requirements for Subcarrier Operation", Broadcast Electronics Inc., Quincy, Illinois, 1984.
17. Steinkamp, Jeffrey H., "Air Flow Measurements Using a Variable Frequency AC Generator", Broadcast Electronics Inc., Quincy, Illinois, 1984.
18. Robinson, John T. and Whipple, L. Glenn, "FCC Regulations Governing the Audio Fidelity Characteristics of FM Broadcast Equipment", Audio Engineering Society Journal, Vol. 16, No. 3, July 1968.
19. Bruene, Warren B., "An Inside Picture of Directional Wattmeters", American Radio Relay League — QST magazine, April 1959.

3.4

Subcarrier Transmissions and Stereophonic Broadcasting

John Kean
Senior Engineer
National Public Radio
Washington, DC

Stereophonic Sound FM broadcasting and SCA services are a form of *multiplexing* that had its origins fifty years ago, when high-fidelity audio and facsimile messages were simultaneously transmitted from the Empire State Building in New York City to experimental receive sites in New Jersey.[1] Those historic multiplexing efforts demonstrated the value of *wideband frequency modulation*, allowing modern FM broadcasting to provide services to the public of both quality and variety. More history of FM engineering and the origins of multiplex transmission are contained in the chapter "FM Transmitters". The purpose of this chapter is to explain the principles involved in multiplexing for FM broadcasting and to discuss the current state of the art.

THE COMPOSITE BASEBAND

This section contains definitions of the terms commonly used in the FM stereo and SCA systems. Since some of these terms are misused or ambiguous, the intention here is to establish meanings that will be used in the rest of this chapter.[2, 3] The list was selected to clarify certain terms and is not a complete glossary.

NOTE: Superscript numbers refer to footnotes and References at end of the chapter.

Glossary of Terms For Stereo and SCA

Multiplexing. In its simplest sense, *multiplexing* implies that two or more independent sources of information are combined for carriage over a single medium, namely, the radio frequency "carrier", and then are separated at the receiving end. In stereophonic broadcasting, for example, program information consisting of left and right audio signals are *multiplexed* onto an FM carrier for transmission to receivers which subsequently recover the original audio signals.

Channel. A transmission path. The distinction between the concept of a *channel* and a *signal* are not always clear. The usage herein distinguishes between transmission channels; e.g., main channel, stereophonic subchannel, etc., and left and right audio "signals".

Composite Baseband Signal. A signal which is the sum of all signals which frequency modulate the main carrier. The signal can be represented by a formula which includes all signal components: the main channel signal, the modulated stereophonic subcarrier, the pilot subcarrier and the SCA subcarrier(s).

FM Baseband. The frequency band from 0 hertz (Hz) to a specified upper frequency which contains the composite baseband signal.

Main Channel. The band of frequencies from 50 (or less) Hz to 15,000 Hz on the FM baseband which contains the main channel signal.

Main Channel Signal. A specified combination of the monophonic or left and right audio signals which frequency modulates the main carrier.

Stereophonic Sound. The audio information carried by plurality of channels arranged to afford the listener as sense of the spatial distribution of sound sources. Stereophonic sound includes, but is not limited to, biphonic (two channel), triphonic (three channel) and quadrophonic (four channel) services.

Stereophonic Sound Subcarrier. A subcarrier within the FM broadcast baseband used for transmitting signals for stereophonic sound reception of the main broadcast program service.

Stereophonic Sound Subchannel. The band of frequencies from 23 kHz to 99 kHz containing sound subcarriers and their associated sidebands.

Subchannel. A transmission path specified by a subchannel signal occupying a specified band of frequencies.

Subchannel Signal. Subcarrier(s) and associated sideband(s) which frequency modulate the main carrier. It is synonymous with *subcarrier*, as in the stereophonic subcarrier or SCA subcarrier.

Frequency Deviation. The peak difference between the instantaneous frequency of the modulated wave and the carrier frequency.

Percentage Modulation. The ratio of the actual frequency swing of the carrier to the frequency swing defined as 100 percent modulation, expressed in percentage. Although current FCC Rules conditionally permit greater than 100 percent modulation when SCAs are transmitted, a frequency swing of ±75 kHz is still defined as 100 percent modulation.

Injection. The ratio of the frequency swing of the FM carrier by a subchannel signal to the frequency swing defined as 100 percent modulation, expressed in percentage. The total injection of more than one subchannel signal is the arithmetic sum of each subchannel injection.

Crosstalk. An undesired signal occuring in one channel caused by an electrical signal in another channel.

Linear Crosstalk. A form of *crosstalk* in which the undesired signal(s) is created by phase or gain inequalities in another channel or channels. Such crosstalk may be due to causes external to the stereophonic generator; consequently it is sometimes referred to as *system crosstalk*.

Nonlinear Crosstalk. A form of *crosstalk* in which the undesired signal(s) is created by harmonic distortion or intermodulation of electrical signal(s) in another channel or channels. Such crosstalk may be due to distortion within the stereophonic generator or FM transmitter; consequently it is sometimes referred to as *transmitter crosstalk*.

Frequency Spectrum and Modulation Limits

The stereophonic transmission standards in Section 73.322 of the FCC Rules, and the SCA transmission standards in Section 73.319, were revised in 1984. The original definition of the "stereophonic subcarrier" was removed from the Rules and the definition of "stereophonic sound" was enlarged to cover any number of audio signals needed to convey the spatial distribution of sound sources.

Stereophonic sound broadcasting now includes, but is not limited to, the familiar biphonic (two channel) service described herein.

The composite baseband has been extended from 75 kHz (the old frequency limit) to 99 kHz and may be used in support of either stereophonic or SCA multiplex services. Within the frequency range of 23 kHz to 99 kHz any form of amplitude modulation (DSB, SSB, etc.), angle modulation (FM or PM) or frequency shift keying of a multiplex subchannel is permitted.

Under certain conditions when SCA multiplex subcarriers are operated, limits on the total maximum percentage modulation have changed. It is no longer required to "back off" the main channel and stereophonic subchannel levels by an amount equal to the SCA subcarrier injection in order to maintain 100 percent modulation; a total modulation of up to 110 percent is legal in some cases.

The term SCA is an acronym for a "Subsidiary Communications Authorization", once required in order for a station to begin broadcasting a multiplex service. Although the term "SCA" continues, the authorization is no longer required. Except for certain "common carrier" service, broadcast licensees may begin transmitting multiplex services without prior notification of or authorization from the FCC.

The figures below show the baseband spectrum in various modes, from monophonic to stereophonic plus fully-loaded SCA operation.

Fig. 1a represents the basic monophonic program mode, where the baseband width is limited to approximately 15 kHz and no other signals are multiplexed. In this case all the modulating energy is contributed by the main channel. Not more than 100 percent modulation is permitted in this case.

Fig. 1b shows the baseband with SCA operation in addition to monophonic main channel service. Total SCA injection up to 30 percent is permitted within the band from 20 kHz to 99 kHz. This injection figure may be contributed by one

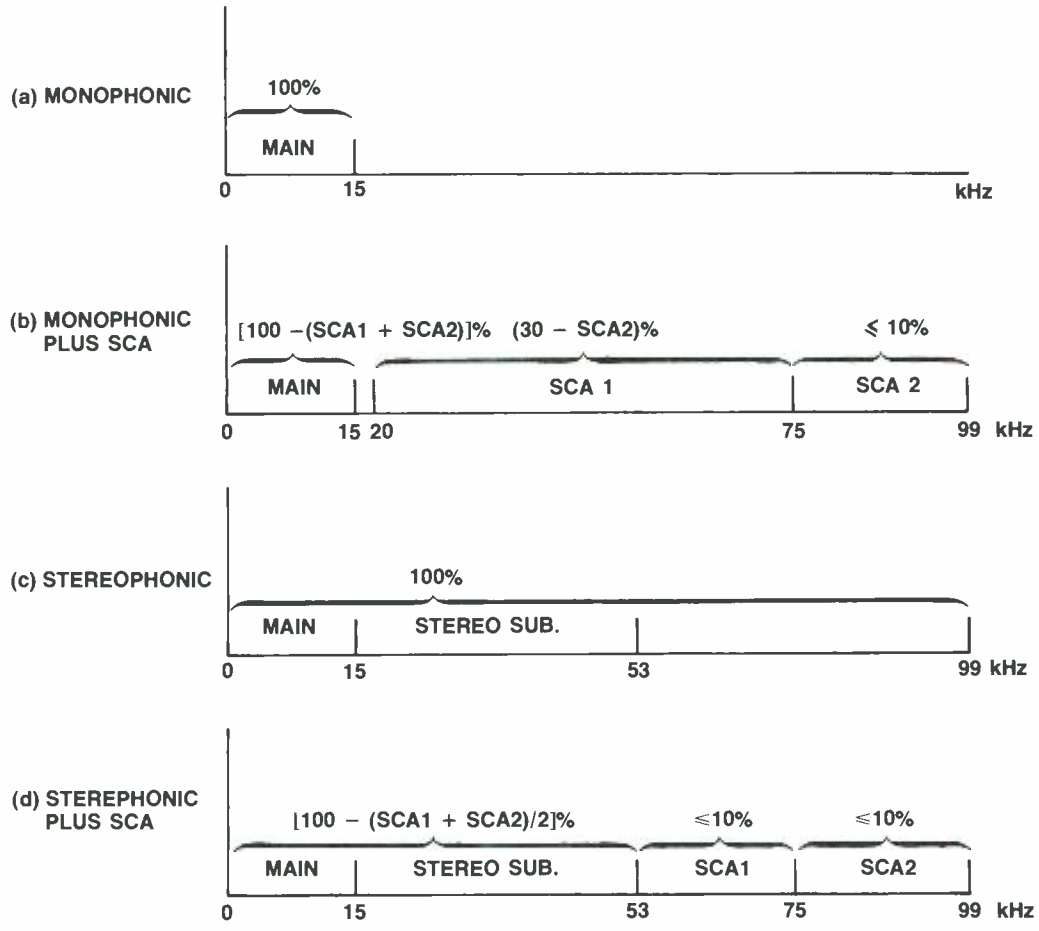


Fig. 1. Frequency spectrum and modulation limits for monophonic, stereophonic and SCA operation. Modulation percentages are referred to 75 kHz carrier deviation.

or more SCA subcarriers, provided that the arithmetic sum of all subcarrier injection above 75 kHz does not exceed 10 percent. Total modulation is not to exceed 100 percent. This is required to insure that the bandwidth of the main carrier (and its interference to other stations on adjacent and alternate channels) is not significantly increased.

When transmitting stereophonic programming, the main channel modulation must be limited to 100 percent minus one-half the total SCA injection. Total modulation, however, is not to exceed 110 percent. Modulation limits were established for the same reasons of protection from increased interference mentioned above.[4]

Note that the FCC Rules permit transmission of multiplex subcarriers when *no* broadcast program service is carried on the main channel, provided that the above modulation rules are met.

Fig. 1c shows the basic stereophonic sound program mode, without SCA operation. As is the case for monophonic program operation, the modulation must be limited to 100 percent. Frequencies up to 99 kHz are available for stereophonic sound program transmission. Actual bandwidths and characteristics of stereophonic signals are discussed in the next section of this chapter.

Fig. 1d adds a single band for SCA operation to the stereophonic mode. While total SCA injection may be up to 20 percent, no more than 10 percent total injection may be employed within the frequency bands from 53 kHz to 75 kHz and 75 kHz to 99 kHz. (There is one exception to determining total SCA injection involving subcarriers that are multiples of and synchronous to the stereophonic pilot. This will be discussed in the SCA multiplex section of the chapter.) The modulation contributed by the main channel and stereophonic subchannel signals must be no more than 100 percent minus one-half the total SCA injection. Since the total injection may be up to 20 percent, total modulation may be up to 110 percent.

STEREOPHONIC TRANSMISSION STANDARDS—PART 73.322

The stereophonic subchannel is the key to multichannel sound broadcasting. Its performance is strictly defined by the FCC Rules:

(a) The modulating signal for the main channel shall consist of the sum of the left and right signals.

(b) A pilot subcarrier at 19,000 Hz plus or minus 2 Hz shall be transmitted that shall frequency modulate the main carrier between the limits of 8 and 10 percent.

(c) The stereophonic subcarrier shall be the second harmonic of the pilot subcarrier and shall cross the time axis with a positive slope simultaneously with each crossing of the time axis by the pilot subcarrier.

(d) Amplitude modulation of the stereophonic subcarrier shall be used.

(e) The stereophonic subcarrier must be suppressed to a level of less than one percent modulation of the main carrier.

(f) Stereophonic sound subchannels must be capable of accepting audio frequencies from 50 Hz to 15,000 Hz.

(g) The modulating signal for the stereophonic subcarrier shall be equal to the difference of the left and right signals.

(h) The preemphasis characteristics of the stereophonic subchannel shall be identical with those of the main channel with respect to phase and amplitude at all frequencies.

(i) The following modulation levels apply to stereophonic sound transmission:

1. When a signal exists in only one channel of a two channel (biphonic) sound transmission, modulation of the carrier by audio components within the baseband range of 50 Hz to 15,000 Hz may not exceed 45 percent and modulation of the carrier by the sum of the amplitude modulated subcarrier in the baseband range of 23 kHz to 53 kHz may not exceed 45 percent.

2. When a signal exists in only one channel of a stereophonic sound transmission having more than one stereophonic subcarrier in the baseband, the modulation of the carrier by audio components which the audio baseband of 50 Hz to 15,000 Hz may not exceed 37 percent and modulation of the carrier by the sum of all subchannel components with the baseband range of 23 kHz to 99 kHz may not exceed 53 percent.

(k) At the instant when only a positive left signal is applied, the main channel modulation shall cause an upward deviation of the main carrier frequency; and the stereophonic subcarrier and its sidebands shall cross the time axis simultaneously and in the same direction.

(l) The ratio of peak main channel deviation to peak stereophonic subchannel deviation when only a steady state left (or right) signal exists shall be within plus or minus 3.5 percent of unity for all levels of this signal and all frequencies from 50 Hz to 15,000 Hz.

(m) The phase difference between the zero points of the main channel signal and the stereophonic subcarrier sidebands envelope, when only a steady state left (or right) signal exists, shall not exceed plus or minus 3 degrees for audio modulating frequencies from 50 Hz to 15,000 Hz.

(n) The separation between any two channels of a stereophonic transmission system must exceed 29.7 dB for all audio modulating frequencies between 50 Hz and 15,000 Hz; this separation will indicate compliance with the amplitude and phase tolerances given in paragraphs (l) and (m) above.

(o) Nonlinear crosstalk into the main program channel caused by signals in the stereophonic subchannel must be attenuated at least 40 dB (measured at RMS noise) below 90 percent modulation; nonlinear crosstalk into the stereophonic subchannel(s) caused by signals in the main channel must be attenuated at least 40 dB (measured as RMS noise) below 90 percent modulation; (nonlinear crosstalk does not include effects of phase delay differences in program audio circuits...these effects are represented by a loss of channel separation and by amplitude distortion in the monophonic reception of stereophonic programs).

GENERATING THE STEREOPHONIC BASEBAND SIGNAL

Fig. 2 shows the composite baseband that modulates the FM carrier for biphonic broadcasting. (SCA multiplex subchannels are not part of this band and will be discussed later.)

The two-channel stereo baseband has a bandwidth of 53 kHz, and consists of:

- A main channel *(L + R)* consisting of the sum of left plus right audio signals; this is the same signal broadcast by a monaural FM station. However, it must not modulate a full 75 kHz since it would lead to overmodulation and interference when the stereophonic signals are added. Instead, it is modulated 45 percent for a full left-only or right-only signal.

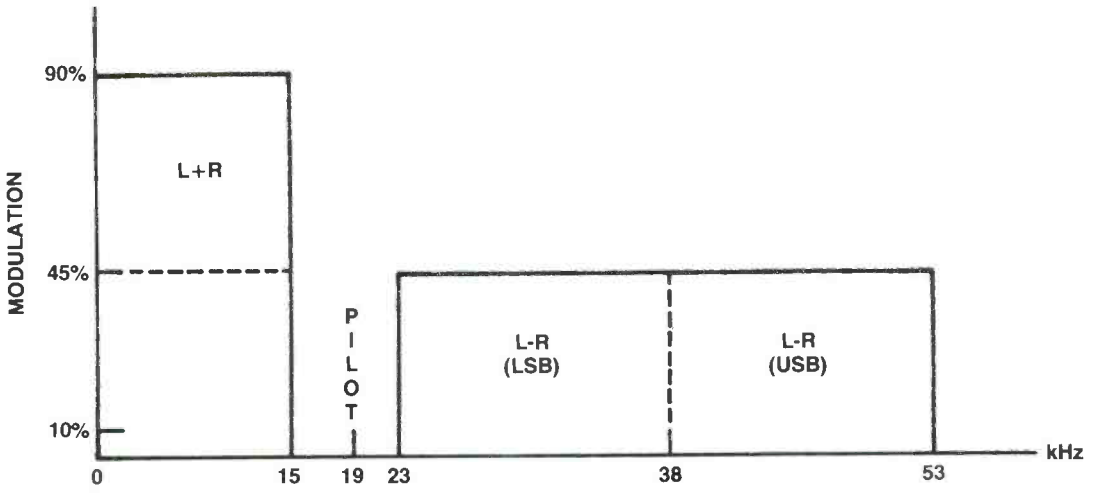


Fig. 2. Bi-phonic (two-channel) stereo baseband.

- A stereophonic sound subchannel *(L − R)* is required, consisting of a double sideband AM modulated subcarrier with a 38 kHz center frequency. The modulating signal is equal to the instantaneous difference of the left and right audio signals. The subcarrier is suppressed to avoid wasting modulation capability. As a result the AM sidebands have the same modulation potential as the main channel.
- A 19 kHz subcarrier *pilot* which must be exactly one-half the frequency of the stereophonic subcarrier and very nearly in phase to it. It supplies the reference signal needed by the stereo receivers to reinsert a 38 kHz carrier for DSBSC demodulation (or, more commonly, to synchronize the synchronous decoder circuitry in a receiver). The frequency tolerance is plus or minus 2 hertz and must modulate the main carrier between 8 and 10 percent.

In general two principles have been used to generate the stereophonic subchannel. The methods are called *time division multiplex* (TDM) or *switching method* and *frequency division multiplexing* (FDM) or *matrix method*.

Frequency Division Multiplexing

A popular method for generating the stereophonic baseband involves the direct generation of the double sideband suppressed L − R subchannel along with the L + R channel.

A simplified block diagram of the FDM system is shown in Fig. 3. Both left and right audio channels are preemphasized and low pass filtered just as a normal monaural signal would be. In the matrix, the left and right audio signals are both added and subtracted. The audio signals are added to form the L + R main channel which is also used as the monaural broadcast signal.

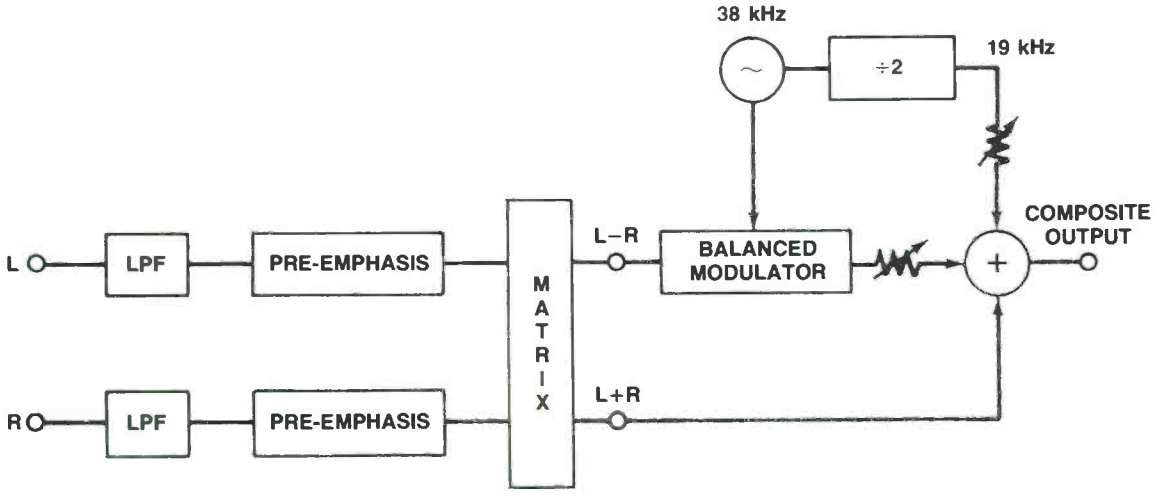


Fig. 3. Functional blocks of a frequency division multiplex stereo generator.

The subtracted signals are fed to a balanced modulator which generates the L – R subchannel. Since a balanced modulator is used, the carrier at 38 kHz will be suppressed, leaving only the modulated sidebands.

The 38 kHz oscillator is divided by 2 to make the 19 kHz pilot tone. Finally, the main channel stereophonic subchannel and pilot are combined in the proper (45, 45, 10) ratio to form the composite output.

An examination of the composite stereo waveform in the time domain (as displayed by an oscilloscope) will illustrate some basic situations. First consider a 1 kHz sine wave applied equally to the L and R audio inputs. This is shown in Fig. 4a without a pilot signal. The only frequency present is 1 kHz, since the matrix produces no difference signal necessary to generate sidebands in the stereophonic subchannel.

Fig. 4b illustrates the ideal composite signal when the same 1 kHz tone is applied to the L and R inputs but exactly out of phase. The pilot is still off. Two frequency components are generated: 37 kHz and 39 kHz. No L + R signal appears out of the matrix; thus, only the sidebands of the modulated 38 kHz subchannel are present.

The symmetrical envelope shown represents a double-sided band suppressed carrier (DSBSC) AM signal. Note that the amplitude of each sideband is one-half that of the L + R component in Fig. 4a. When demodulated in the receiver's stereo decoder, the sidebands are added together to produce an output equal to the full L + R signal.

Finally, consider the waveform in Fig. 4c, when the composite signal (still without pilot) is generated by applying a 1 kHz tone to the L in-

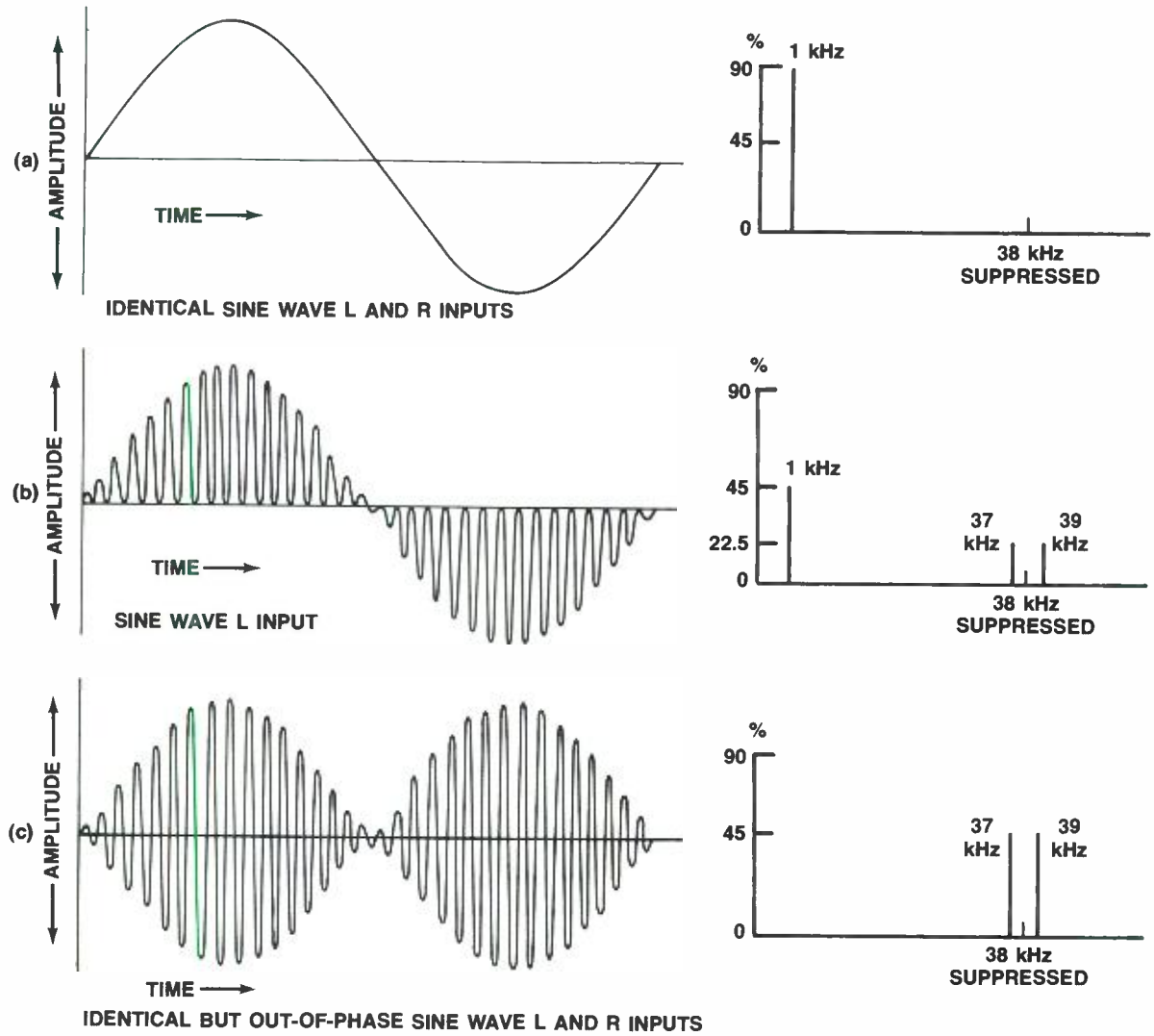


Fig. 4. Time domain (oscilloscope display) and frequency domain diagrams of stereo baseband signal with (a) identical sine wave L and R inputs, (b) sine wave L input, and (c) identical but out-of-phase sine wave L and R inputs.

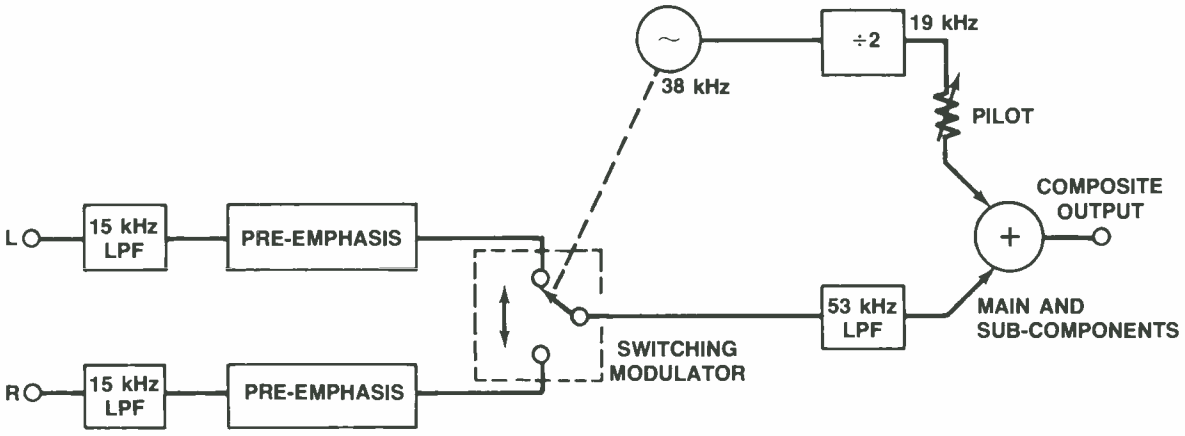


Fig. 5. Functional blocks of a time division multiplex stereo generator.

put alone. The baseline of the waveform envelope will be a straight if there is no amplitude or phase subchannel. Three frequency components are present: 1 kHz, 37 kHz and 39 kHz. These sidebands are each one-half the voltage amplitude of the 1 kHz signal in the main channel; together they equal the energy of the main channel in this instance.

The last diagram looks the same when an R-only 1 kHz tone is applied, although the phase of the two sidebands would be reversed with respect to the 38 kHz subcarrier (and the pilot). Adding the pilot, at its relatively low amplitude of 10 percent, produces the same overall waveforms, but its "spreading" effect makes display of the basic waveform less clear. That is true in practice, as well, which is a reason most stereo generators have provision for testing without the pilot.

Time Division Multiplex

A different type of stereo generator is in use which produces the same result as frequency division multiplexing by using a switching technique.

Generation of both the L + R and L − R channels is accomplished by an electronic switch which is toggled by a 38 kHz signal. The switch alternately samples one audio channel and then the other, as shown in Fig. 5. The original signal can be reconstructed from periodic samples, provided that the samples are taken at a rate at least twice the frequency of the highest audio frequency component (approximately 15 kHz in broadcast FM).

The output waveform for the TDM generator is next shown first in the time domain (as an oscilloscope would display the signal) for a sequence of input signals. The diagrams at the right

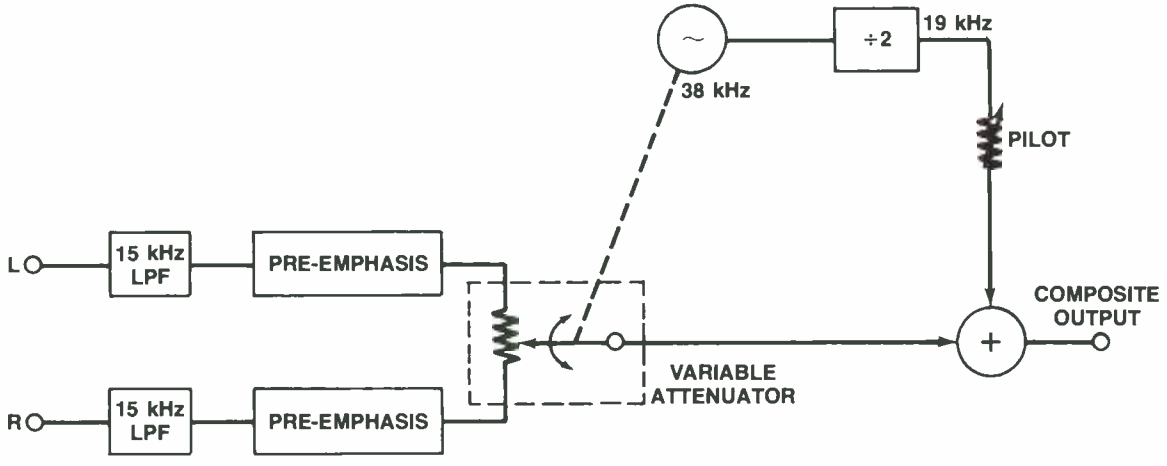


Fig. 6. Functional blocks of a time division multiplex stereo generator using a variable attenuator.

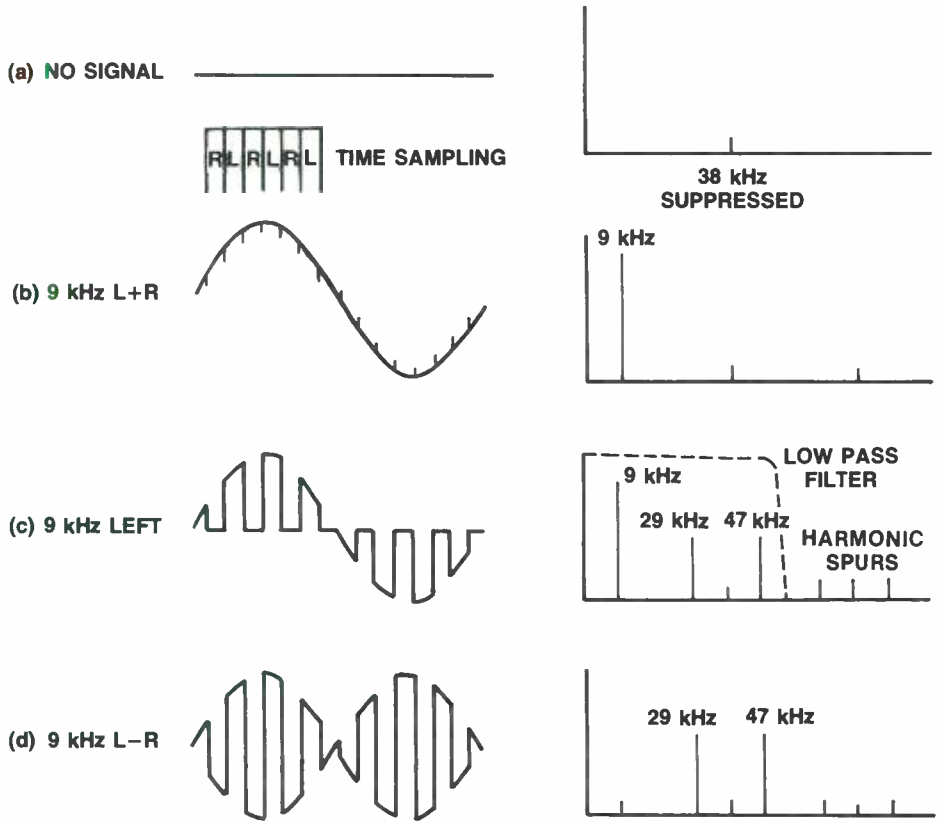


Fig. 7. Time domain and frequency domain diagrams of stereo baseband signals.

of the waveform show the same signal in the frequency domain (as would be displayed on a spectrum analyzer).

In Fig. 7a, there are no input signals present. Ideally, no output signals are possible, and in practice only a small amount of leakage of the switching transients are present. Since the transfer time of the switching signal is extremely quick, harmonics of the fundamental 38 kHz are possible.

A 9 kHz audio tone is applied to the L and R inputs in Fig. 7b. The 9 kHz input signals are combined at full amplitude (90 percent modulation) and no subchannel sidebands are generated.

In Fig. 7c, only the left channel has a signal present. As the switch selects the L audio line, samples are passed along to the composite output. Therefore, the output waveform shows the same signal, chopped into segments of 1/38,000th of a second. Since the total area under the waveform has been divided in half, it should be apparent that the energy of the 9 kHz signal in the L + R channel is only half the amplitude that it would be if an equal 9 kHz signal were also present at the right channel. The equation for the output signal e for an input signal σ at any instant t is

$$e = 1/2 \sin \sigma t \quad \textit{(main ch. audio)}$$
$$+ 1/\pi \left[\sin(\phi+\sigma)t + \sin(\phi-\sigma)t\right] \quad \textit{(DSBSC)}$$
$$- 1/3\pi \left[\sin(3\phi+\sigma)t + \sin(3\phi-\sigma)t\right] \quad \textit{(3rd Harmonic)}$$
$$\ldots \textit{etc.} \quad \textit{(higher harmonics)}$$

Fig. 7c shows the original 9 kHz signal (at half amplitude), and a pair of sidebands centered about the 38 kHz switching frequency. No 38 kHz signal is generated if the switching waveform has perfect symmetry, that is, if the switch is connected to the left and right channels for precisely equal periods. Note that a harmonic of the stereophonic subcarrier is shown, centered around 114 kHz which is three times the switching frequency. Only one extra term was shown in the equation, however, other terms at the 5th, 7th, etc. are present.

In addition to the odd-order harmonics of the 38 kHz subchannel, asymmetry in the switching signal or other circuit imbalances can create some sidebands centered about the second harmonic at 76 kHz. All these harmonics must be removed by filtering, as shown in the diagram.

When the odd harmonics are filtered out, the proper DSBSC waveform results. However, it is slightly greater in amplitude than the L + R signal. (Because the fundamental component of the square wave is $4/3\pi$ times larger than the square wave amplitude, the DSB component is larger than the L + R component.) This is easily corrected by adding enough of the L and R audio to the output to equalize the amplitude.

In Fig. 7d, the TDM signal is shown when the L and R signals are equal in amplitude and exactly reversed in phase. This waveform matches the composite stereo signal shown in Fig. 4c.

The composite lowpass filter should have very steep cutoff characteristics but should have flat amplitude response and linear phase shift with frequency (equal time delay at all frequencies) below 53 kHz. While this approach to stereophonic generation is simple and stable, the filter can degrade stereo separation, especially at higher audio frequencies.

A significant improvement on the original switching concept is shown in Fig. 6. As mentioned earlier, the higher order terms of the square wave-driven switch are responsible for generating the harmonics of the 38 kHz subchannel which must be removed by filtering. By using a "soft switch" to connect back and forth between the L and R channels it is possible to eliminate the lowpass filter and its side-effects. This is accomplished by using a variable attenuator, shown in the diagram by a potentiometer. The slider is driven from end to end of the potentiometer by a sinewave. Since a sinewave is represented only by a single, fundamental frequency, the signal output at the slider has the proper DSBSC characteristics without the harmonics. The equation for the composite signal generated in this way is

$$e = 1/2 \sin \sigma t \qquad \text{(L + R audio)}$$
$$+ 1/\pi \left[\sin(\phi + \sigma)t + \sin(\phi - \sigma)t\right] \qquad \text{(38 kHz DSBSC)}$$

As the equation shows, only the fundamental sidebands of 38 kHz are present in the sampled signal, along with the main channel component. Like the fast-switching TDM system, the L + R and L − R channels are generated in one operation so that the circuit remains relatively simple. No filter of the output is required, provided that the 38 kHz sinewave is free from harmonics and the variable attenuator has good linearity.

Stereo Decoder Circuits

Stereo FM receivers include a circuit to convert the multiplexed composite signal at the FM detector into the original Left and Right audio channels transmitted by the FM station. There are at least as many ways to decode the stereophonic signal as there are ways to encode (generate) the composite signal. In practice, only one type of decoder is commonly used, the so-called "phase-locked loop" integrated circuit.

The circuit in Fig. 8a is seldom used, but is shown for comparison. It is the closest complement to stereo generators using frequency division multiplexing. At the input, the composite signal is split with three filters into the main (L + R) channel, pilot signal and stereo (L − R) subchannel. Next, the pilot is doubled to 38 kHz and this regenerated carrier is reinserted into the double-sideband AM signal from the subchannel filter. This AM signal is demodulated to yield the L − R (difference) audio. Finally, the L + R and L − R signals are combined in a sum and difference matrix to produce to original Left and Right audio channels.

Because of the costly filters needed to separate the composite spectrum, the frequency division multiplex circuit is not used in consumer equipment. Similar circuits have been used in broadcast modulation monitors, where metering of the separate channels is required.

The circuit shown in Fig. 8b is universally used, due to its simplicity, high performance and low cost. While commonly referred to as a "phase locked loop" (PLL) stereo decoder, its distinction is really as a time division demultiplexer (shown in the dashed box as a toggle switch).

Following a buffer amplifier, the composite baseband signal is sampled by a phase locked loop within the IC. A voltage controlled oscillator, usually running at 76 kHz (four times the pilot frequency) is held in phase with the pilot by a reference signal from the phase comparator and loop filter. When divided by two, the result is a square wave at 38 kHz having nearly perfect duty cycle (high and low states have equal timing) and very fast rise and fall times. This signal is ideal for driving the output audio switcher (demultiplexer). This stage is a transistor matrix designed to rapidly transfer the composite baseband to the Left and Right audio output in time with the switch in the station's stereo generator. Fast, clean audio switches are relatively easy to make, and because they are only "on" or "off", they are not subject to drift.

Because PLL stereo decoders normally use square wave switching, the circuit is able to demultiplex (demodulate) baseband signals which are odd harmonics of 38 kHz. The third harmonic (114 kHz) is most troublesome, since noise and spurious signals near this frequency are shifted to the audio baseband, as is the 38 kHz stereophonic subchannel.

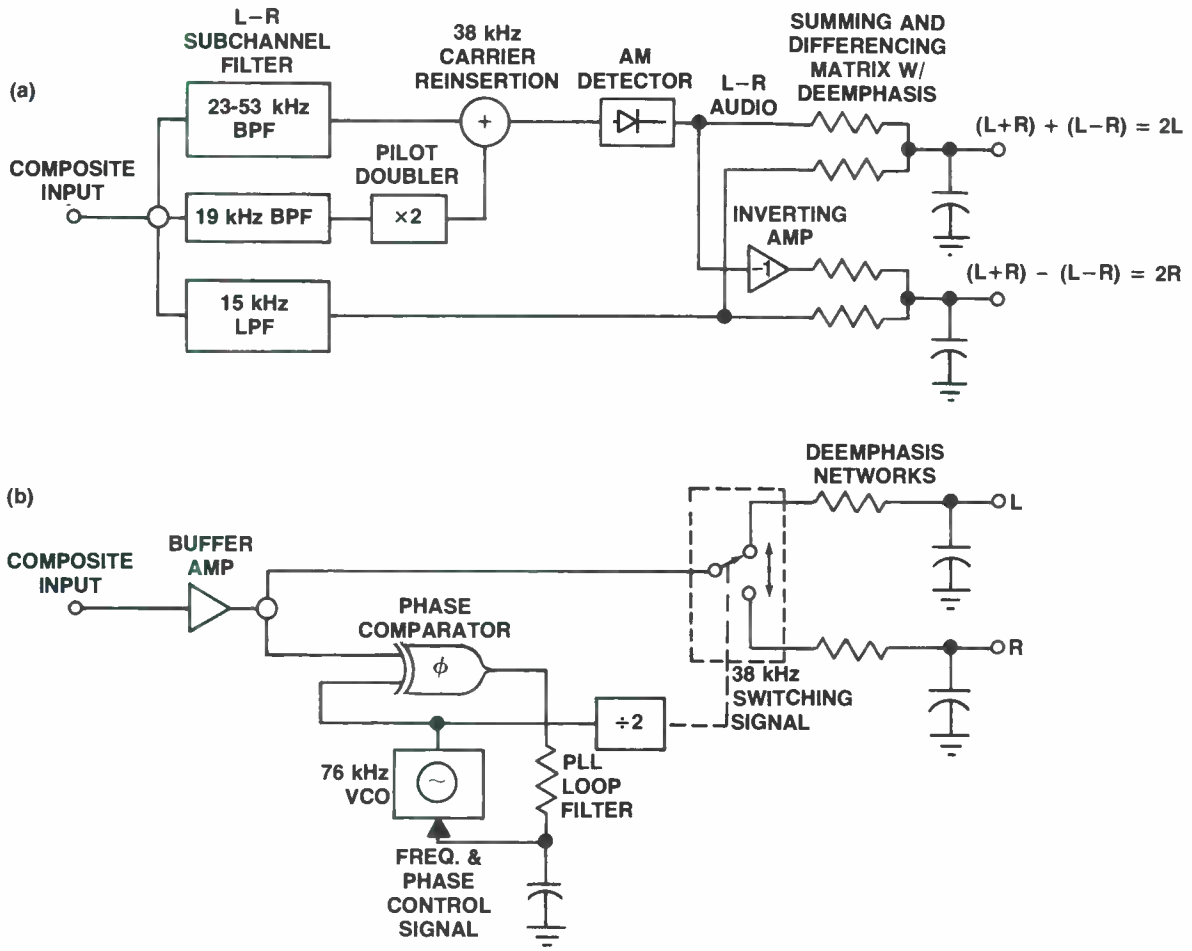


Fig. 8. Functional blocks of stereo decoders using (a) L+R and L–R matrixing and (b) phase-locked time-division multiplexing.

Engineers should be watchful of the frequency band centered on 114 kHz in their transmitted signal since audible noise may occur in consumer receivers. Some recent stereo decoder ICs utilize a second composite audio toggle switch operated at 114 kHz. The demodulated product is inverted and mixed equally with the 38 kHz switching outputs, cancelling the response to signals in the 114 kHz range.

FM SCA TRANSMISSION

Background

From its beginning as a broadcast service, people have recognized the potential of FM for multiplexed services. As early as 1940, the FCC permitted multiplex facsimile transmission on FM stations, but not until much later did auxiliary FM services attain a wide acceptance among FM broadcasters.

In 1955 the FCC established the Subsidiary Communications Authorization and created an entirely new industry. The original intent of the authorization was to permit programming of background music to offices, stores, restaurants, etc. where it was uneconomical to provide this service via telephone lines. For many commercial FM stations, the SCA operation became a major source of revenue which enabled them to survive in the 1950s.

Because educational broadcasters had not indicated a real desire for additional programming services, they were specifically excluded from providing any SCA services. However, in 1961 the FCC authorized SCA operation in a manner consistent with their noncommercial status.

By the early 1980s, improvements in transmitter and receiver technology and the desire for new revenue prompted commercial and noncommercial broadcasters to seek changes in the SCA rules. In a series of rulemakings in 1982 and 1983 the Commission made numerous changes to expand technical opportunities and reduce legal regulation:[5]

- elimination of the requirement for an FCC authorization (Subsidiary Communications Authorization) prior to operating multiplexed services;
- extension of the baseband frequency limit from 75 kHz to 99 kHz;
- allowance of any type of subcarrier modulation to be used for multiplexed services;
- changes in the subcarrier injection requirements to permit multiple services;
- increased limits for the total modulation during SCA multiplex operation to reduce main channel modulation loss;
- operation of SCA services on noncommercial FM stations under the same rules as commercial FM stations.

FCC Rule Requirements for SCA Operation

The FCC rules have no standards for SCA subcarrier performance. This is left for the broadcaster or lessee of the service to determine. However, the Commission is quite specific in defining the transmission conditions under which subcarriers may be operated, in order to minimize interference to the main channel and stereophonic subchannel or to other FM stations.

The constraints of injection and subcarrier bandwidth will be considered in detail for the stereophonic mode, since stereo transmission is by far the most common FM service. Fig. 9 shows the upper portion of the composite baseband, from approximately 50 kHz to 100 kHz. This is the same as the upper portion of Fig. 2 with the addition of two hypothetical subcarriers. (Any number of SCA subcarriers may be operated within this frequency range provided that each subcarrier has adequate bandwidth and injection. This will be discussed later in the chapter.)

On the baseline are several frequency markers at the upper and lower frequency limits of the two subcarrier ranges. The actual frequencies of the subcarriers are not specified, but are referred to as "fc_1" and "fc_2".

Alongside each subcarrier are arrows marking the level in dB below 100 percent modulation of the main carrier. For example, -20 dB marks the injection at the center frequency of both subcarriers. Since 10 percent is the maximum injection permitted under the Commission Rules within each SCA subchannel,

$$\text{injection} = 20 \times \log_{10}(0.1) = 20 \times (-1) = -20 \text{ dB}$$

At 53 kHz, an arrow marks a level of -60 dB. The FCC requires that any frequency modulation of the main carrier due to the SCA operation shall be at least 60 dB below 100 percent modulation in the frequency range of 50 Hz to 53 kHz when stereo is transmitted. This figure must include spurious and intermodulation products as well as subcarrier sideband energy.

At 99 kHz, the level of -20 dB is marked, denoting the FCC requirement that "instantaneous sidebands" be restricted within this frequency limit. The Commission has not officially defined instantaneous sidebands, but it is normally considered to be the instantaneous frequency of the subcarrier at its peak deviation (for frequency modulated subcarriers) or the highest sideband frequency (for amplitude modulated subcarriers).

Interference Between FM SCA Subcarriers

In practice, two subcarriers should be separated as far apart in frequency as possible, while observing the limit of spurious energy below 53 kHz and the instantaneous sidebands at 99 kHz. While the FCC Rules are silent on the choice of

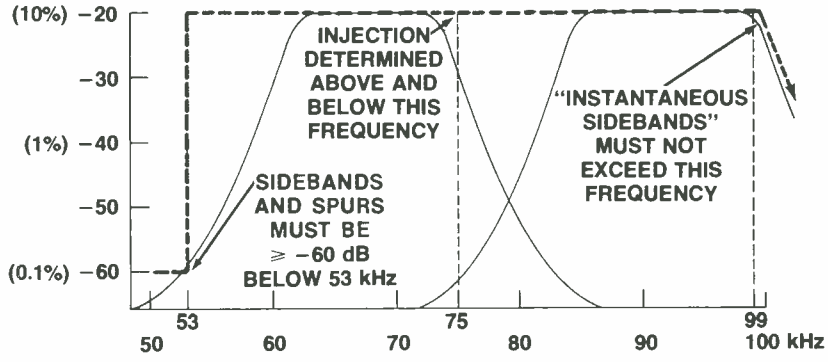


Fig. 9. Injection, channel bandwidths and spurs limits for SCA operation when stereo is transmitted. Two possible subcarriers (at 67 and 92 kHz) are shown.

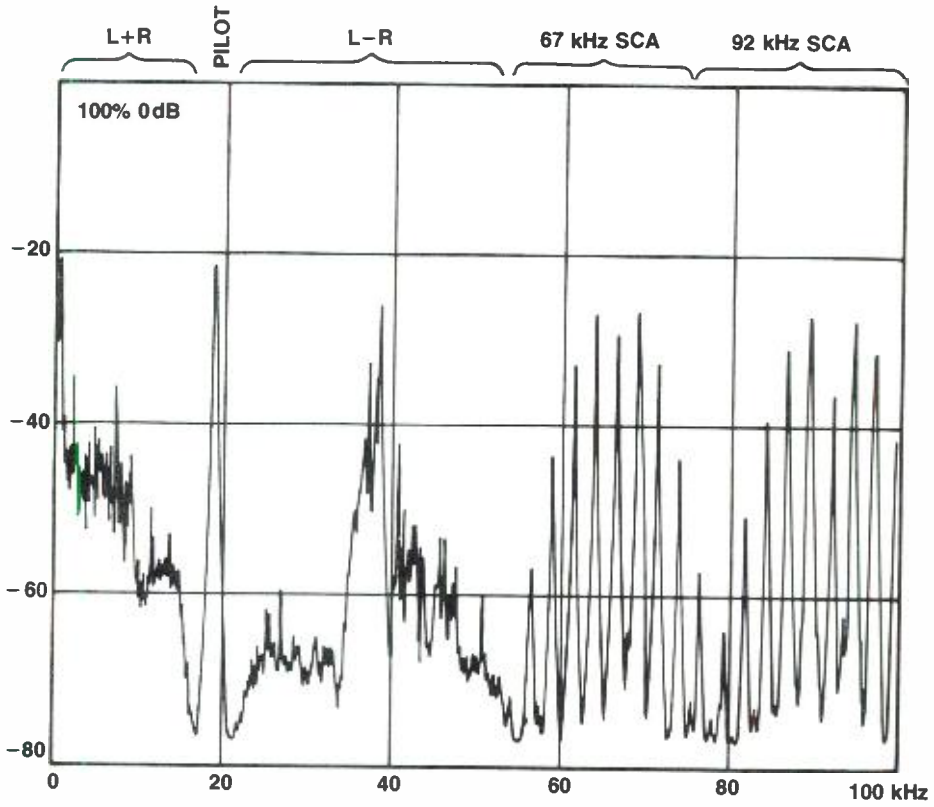


Fig. 10. Composite baseband of FM station with 67 kHz and 92 kHz FM-SCAs, modulated with 2.5 kHz tone at 5 kHz and 7 kHz peak deviation, respectively. Note overlap of sidebands between subcarriers. Station is carrying stereo programming.

SCA frequencies, the industry has two defacto standards for frequency modulated subcarriers: 67 kHz and 92 kHz. The first frequency was adopted when the original stereophonic standards placed an upper limit of 75 kHz on the baseband. The second frequency was recommended to situate the instantaneous sidebands below 99 kHz while remaining safely distant from a 67 kHz subcarrier.[6]

Some overlap of the subcarrier sidebands does occur, as depicted in Fig. 10. This does not cause significant interference between the two SCA subchannels when the systems use frequency modulation:

- unweighted 67 kHz SCA S/N ratio referred to 5 kHz deviation: 57.5 dB
- same, with 4 kHz tone modulation of 92 kHz subcarrier at 7 kHz dev.: 56.5 dB
- same as first case w/ tone mod. of main channel at 67.5 deviation: 52.5 dB

(Receiver used for data: McMartin TRE-6 with regulated power supply substituted for standard equipment)

The above data shows that crosstalk from main-to-subchannel is significantly higher than crosstalk from one highly modulated subcarrier in the adjacent subchannel.

Other Types of Subcarrier Modulation

Other frequencies and total number of subchannels are permissable, according to the occupied bandwidths and interference margins required. An example of an SCA baseband spectrum combining five amplitude-modulated subcarriers is shown in Fig. 11.

Here, a variety of bandwidths and injection levels are used. At 57 kHz, a very narrow double-sideband AM subchannel is shown. This system was developed in Europe for "Automotive Road Information" (ARI), to identify stations which broadcast traffic information and to activate specially-equipped FM car radios during traffic announcements. (The system is now being introduced on selected stations in this country by Blaupunkt.) An interesting effect of adding the 57 kHz subcarrier in phase to the stereophonic pilot is that there is virtually no increase in peak modulation of the main carrier. (A third-order

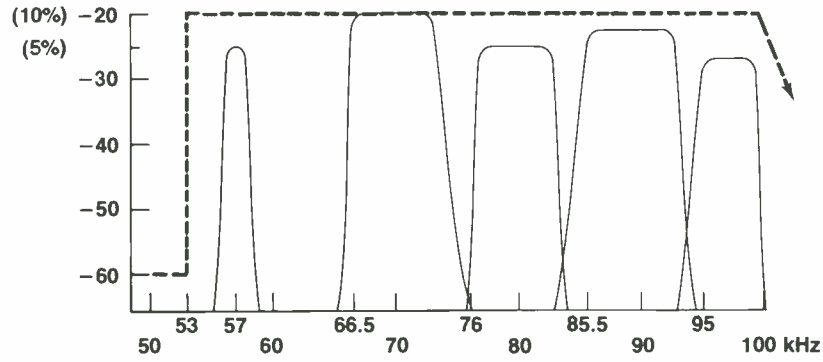


Fig. 11. Carrier envelope spectrum, DSB-AM and SSB-AM SCA subcarriers. Vertical markings are dB referred to 75 kHz deviation.

harmonic does not increase the peak amplitude when in-phase and at an amplitude one-half the fundamental.) This allows 57 kHz double-sideband AM subcarrier to be added to the baseband without being counted toward the injection from 53 kHz to 75 kHz and without requiring the backoff of main channel modulation. However, this subchannel must have very narrow bandwidth to operate with an acceptable margin of reliability, and thus it has limited information capacity.

Note in Fig. 11 that upper-sideband, suppressed carrier AM (SSBSCAM) systems are used for the four other subchannels. On the first (at 66.5 kHz), nearly 10 percent peak envelope injection is being used, while the other three use a combination which adds up to ten percent to satisfy the limit for the 75 to 99 kHz range.

Examples of SCA Operation

Fig. 12a shows the functional blocks of a standard aural SCA generator using frequency modulation. At the input, audio is lowpass filtered to limit the generation of high-order sidebands which could cause excessive bandwidth and possibly interfere with the stereophonic subchannel or an upper SCA subchannel.

A 5 kHz audio cutoff is frequently used so that fidelity compares favorably to unequalized telephone service. Using a Bessell function analysis, one can determine the peak deviation which may be used to maintain FM sidebands below 53 kHz within FCC limits:

SCA Modulating Frequency	SCA Peak Deviation
3.5 kHz	5.0 kHz
5.0	3.5
7.5	2.0

For the above protection requirements, equipment manufacturers often recommend 3.5 or 4.0 kHz peak deviation with a 5 kHz lowpass filter when stereo is transmitted. In practice, slightly higher deviation may be used since the calculations assume single-tone modulation which has greater modulation power than program audio.

Preemphasis follows the lowpass filter in the sample FM SCA generator. A value of 150 Sec is commonly used to combat the rising high-frequency noise characteristic in the FM SCA channel. Unfortunately, this extreme boost (almost 17 dB at 5 kHz, compared to 400 Hz) requires substantial amounts of peak limiting to allow full modulation at low and middle audio frequencies.

The processed audio signal is fed to the FM modulator, usually with a provision for subaudible (less than 30 Hz) channel for telemetering return. The telemetry channel takes advantage of the extended low frequency response capability of FM subcarriers by sending tone signals in the 10 to 30 Hz range at a level of 15 to 25 dB below reference peak deviation. A highpass filter is inserted ahead of the audio input when subaudible telemetry is used to avoid interference to the low frequency channel.[7]

Ideally, no filtering of the frequency-modulated subchannel is required. However, some of the FM generator circuits produce spurious or harmonic energy. For this reason, a bandpass or lowpass filter is used which passes all the significant sidebands but suppresses spurious signals to acceptable levels. The modulated subchannel signal is amplified to a level required by the subcarrier input of the FM exciter or studio transmitter link equipment.

A simplified block diagram of a SSBSCAM subchannel generator is shown in Fig. 12b. The input audio is bandpass filtered to control subchannel bandwidth (to 5 kHz, for example), and may be compressed according to specific amplitude and spectral standards. A complementary expander circuit in the receiver restores the

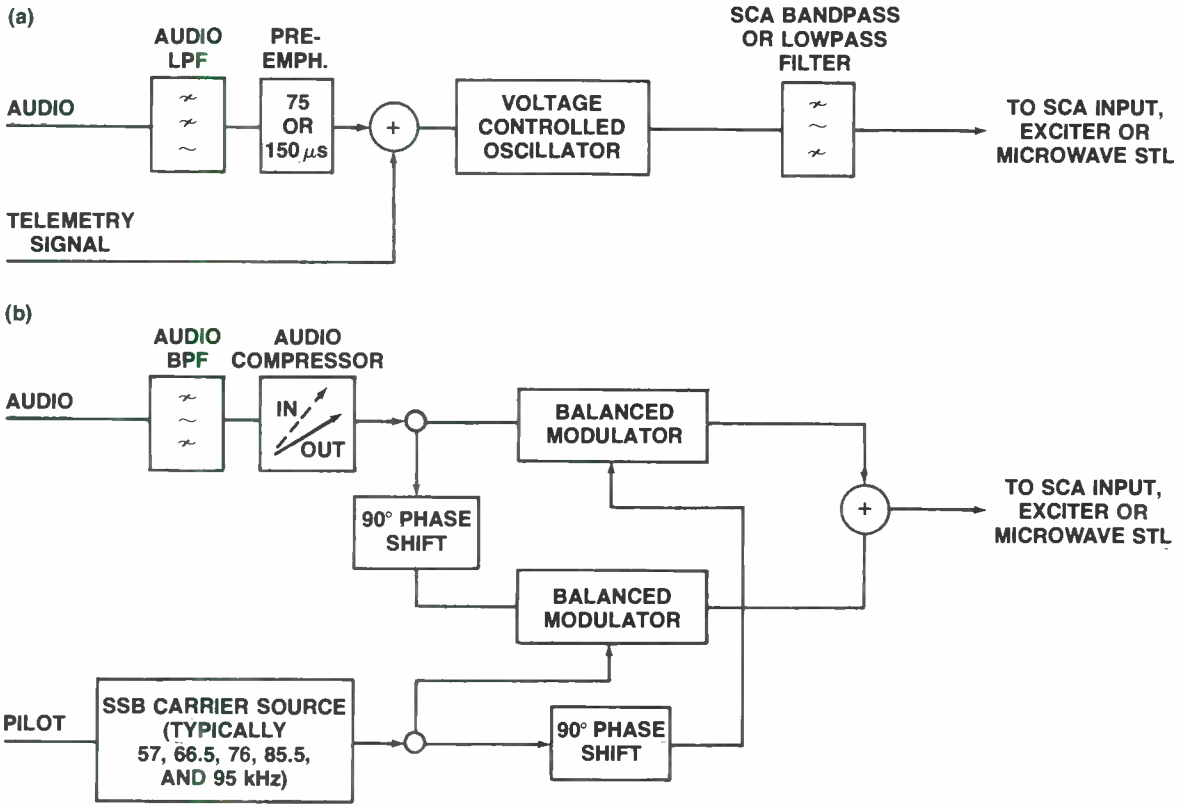


Fig. 12. Functional blocks of (a) a frequency-modulated SCA subcarrier generator, and (b) a single-sideband AM subcarrier generator.

original program dynamics and reduces noise in the channel. Large amounts of preemphasis are not as important since the spectral characteristic of the noise is flat with a linear modulation system, not rising with frequency as in angular modulation systems.

The processed audio signal is fed to a pair of balanced modulators, one path going through an allpass filter which shifts the audio phase 90 degrees throughout the required audio range. The balanced modulators are driven by a subcarrier frequency source which may be frequency-locked to a harmonic of the stereophonic pilot (and its half-frequency of 9.5 kHz, as shown). One of the modulators is driven by a carrier signal which is shifted 90 degrees. When the two modulated carriers are summed, cancellation of the lower (or upper) sidebands creates the desired single-sideband signal.

Since SSBSCAM requires a carrier for detection, the pilot provides an excellent source for reinsertion at the receiver. With monophonic audio, no pilot is transmitted, so another carrier reference must be used. One approach is to carry the 19 kHz reference at a reduced level which will not trigger the stereophonic decoders in FM receivers.

SCA DATA SYSTEMS

SCA subchannels have characteristics which are quite favorable for data transmission: while the channels are noisy for high fidelity audio services, they can provide good to excellent data error performance, and moderately fast data rates are possible without complicated or expensive receivers. Combined with the high power and elevation of FM broadcast stations, SCA data systems may be operated over large service areas.

Indirect Data Modulation

There are many methods of putting data on an SCA subchannel, but most can be separated into two broad groups: direct and indirect carriage. Indirect methods have been used on SCAs for years and are the most similar to data circuits over phone lines. Here, an audio oscillator is switched between two frequencies, e.g., 1070 Hz and 1270 Hz, representing the "0" and "1" states of binary data. This method is commonly called "Audio Frequency Shift Keying" (AFSK).

Since the product of AFSK signalling remains within the audio band, a standard SCA generator and receiver may be used, just like a background music service. There is little cost or complexity

involved in starting this data service on SCAs since there is a great deal of AFSK-type equipment in use, and the data modulator and demodulator functions have been reduced to single integrated circuits. This technique is, however, relatively slow: the highest practical speed is 1,200 bits/second. This may be acceptable where the hardware must be "off the shelf" and there is no premium on SCA channel efficiency. A single-sideband AM subcarrier (discussed earlier) would, of course, increase channel efficiency.

Direct Data Modulation

Direct data modulation eliminates the intermediate steps that convert the data into audio signals, allowing the subcarrier to be directly modulated by the binary data. There are several types of direct data modulation which are discussed below.

In Frequency Shift Keying (FSK), the two binary states are represented by two different subcarrier frequencies. For example, a "0" could be 65 kHz and a "1" 69 kHz. FSK is the most popular form of direct data modulation at this writing, probably because of its robust performance, simplicity and low cost. Maximum speed of 4,800 to 9,600 bits/second are typical for current FSK systems using a nominal injection of 10 percent and a modulated bandwidth similar to that of background music services, i.e., about 16 kHz at a point about 25 dB below subcarrier injection level.[8]

All data FSK systems us filtering methods to control occupied bandwidth, since too-rapid frequency transitions could generate high-order sidebands that could interfere with adjacent subchannels and violate FCC Rules.[9] Filtering is accomplished in several ways, shown in Fig. 13:

- Where a pair of oscillators are alternately toggled by the data states, filtering must be done to the output spectrum to directly reduce occupied bandwidth.
- Where analog FM modulators are used, slew rate filtering of the switching signal tends to reduce high-order sidebands indirectly.
- In some cases, occupied bandwidth is reduced through the use of both pre- and post-modulation filtering.

The spectrum of the composite baseband of an actual FM station is shown in Fig. 14, carrying a 4,800 bits/second data signal. The spectrum was generated by a standard SCA generator driven by a filtered data signal. All reduction of the bandwidth was accomplished *prior* to modulation.

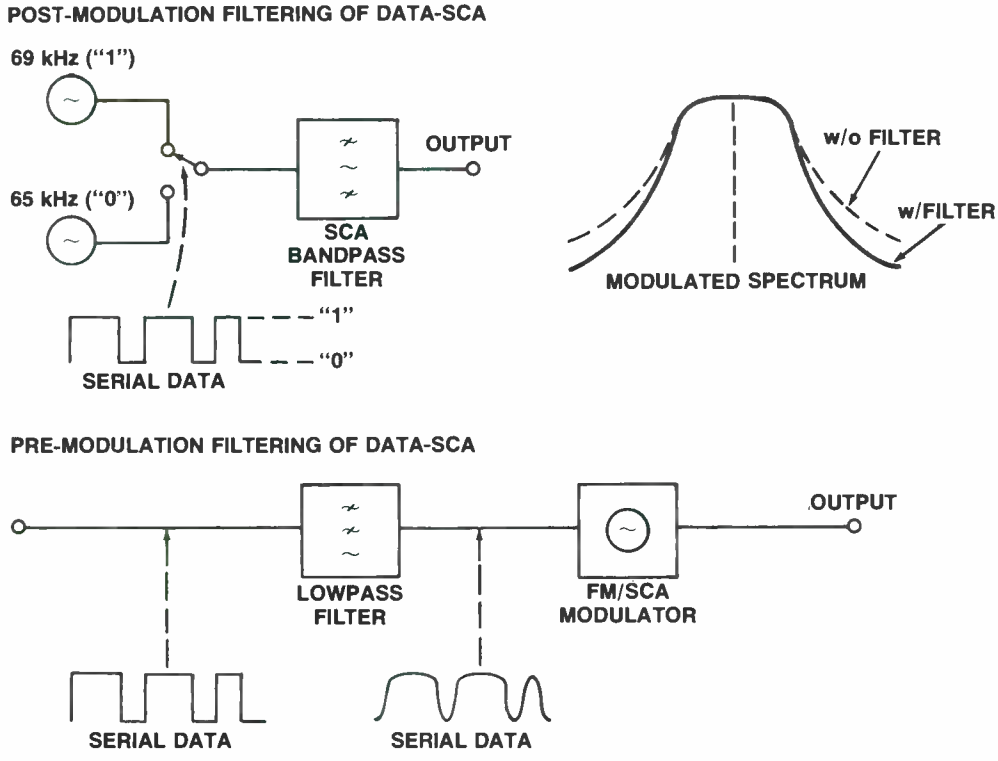


Fig. 13. Two basic methods for generating and controlling the bandwidth of data subcarriers used for SCA.

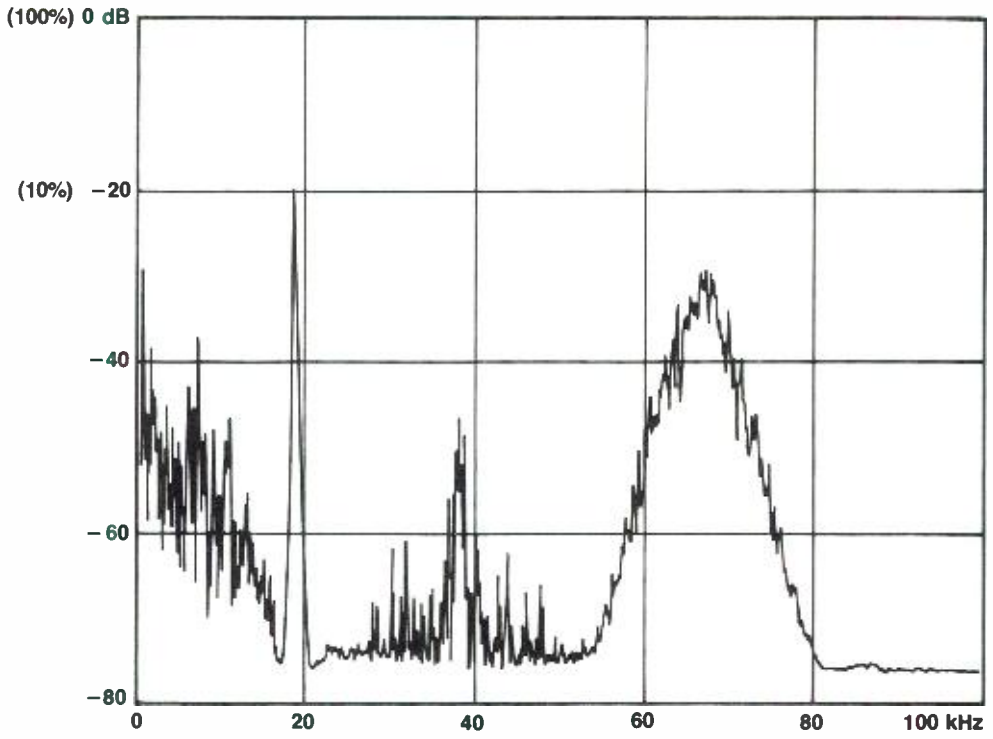


Fig. 14. Composite baseband of an FM station carrying a 4800 baud frequency-shift-keyed data subcarrier. Center frequency of the subcarrier is 67 kHz, with an injection of 9%. Station is carrying stereo programming.

Phase Shift Keying (PSK) is another technique for transmitting high-speed data. With PSK, one phase of the carrier represents one binary state and a second phase (usually 180 degrees apart) is used for the second state. To decode such modulation, a phase reference is required. Deriving a stable reference from the average phase of the incoming signal is quite difficult. But, since an external phase reference is permissible, the stereophonic pilot, if available, is well suited for this purpose. Pilot-tone-locked PSK systems hold considerable potential for high speed data transmission on SCA, with 56,000 bits/second practical. However, most of the 53 to 99 kHz bandwidth might be required and receiver/decoders would be much more expensive than those for moderate speed FSK systems.

Data Multiplexing

One of the problems for broadcasters is not the *speed* of data SCA subchannels, but data multiplexing. Multiplexing carries the same definition for data as it does in the analog domain: several channels of information share the same carrier. SCA subchannels operate independently of the main channel program because of Frequency Division Multiplexing (FDM). However, the use of this spectrum is not 100 percent efficient because *guard bands* are necessary between the channels: analog filters have less-than-ideal cutoff characteristics. In the data domain, on the other hand, a stream of bits may be divided with near-ideal precision by time division multiplexing (TDM) or statistical multiplexing (which can apportion time and data dynamically according to each channel's momentary need).

At this writing, no publicly-accessible data protocol has been adopted by the SCA broadcast industry. It is, therefore, difficult for broadcasters to establish services which can share independent users, even though the data speeds of the equipment available to them exceed the needs of most single users. This will tend to limit data services to users who can pay for an entire subchannel, even if their need does not require the channel's full capacity.

MONOPHONIC, STEREOPHONIC & SCA PERFORMANCE

While monophonic, stereophonic and various SCA services are conveyed by the same FM carrier, performance varies considerably due to the relative carrier deviation of each and the particular frequency span occupied within the composite baseband. The performance of a channel may be expressed in terms of demodulated signal-to-noise ratio for a given radio frequency carrier

level, or, conversely, coverage range for a given signal to noise ratio. The purpose of this section is to summarize and illustrate these relations but not present the lengthy derivations for the equations.

The performance of a conventional FM receiver in the presence of random (thermal) noise is commonly judged on the basis of the variation of the output signal to noise power ratio as a function of the carrier to noise power ratio contained within the receiver bandwidth, usually determined by the IF bandwidth. An estimate of the IF bandwidth required for transmission of (monophonic) broadcast FM is given by[10]

$$\beta_{IF} = 2(F_{dev} + 2f_m) = 210 \text{ kHz} \quad [1]$$

Where:

F_{dev} = the peak frequency deviation (75 kHz), and

f_m = the highest baseband modulating frequency (15 kHz).

This β_{IF} figure is rounded to 200 kHz for later use.

The equivalent input noise power in a bandwidth β launched into a noise-free (cool) receiver is

$$rB = 4 \times 10^{-21} \beta f_N = 8 \times 10^{-16} f_N \text{ Watt} \quad [2]$$

Where:

f_N = the receiver noise figure, and

β = nominal noise bandwidth in Hz.

The carrier power is

$$C = (V\mu v^2/R) \times 10^{-2} \text{ Watt} \quad [3]$$

Where:

$V\mu v$ = the rms input voltage in microvolts

R = the receiver r.f. input resistance.

For R = 75 ohms, the carrier to noise ratio in decibels is

$$CNR = 10\log_{10}(C/rB) = 12.2 + 20\log_{10}V\mu v - 10\log_{10}f_N \quad [4]$$

For example, for a 10 dB noise figure, the carrier to noise ratio is 0 dB for an input voltage of 0.77 V over 75 ohms (1.55 μv over 300 ohms).

For a half-wave dipole antenna matched to a 75 ohm receiver, the input voltage is related to the field strength as

$$V\mu v = 48.5\ E\mu v/f_{MHz} \quad [5]$$

Where:

$E\mu v$ = the field strength in μV

f_{MHz} = the carrier frequency in MHz.[11]

Thus, for 98 MHz (middle of the FM band)

$$V\mu v = E\mu v/2 \quad [6]$$

With the FCC F(50,50) field strength curves, it is possible to relate $E\mu v$ to the distance to the transmitter, effective radiated power, and antenna heights. Ultimately, it is possible to predict the carrier to noise ratio for a given broadcast system. For a 200 kHz nominal bandwidth the CNR in dB can be shown to be

$$CNR = Eo + P + G - F + 20\log_{10}(h/30 \times 98/f) + 6 \quad [7]$$

Where:

Eo = field strength for 1 kW ERP @ 1000′ HAAT, in dB$\mu V/m$

P = ERP in dBkW

G = receiver antenna gain relative to dipole, in dB

h = receiving antenna height above ground, in feet

F = receiver noise figure in dB

f = frequency in MHz.

For example, if $F=10$, $P=10$, $G=0$, $h=30$, and $f=98$, then the $CNR = Eo + 6$.

Next, the signal to noise ratio is established by the carrier to noise ratio

$$SNR = 40 + 10\log_{10}CNR \text{ dB} \quad [8]$$

This expression assumes a peak deviation of 75 kHz, a de-emphasis corner frequency of 2.1 kHz (75Sec) and a nominal intermediate frequency noise bandwidth of 200 kHz.[12]

From the above, a carrier to noise ratio of 0 dB would result in a signal to noise ratio of 40 dB. However, standard FM demodulators typically exhibit a "threshold" at about 12 dB CNR, below which the noise floor changes from a "hiss" to a raspy kind of noise with noticeable "clicks" jutting above the noise. For this reason, the monophonic channel actually deteriorates below a signal-to-noise ratio of about 52 dB.

A well-known effect of FM demodulation is that the noise voltage in a narrow band (for example, 1 Hz) increases directly with frequency. This has important implications for systems which employ subchannels since both their frequency span and the specific bottom and top frequencies are necessary in predicting relative signal-to-noise ratios. The stereophonic (L – R) subchannel, as shown in Fig. 2, extends nominally from

23 kHz to 53 kHz and occupies twice the bandwidth of the main (L + R) channel. When the subchannel noise is combined with the main channel noise during stereo decoding, the resulting noise floor is 23.1 dB higher than a monophonic system.[13]

The signal to noise ratio of an SCA subcarrier, relative to the main channel, is a function of a number of variables and is

$$Ns/No = (2fc^2/m^2D^2)\frac{f_1^3(b_1 - \arctan\ b_1)}{f_0^3(b_0 - \arctan\ b_0)} \quad [9]$$

Where:

F_{dev} = the peak frequency deviation (75)
fc = subcarrier frequency,
m = injection level as a percent of 75 kHz
D = deviation of FM subcarrier
f_0 = −3 dB freq. of de-emph. in main audio ch. (2.12 kHz)
f_1 = −3 dB freq. of de-emph. in SCA audio ch. (1.06 kHz)
b_0 = main channel audio output bandwidth (15 kHz)/f_0
b_1 = SCA channel audio output bandwidth (5 kHz)/f_1

An example of the excess noise in the 5 kHz SCA audio channel, compared to the 15 kHz main channel is given below, if $m = 0.1$ (10%). Note that the noise level of a 67 kHz subcarrier with 5 kHz deviation and a 92 kHz subcarrier with 7 kHz deviation are nearly equal. Comparative tests by the author have indicated that susceptibility to impulse noise, e.g., gasoline engine ignition radiation, is greater at the higher subcarrier frequency even though gaussian noise levels are approximately the same. This may be due to a higher noise threshold in the 92 kHz demodulator (due to a wider predetection bandwidth than the 67 kHz demodulator) or to differences in the spectral distribution of impulse noise compared to gaussian noise in the IF (composite) demodulator.[14]

fc (SCA freq., kHz)	67	92	92
D (deviation, kHz)	5	5	7
Ns/No (above main, dB)	36.4	39.2	36.2

Fig. 15 graphs the relative subcarrier noise level against increasing frequency of a subcarrier, compared to the main (monophonic) channel for the same receive conditions. Shown are two peak deviations (5 kHz and 7 kHz) for FM SCA, and SSBSCAM SCA with 10 percent peak envelope injection. The graph segment representing 7 kHz deviation is dashed below 70 kHz since excessive interference to the L − R subchannel is possible in this frequency range when stereo is transmitted.

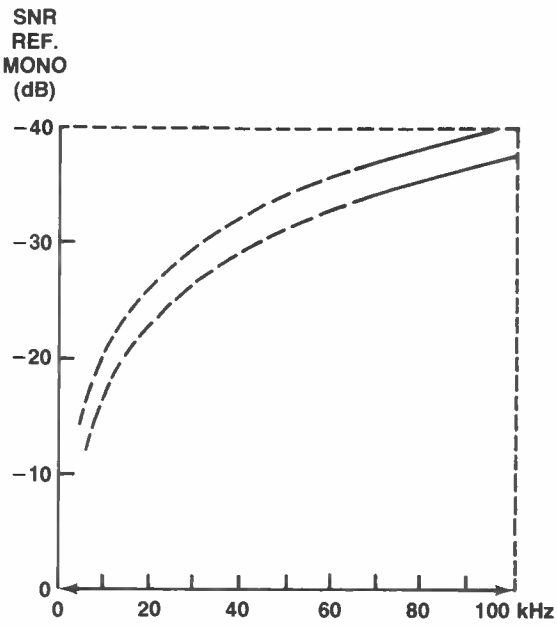


Fig. 15. SNR of FM/SCA audio (5 kHz bandwidth) versus subcarrier frequency, compared to monophonic reception, referred to 5 kHz and 7 kHz deviation.

Single Sideband AM Subcarriers

The conditions under which standard SCA subcarriers are operated are quite close to those existing with narrow band frequency modulation. For example, when a maximum audio bandwidth f_m of 5 kHz and peak deviation f_d of 5 kHz are used, the modulation index is one.

$$i = f_d/f_m = 5/5 = 1$$

After frequency demodulation, the signal-to-noise power ratio S/N will be[15]

$$S/N = \frac{3 \cdot i^2}{C/N} = \frac{3 \cdot 1}{C/N}$$

where C/N is the carrier to noise power ratio in the bandwidth occupied by the modulated signal. The noise power bandwidth β_i is difficult to predict for two reasons. First, the (usually) inexpensive SCA pre-detection filter has sloping skirt selectivity, thus departing from the ideal rectangular shape assumed in the calculation. Second, the actual bandwidth may vary, depending on the amount of audio distortion to be tolerated. The extremes of choice may be

for $\beta_i \leqslant 1$, $B_n = 2f_m = 10$ kHz
for $\beta_i \gg 1$, $B_n = 2(f_d + f_m) = 20$ kHz

A noise power bandwidth of 15 kHz is a compromise value that happens to represent the measured performance in some common FM SCA receivers.

In single sideband systems, one is simply frequency shifting the modulation passband to the baseband, so that the recovered signal-to-noise ratio is

$$S/N = C/N$$

where the noise power bandwidth is equivalent to the audio bandwidth (assumed to be 5 kHz).

From the above, it can be seen that while the FM system improves S/N, there is also three times the noise power. Thus, the 3 in the numerator is cancelled by a C/N in the denominator which is three times larger. At a modulation index of one, the FM improvement is approximately 10log (1) or 0 dB for an ideal detector. The use of preemphasis and de-emphasis improves the FM system S/N without significantly changing the subcarrier's occupied bandwidth. The choice of 150 microseconds adds an estimated 8.8 dB improvement in rms signal-to-noise ratio, but the author has measured typical improvements of approximately 4 dB in production samples.[16]

Since single sideband modulation is spectrally efficient, even when compared to narrow band FM, it is practical to divide the 53-99 kHz range into a number of independent subchannels. In the one system, five subchannels each having a 5 kHz baseband are operated at 57, 66.5, 76, 85.5 and 95 kHz. These are shown in Fig. 11.

Twenty percent peak injection is the maximum permitted by the FCC Rules when stereo is transmitted, therefore, each subchannel would receive four percent injection (20/5 = 4). It is reasonable to assume that slightly higher injection could be permitted for each subchannel due to the random interleaving of the total subchannel injection. If five percent were employed, then, the S/N would be lower than that for a channel using ten percent peak injection.

$$\text{change in } S/N = 20\log (10/5) = -6 \text{ dB}$$

Assuming an approximated improvement of 4 dB for a standard FM subchannel, and a reduction of 6 dB for one of five single sideband subchannels, there is an estimated difference in S/N, assuming the same center frequency of both subchannels and flat noise density over this spectrum.

$$S/N_{FM} - S/N_{SSD} = 4 - (-6) \cong 10 \text{ dB}$$

The power density from AM demodulators remains uniform across the baseband (unlike FM demodulators, in which noise density rises in proportion to frequency), therefore, preemphasis/de-emphasis is not important. The use of a complementary noise reduction system (compandor) can significantly improve the signal-to-noise ratio of either system.

Using the above estimates, the performance of the (uncompandored) single sideband and (de-emphasized) FM subchannels is compared to main channel and stereo in Fig. 16. The coverage radii are based on the FCC F(50,50) field strength predictions for an FM station having 10 kW ERP, 1000 feet height above average terrain, and a dipole receiving antenna at 30 feet above ground level into receiver having a 10 dB noise figure.

SCA-to-Stereo Interference Considerations

Introduction of new signals into the modulating baseband of an FM station requires attention to its possible interactions with existing baseband signals, as well as its chosen performance characteristics. Several recent findings regarding the potential for perceptible interference (crosstalk) are summarized here.

FM stereo receivers having stereo decoders with diode switching bridges driven by a high-level 38 kHz sinusoid (usually identified by discrete component construction and tuned transformer stages) were responsible for the original "birdie" or beat-note interference in early SCA/Stereo broadcast systems. For historical perspective, the sources of this interference were

- nonlinearity in the diode bridge due to the conduction characteristics of the diodes and the sinusoidal drive signal;
- imbalance in the center-tapped transformer driving the diode bridge and second harmonics of the 38 kHz sinusoid at this point.

The result caused a second-order intermodulation (mixing) of twice the 38 kHz switching frequency minus the instantaneous frequency of the SCA subcarrier as

$$9 \text{ kHz} = 76 \text{ kHz} [38 \text{ kHz} \times 2] - 67 \text{ kHz}$$

The product is not 10 kHz as was often believed. Today, the small amount of beat note interference that results from a 67 kHz subcarrier is 10 kHz, but due to an entirely different mechanism.

Over the past decade these receivers have been entirely replaced by sets with integrated circuit decoders, which have virtually no internally-generated beat-note problem. As a result, the interference to stereo service from SCA operation has dropped significantly.

Contemporary receivers create very little beat-note interference from SCA operation because of the type of stereo decoding done within the integrated circuit. The fact that the circuit contains

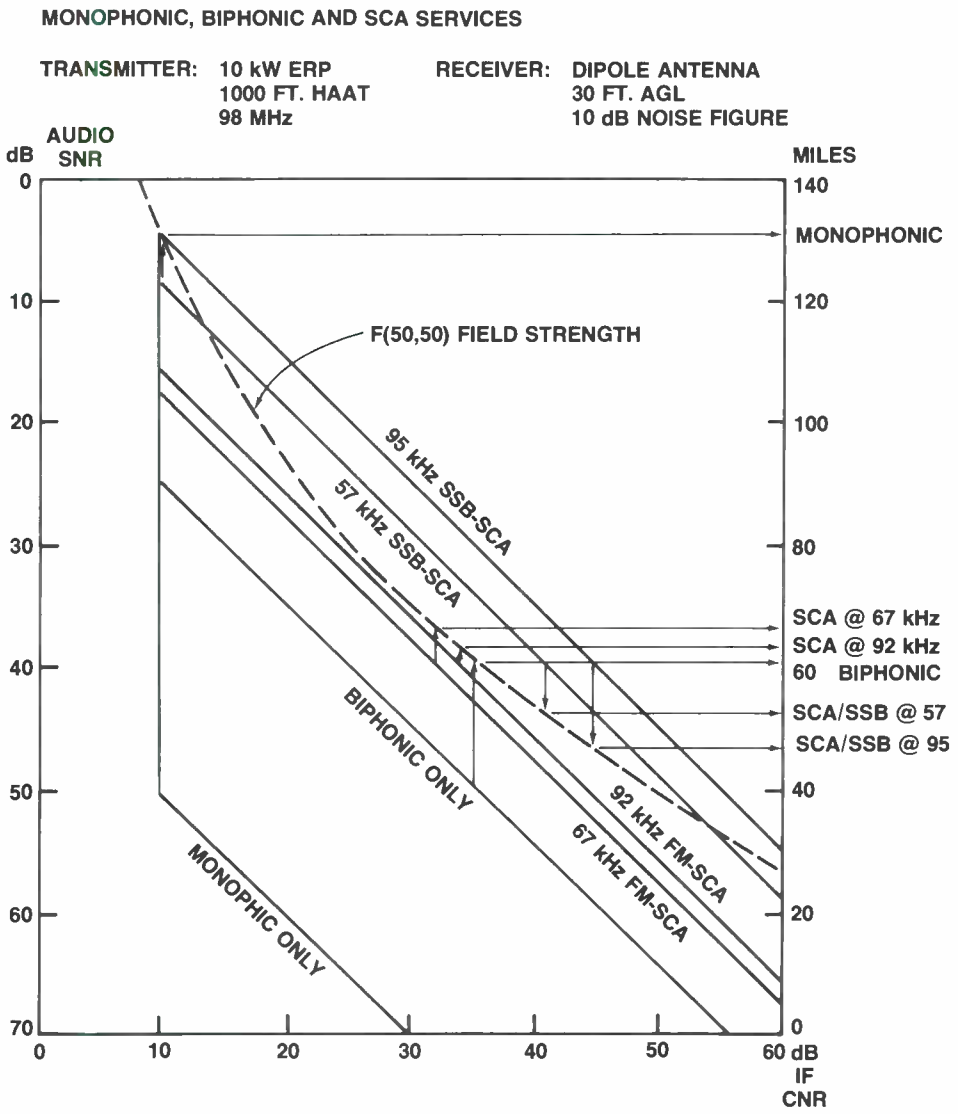


Fig. 16. Predicted service distances for 50 dB monophonic and biphonic SNR, and 40 dB SCA SNR. To use, find intersection of desired SNR with service (diagonal) line; next move up (or down) to F(50,50) dashed line; then read across to mileage scale.

a phase-locked loop (PLL) has little to do with this improvement. Modern decoders derive their 38 kHz signal by a digital technique, which is well-suited to circuit integration. This results in a 38 kHz square wave of fast rise time and balanced duty cycle (equal time in high and low states). The output circuit is usually a differential transistor pair configured as a balanced demodulator. When driven by the 38 kHz square wave (which has virtually no even-order harmonics), *very* little mixing is possible which can result in the product shown in the above equation.

If SCA beat-notes created within stereo receivers was the only source of interference, there would be virtually no problem with SCA operation. However, experience shows that a minor source of interference remains when certain SCA frequencies are used. The source of this interference is *external* to the receiver: multipath distortion of the radio frequency signal itself.

Large obstructions such as mountains, hills, and tall buildings can reflect VHF broadcast waves well enough to create the simultaneous reception of a direct and one or more reflected-path signals. Upon demodulation the baseband signals will include a combination of linear, second and third order distortion products, as shown in Fig. 16. Higher order distortions are negligible when the distortion is small.[17] Hence, these products take the form

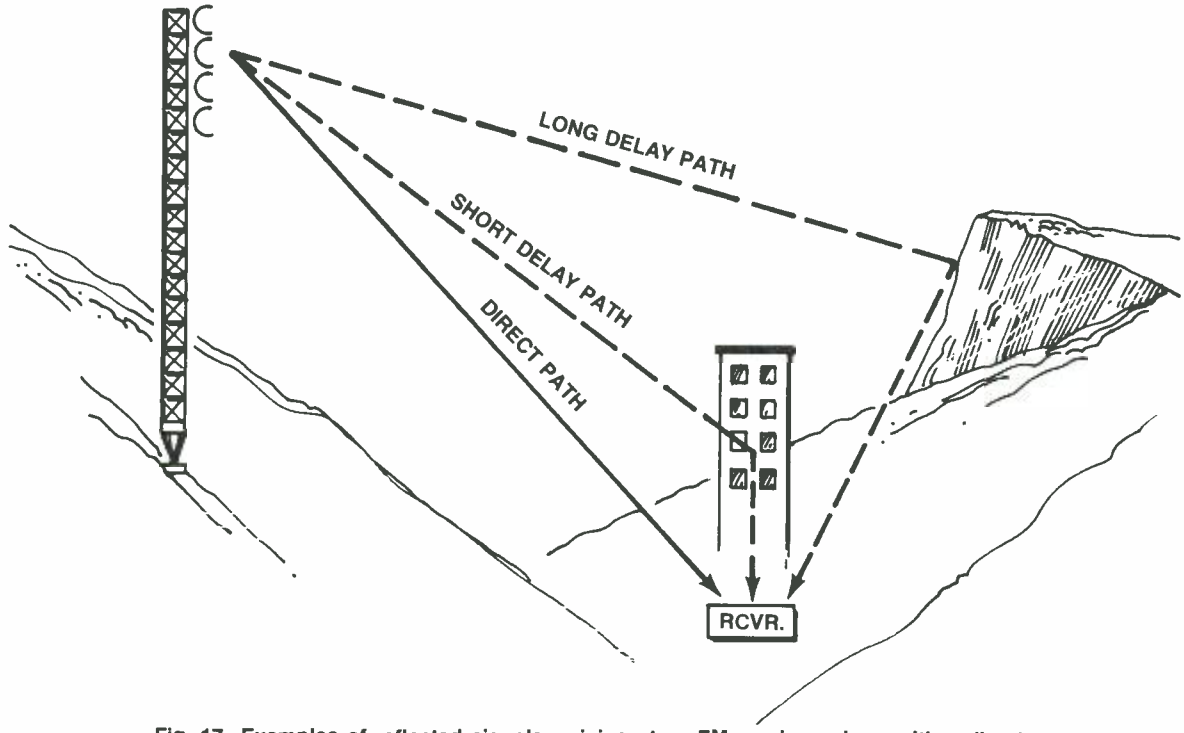


Fig. 17. Examples of reflected signals arriving at an FM receiver, along with a direct path RF signal. Distortion of the demodulated FM signal is related to both the direct/reflected signal ratio and delay time of the reflected signal; distortion increases as the signal ratio approaches 1:1 and as the secondary path delay time rises.

$2A$, $2B$, $2C$, etc. (where A, B, and C are the fundamentals)

$A+B$, $A-B$, $A+C$, $A-C$, $B+C$, $B-C$, ...*etc.*

$2A+B$, $2A-B$, $2B+A$, $2B-A$, ...*etc.*

Second order distortion (frequency sum and difference) is the most troublesome, because new product frequencies are created which may fall within the main and stereophonic channels where they can become audible. This is illustrated in Fig. 17, which shows the baseband of an actual FM station. The only modulation present in the transmitter is the stereo pilot and unmodulated SCA subcarriers at 67 kHz and 92 kHz, plus a small amount of noise from the audio chain which can be seen from zero to 15 kHz and centered around 38 kHz in the L – R subchannel.

Several second order products are visible in the spectrum graph. This distortion takes the form:

$$f_{SCA1} \pm f_{SCA2} = f_{IM\ product}, \text{ or}$$
$$f_{SCA} \pm \text{pilot} = f_{IM\ product}$$

In the case of 67 and 92 kHz subcarriers, significant products are

(*J*)	92 – 67	=	25 kHz
(*K*)	67 – 19	=	48 kHz
(*L*)	92 – 19	=	73 kHz
(*M*)	67 + 19	=	86 kHz

While these IM products are not directly audible, some may be once they are demodulated by a stereo decoder:

25 – 38	=	13 kHz
38 – 48	=	10 kHz
111 – 114	=	3 kHz

(The last product could be demodulated by IC stereo decoders using a 38 kHz square wave switching signal. However, a 111 kHz product of significant amplitude is quite rare.)

Some other general findings about multipath effects are[18]

- Multipath distortion is almost inversely proportional to the DU (desired-to-undesired path signal ratio) if the ratio is greater than about 10 dB.
- Baseband signal distortion increases almost proportionally to the delay time up to about 10 μS, then increases with delay time at a slower rate.

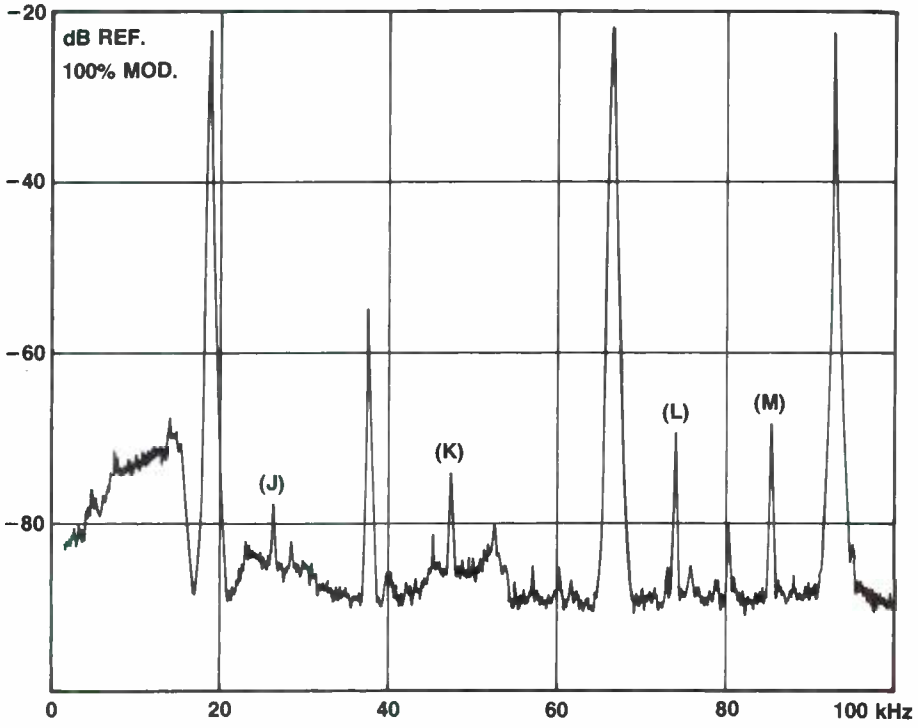


Fig. 18. Composite baseband of an FM transmitter system with pilot, 67 kHz, and 92 kHz SCAs at 9 percent injection. IM products are identified by letters and are described in the text.

- A high DU ratio required to suppress the beat-note interference to stereo program reception from an SCA subcarrier (about 20 dB at a delay time of around 5 μS and about 30 dB at around 20 μS).

It should be emphasized that the perceptibility this form of beat-note interference depends on the loudness and consistency of main channel programming, i.e., program audio in most broadcast FM stations is capable of masking the beat-note. Generally, only stations which do light amounts of audio processing and broadcast programming with wide dynamic range are even aware of an occasional case of interference.

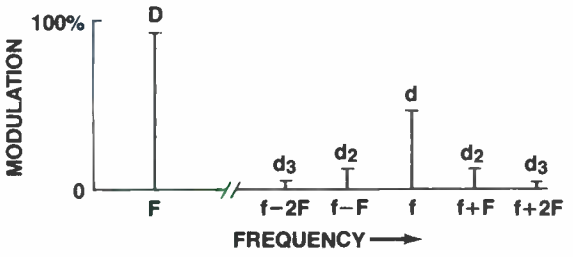


Fig. 19. Spectrum of a subcarrier "f" shown with second and third order distortion products resulting from low frequency modulation "F".

The *type* of SCA modulation or the subcarrier frequency may significantly affect the perceptibility of any beat-note. For example, properly-encoded high-speed data subcarriers using FSK or PSK spread the carrier energy in such a way that it sounds like faint, band-limited noise which is most easily masked. Furthermore, higher subcarrier frequencies will shift the beat-note image out of the audible range: experience has shown that 92 to 95 kHz subcarriers have little problem in this regard.

Crosstalk From Main Channel Program Into SCA Subchannels

Crosstalk remains a knotty problem for audio SCA services, despite the development of low-distortion receivers for SCA use. The cause is the same as SCA-to-stereo beat-notes: multipath distortion.

In the reference case illustrated in Fig. 19, the baseband signal consists of one low frequency sinewave of frequency F, e.g. 1kHz, which modulates the main carrier by a deviation D (95 percent or 71.25 kHz for broadcast FM), and a sinewave subcarrier at a variable frequency f Hz which modulates the main carrier with a very small deviation d, having a modulation index less than 0.3.

Second order distortion will cause sidebands at frequencies of $f-F$ and $f+F$ with an output injection $d_2(f-F)$ and $d_2(f+F)$. The sum of the sideband amplitudes is

$$d_2(f) = d_2(f-F) + d_2(f+F)$$

The distortion is defined as the ratio of the sum of the sidebands to the amplitude of the subcarrier d_1 is

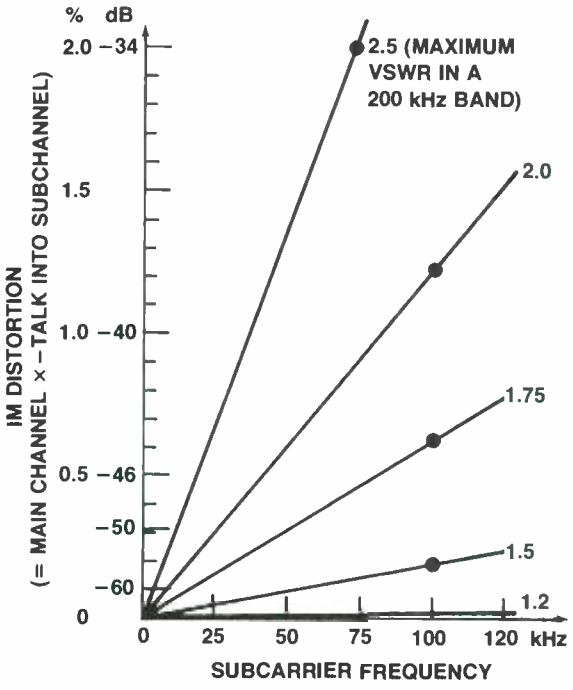
$$\delta_2(f) = d_2(f)/d_1(f)$$

This distortion is easily measured as a function of the subcarrier frequency f with a spectrum analyzer. If the sidebands are equal, they may in the extreme either amplitude modulate or phase modulate the subcarrier. In general, there is a combination of amplitude and phase modulation.

Third order distortion is similarly defined by the sidebands created at frequencies $f-2F$ and $f+2F$.

While FM SCA detectors usually include amplitude limiting, they are intended to convert any angular modulation, whether program audio or not, into an output signal. Thus, any phase non-linearity in the RF system or multipath will generate second and higher order sidebands around the subcarrier, causing main-to-SCA crosstalk at audio modulating frequencies.

Fig. 20 shows the relationship between main-to-SCA crosstalk, subcarrier frequency, and maximum antenna VSWR in a 200 kHz band. It is evident that higher frequency subcarriers require somewhat larger, but not very much larger bandwidth. It has also been determined that antenna matching must be improved as the transmission line becomes longer. This is especially important for higher frequency subcarriers since the phase error is compounded rapidly with an increase in subcarrier frequency. Distortion is proportional to the subcarrier frequency. Thus, for equal distortion, doubling the subcarrier frequency requires halving the reflection coefficient.[19]



NOTE: ANTENNA IS MATCHED TO TRANSMISSION LINE AT THE CENTER FREQUENCY.

Fig. 20. Distortion due to limited antenna bandwidth vs frequency of subcarrier with max VSWR in 200 kHz band as parameter.

FOOTNOTES AND REFERENCES

1. Edwin H. Armstrong, "A Method Of Reducing Disturbances In Radio Signalling By a System of Frequency Modulation", Proceedings of the I.R.E., May 1936, Vol. 24, No. 5, pp. 689-740.
2. Electronic Industries Association, "Report of the National Quadraphonic Radio Committee to the Federal Communications Commission", Vol. II, Chapter 1, pp. 21-29.
3. Federal Communications Commission, "Rules and Regulations", Vol. III, Part 73.310.
4. NAB/Group W/NPR (National Association of Broadcasters, Westinghouse Broadcasting and Cable, Inc., National Public Radio), "Increased FM Deviation, Additional Subcarriers and FM Broadcasting: A Technical Report," August 30, 1983, pp. 5-6.
5. Federal Communications Commission BC Docket Number 82-536, First Report and Order (April 7, 1983), Second Report and Order (March 29, 1984).
6. John Kean, "Laboratory & Field Tests of Several FM/SCA Frequencies", National Public Radio Engineering Report, October 15, 1981, pp. 13-14.
7. Technical Manual for Moseley SCG-8 SCA generator.
8. Eric Small and Eric Stoll, "Data SCA: Some Real World Experiences", Modulation Sciences, Inc., pamphlet, August, 1984.
9. Harry Anderson and Ronald Crane, "A Technique For Digital Information Broadcasting Using SCA Channels", IEEE Transactions on Broadcasting, Vol. BC-27, No. 4, pp. 65-70.

10. *Reference Data for Radio Engineers, 6th Edition.* Indianapolis: Howard W. Sams, Inc., 1975. pp. 23-9 - 23-12.

11. Report of the National Quadraphonic Radio Committee to the Federal Communications Commission, Volume II-I, Chapter I, pp. 31-40.

12. Ibid., Supplement to Volume II, Chapter 1, Section 1.4, p. xviii.

13. Ibid., pg. 36.

14. Ibid., John Kean, pg. 24.

15. *Reference Data for Radio Engineers, 6th Edition.* Indianapolis: Howard W. Sams, Inc., 1975. pp. 23-4 - 23-12.

16. Ibid., John Kean, pg. 24.

17. Ibid., NQRC Report, Section by James Gibson, RCA, Chapter III, pg. 3/7.

18. Mitsuo Ohara, Distortion and Crosstalk Caused by Multipath Propogation in Frequency-Modulation Sound Broadcasting, IEEE Transactions on Broadcasting, Vol. BC-26, No. 3, Sept. 1980, pp. 76-81.

19. Ibid., NQRC & J. Gibson, pg. 3/11.

3.5

Television Transmitters

W.A. Resch
W.A. Resch & Associates
Quincy Illinois
C.E. Daugherty
M.R. Griesbaum
D.W. Myers
A.A. Spielbauer
Broadcast Division
Harris Corporation
Quincy, Illinois

INTRODUCTION

Many improvements have been made in TV transmitters in the last decade (1974 to 1984). These improvements, along with a tutorial description of the principal subsystems, will be highlighted in this chapter. Transmitter improvements have generally been market driven as opposed to being mandated by the Federal Communication Commission. Competition among broadcasters seeking a technical edge and among manufacturers to deliver a better transmitter at a lower cost directs the industry forward.

The advances can be divided into four broad technologies, UHF, VHF, measurements, and multichannel sound. UHF technology affects transmitters on channels 14 to 69, 470–806 MHz. In this frequency range the most important advance is the improvement in electrical plant efficiency. To the broadcaster, efficiency improvements means saving millions of dollars in energy costs each year. VHF covers channels 2 to 13, 54–216 MHz. Two areas of progress are the universal acceptance of IF modulation and the elimination of tubes in low-level stages and bias supplies. As a result transmitters are more reliable, require less routine maintenance, and deliver consistently better sound and pictures. Another VHF development is the adoption of circular polarized antennas with maximum radiated power in both the horizontal and vertical planes. To satisfy the need for double the RF power, that is equal power in both planes, higher power tubes and transmitters were developed.

The efforts to select a multichannel sound system was led by the Electronic Industry Association. The result is a compatible system with enhanced service and performance. Sophisticated signal measuring instruments have aided manufacturers and broadcasters in achieving nearly a twofold improvement in performance characteristics over the last decade.

VISUAL EXCITER

The visual exciter contains the necessary processing circuits to accept the studio video output and convert it to a fully modulated NTSC visual television signal. The functions of the visual exciter include IF and RF signal generation, sideband filtering, group delay equalization, linearity precorrection, and modulation control. These functions are grouped into circuits which are represented by the block diagram shown in Fig. 1. As a minimum, the TV exciter accepts a standard NTSC video signal, converts it to RF, and corrects for processing and power amplifier distortions. In other words, the exciter contains the necessary circuits for the transmitter to be transparent in the TV transmission system.

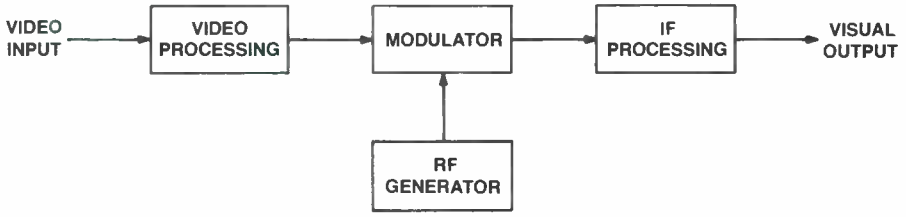


Fig. 1. Simplified visual exciter block diagram.

Basic Primer

The fundamentals of video and the associated waveforms are a foundation for understanding the purpose and operation of the overall transmission system.

Nowhere else is this more important than in understanding the operation of the visual exciter. Before introducing video processing, this section provides familiarization with units of measure, nomenclature, and signals.

The Picture

A picture is developed using a raster scanning technique and modulating the Z axis for the necessary gray shades. Each picture is defined as a frame that is created by interlacing two fields. Interlacing of two fields, each containing 262.5 horizontal lines, effectively doubles the frequency of field occurrence to 60 fields/second and eliminates visible flicker (Fig. 2).

Measurement Units

The television, or composite video waveform, consists of horizontal sync, vertical sync, video information, and test signals. This waveform and its various components are specified by the Institute of Electrical and Electronic Engineers and are defined in IRE units ranging from −40 to +100. One hundred IRE units equates to 0.714 volts peak-to-peak with +100 and +7.5 corresponding to white and black video levels respectively. Timing measurements are usually in the microsecond range.

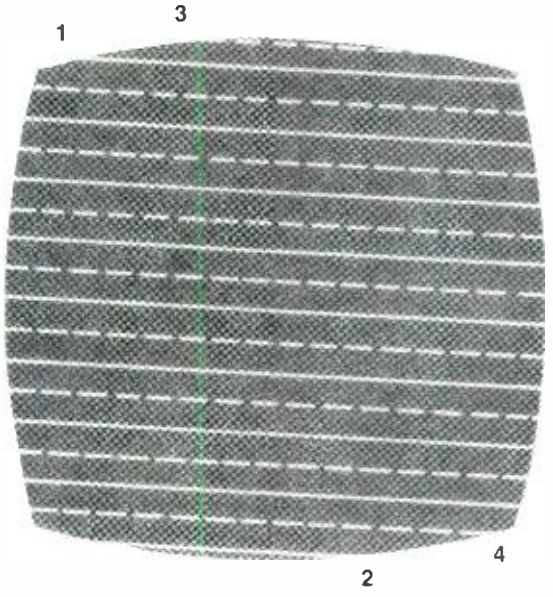


Fig. 2. One complete frame interlaced with field (1 to 2) and field 2 (3 to 4). The scanning sequence is horizontally left to right, and vertically top to bottom.

Frames and Fields

In the NTSC system, one frame of information creates a complete picture. Each frame contains two interlaced fields with a total of 525 lines. Each field contains 262.5 lines, 21 of which are blanked (The Vertical Interval) for beam repositioning to the top of the screen (Fig. 3).

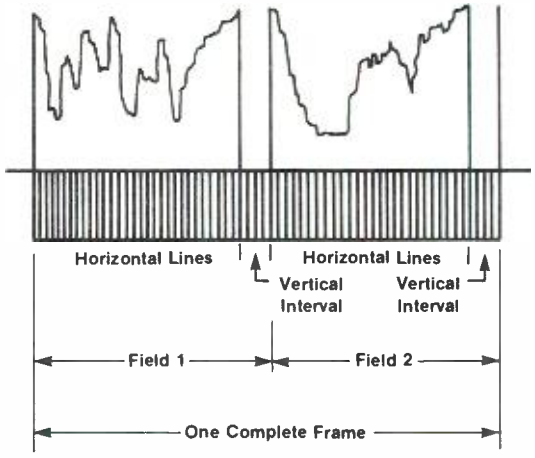


Fig. 3. The basic combination of fields and vertical intervals.

Horizontal Interval

The horizontal portion of the composite video waveform consists of horizontal lines, each containing video information, and sync pulses which provide blanking, retrace time, and other information. A detailed picture of horizontal line sync pulses, various IRE levels, and timing information are valuable in the video world (Fig. 4). Descriptions of various events within the horizontal line provide insight into the many purposes of the waveform.

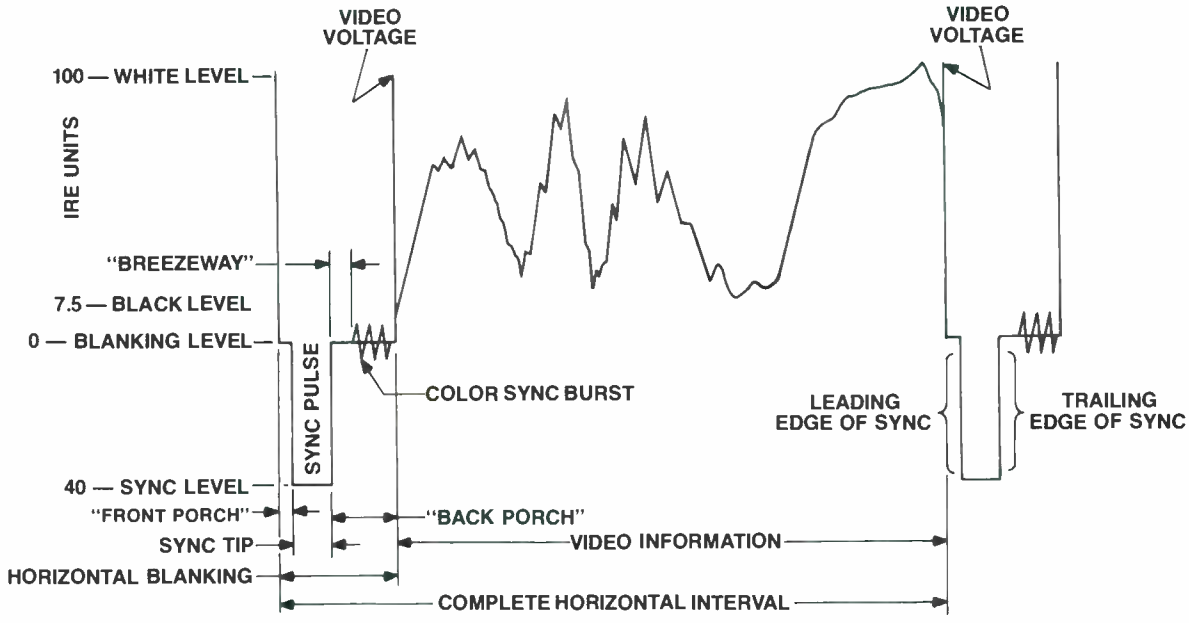


Fig. 4. Horizontal line.

The "front porch" prevents video voltages from prematurely triggering the sync circuits by isolating transients from the sync pulse. The horizontal sweep oscillator is reset by the leading edge of the sync pulse, while the tip of the pulse is a reference point for dc restoring in receiving sets. The "back porch" provides time for the blanked beam to return to the left side of the screen. During color transmission, a 3.58 MHz sine wave color sync burst is added to the "back porch" to frequency and phase lock the picture color information. Video information is contained between the end of the "back porch" and the beginning of the next "front porch" and is transmitted by modulating the carrier signal from black to white levels.

Vertical Interval

Prior to sweeping each field, the beam must be repositioned vertically. The repositioning time, called the vertical blanking interval, is composed of 21 horizontal lines which are not displayed. This portion of the composite video waveform is extremely important since it contains critical pulses, test signals, source identification codes, reference signals, captioning and teletext (Fig. 5).

The first six pulses, known as equalizing pulses, synchronize video information in fields 1 and 2. These pulses occur at twice the horizontal sync rate (period = 63.5 μS, 15.75 kHz) and assure that vertical triggering occurs at the same time for odd and even fields.

The serrated vertical (sync) pulses follow next. The second set of six equalizing pulses ensure field frequency regularity. The remainder of the 21 blanked horizontal lines contain various test and information signals, including teletext and captioning.

The tradition of using test signals during the vertical interval began with FCC Rules and Regu-

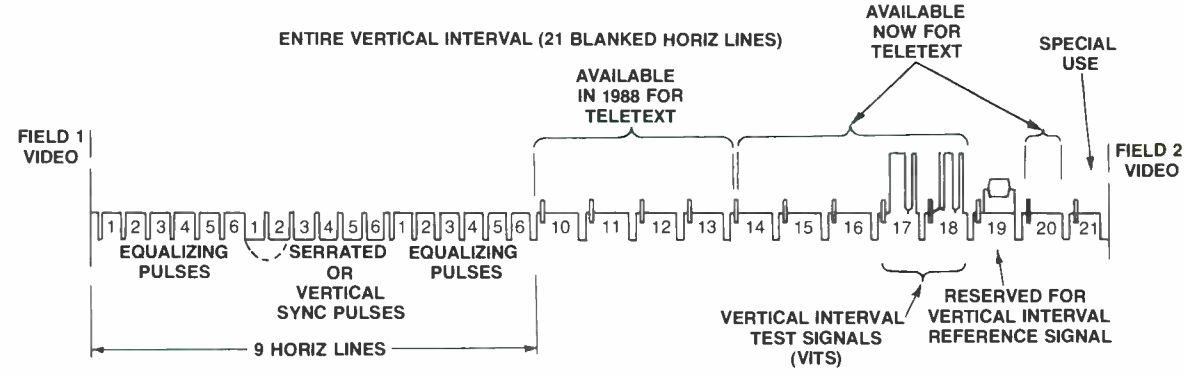


Fig. 5. Entire vertical interval (21 blanked horiz lines).

lations. Recently these test signal requirements have been relaxed. The test signals themselves continue to be in wide spread use.

Vertical Interval Test Signals (VITS)

Vertical Interval Test Signals (VITS) are used to evaluate various parameters of a broadcast system performance and are monitored daily. The VITS are transmitted during active operation to ensure continuous quality and accuracy in terms of color and distortion. In regard to transmitter performance, the quality of the VITS frequently determines if a problem warrants a trip to the transmitter site.

The type of test signal, as well as specific line location, is determined by individual networks, stations, and the FCC. Generally lines 17 and 18 are used for VITS: multiburst on field 1, line 17 Fig. 6; color bars on field 2, line 17 Fig. 7; composite radiated signal on fields 1 and 2, line 18 Fig. 7. In cases where the network determines the type and location of the VITS, several alternatives are available. These signals may be on line 17 or 18, field 1 or 2. Some frequently used VITS are highlighted with measurement applications emphasized in the following paragraphs.

The multiburst (Fig. 6), a VITS aimed directly at frequency-gain characteristics, also monitors setups and frequency selective compression. This

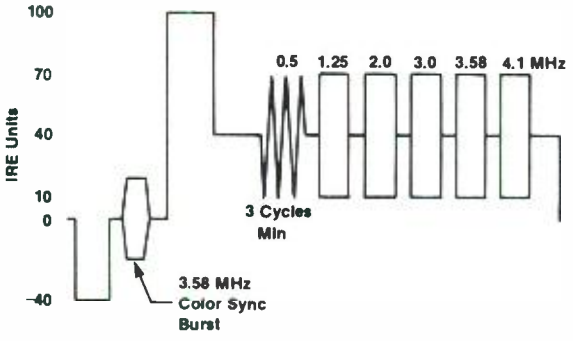


Fig. 6. Multiburst.

test pattern usually consists of a white bar (100 IRE) followed by six bursts of sine wave frequencies ranging from 0.5 MHz to 4.1 MHz. The six bursts must have equal amplitude for the correct response.

The Composite Radiated Signal (Fig. 7) contains several distinct signals, each having its own diagnostic capability. Differential gain and phase are evaluated through the modulated stairstep. This signal is composed of six equal amplitude steps, ranging from −20 to 100 IRE levels, each step is modulated with a 3.58 MHz sine wave burst on its dc level. Variation in sine wave amplitude is a measure of differential gain. The 2T

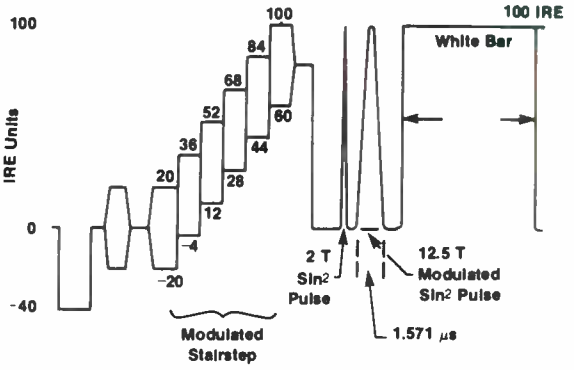


Fig. 7. Composite radiated signal.

sine-squared pulse is especially useful for determining frequency response and group envelope delay. The relative amplitude of the 2T pulse in relation to the white bar indicates frequency response while the symmetry of the 2T pulse indicates delay. The 12.5T modulated sine-squared pulse provides an indication of amplitude frequency response errors where the 2T pulse is less sensitive, namely from 3 to 4 MHz which are the chrominance frequencies. The detection of chrominance/luminance gain and delay, which cause color saturation and distortion problems, is easily accomplished with this pulse.

The color bar test signal (Fig. 8) is one of the most widely used test waveforms in color television broadcasting. The waveform consists of the three primary colors (red, green, blue), their complements (cyan, magenta, yellow), and a white reference bar. The color bars are arranged in order of luminance, with the brightest colors on the left and the darkest on the right. This signal provides a quick method of assessing color transmission quality. The confirmation of performance, either satisfactory or unacceptable, is the oscilloscope's main objective. Beyond a status indication a vectorscope must be used to evaluate the encoding and processing of color signals.

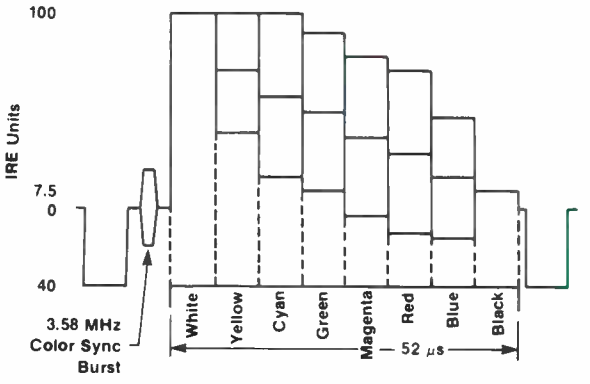


Fig. 8. Color bar test signal.

NTSC Color Transmission System

Two items were considered in adopting the NTSC system: 1) the pattern resolving power of the eye for patterns having only color contrast is considerably less than when there is also luminance contrast, and 2) the smaller an object is, the more difficult it is to determine its hue. This means that for the finer picture details, loss of chrominance resolution will not necessarily be noticed. The coding of chrominance signals also takes advantage of variations in the resolving power of the eye for colorimetric variations.

Initially, the light reflected from the scene being televised is optically separated by color selective filters. Three distinct colors (red, blue, and green) result, each activating a color pickup tube in the camera and converting the light into their respective signals. In an effort to transmit the minimum amount of information needed to reconstruct the actual scene, the colors are combined to give precise information about the brightness, saturation, and hue.

A portion of each color signal is matrixed to generate a luminance signal, which completely describes the brightness of the scene. A complete description of the scene requires precise information about each color, and three linear combinations of the color would satisfy all of the receiver requirements. Since one linear combination is transmitted with the luminance signal, the two remaining sets of information are transmitted with color difference signals. These signals, I and Q, are composed of linear combinations of each color and completely describe the scene. The two color difference signals each amplitude modulates a subcarrier of identical frequency but different phase, which are added to produce the chrominance signal. The resultant is an amplitude and phase modulated wave. In the simplified color diagram (Fig. 9), phase represents the characteristic angle (hue) on the vector diagram, and amplitude determines the degree of saturation.

At the receiver, a method of synchronous detection is used to separate the color signals which are applied to the control grids in a tricolor viewing tube. This is only possible if the phase oscillators are stable. A 3.58 MHz reference burst at the beginning of each line reestablishes the correct phase relationship. This method of color transmission links the chrominance directly to the phase modulation of the subcarrier.

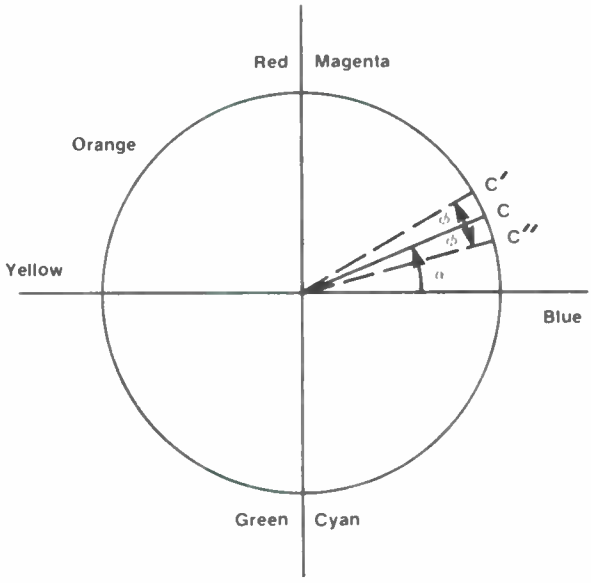


Fig. 9. Simplified color diagram.

Video Processing

The division between studio video signal processing and the transmitter video processing can be difficult to separate. Often times video automatic gain control, sync and burst regeneration, white limiting, cable length compensation, dc restoration and ac hum canceling circuits are required for a plant to operate satisfactorily. These problems usually arise from the distribution of the video signal rather than in the studio production or transmission processing. Traditionally video processing amplifiers, called proc amps, are used to clean up distribution distortions.

The video processing circuits commonly included in a transmitter are dc clamp, differential gain, and differential phase precorrectors. These circuits condition the signal prior to modulation.

Clamp Circuit

The clamp circuit or dc restoration circuit reestablishes the proper dc video signal level. This function is important because picture brightness information is contained in the dc video level. Since dc information can not be transmitted by a single sideband signal the TV signal is AM modulated about carrier.

In order to maintain accurate video amplitude information, the video signal is clamped to a static portion of the horizontal waveform. Clamping the video to a fixed reference voltage represented by the static portion of the waveform allows further amplitude dependent processing to be done prior to modulation.

Hum distortion can be observed in the picture when alternate light and dark bars on the picture appear to move slowly up the picture. The bars are caused by the sinusoidal effect of increasing and decreasing brightness at a low-frequency rate. The slow movement is caused by the vertical frame-rate being slightly slower than the line frequency. The number of bars indicate the frequency of distortion. One dark bar indicates 60 Hz distortion while two dark bars indicate 120

Hz distortion, etc. Care should be taken in attributing a picture distortion to one part of the transmitter. Hum bars, for instance, can also be caused by power supply filter failure or even produced in the monitor itself.

Fig. 10 is representation of a video signal with hum superimposed. This hum can be conducted interference induced by differences in ac grounding potentials between video distribution equipment. It could also be caused by inductive pick up of radiating ac magnetic fields emanating from an ac transformer or power supply choke.

The horizontal sync is used to trigger an electronic switch which inserts a dc reference potential to a portion of the static waveform either during sync or burst. Fig. 11 shows the same signal after being clamped. The horizontal line period is many times faster than the hum period so by forcing the video to a reference voltage during a static portion of the video, the line-to-line change is practically not discernible. By clamping in the transmitter, ac coupling of the video signal can be allowed in the signal distribution system. AC coupling is convenient since differences in ac and dc ground potentials can be ignored without causing picture distortions.

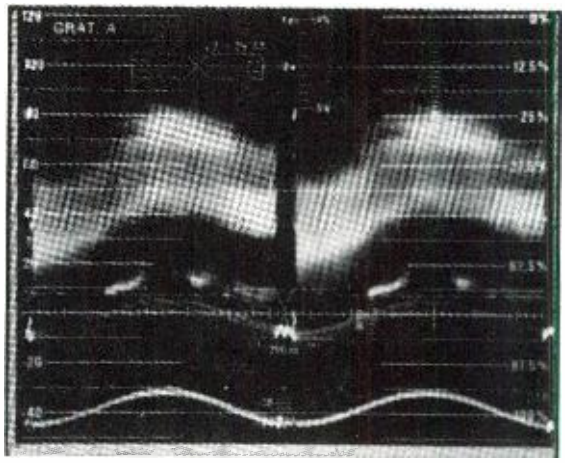
Video Precorrection

Errors in chrominance amplitude and phase amplifications that are level dependent are often corrected at video. A picture affected by nonlinear chroma gain shows a change in the saturation of the colors. A piecewise linear gain curve is normally fitted by using diodes which are adjusted to conduct at preset amplitude levels. Gain can be controlled to either increase or decrease as needed. This type of corrector is called differential gain.

Differential gain correctors are usually broadband in that gain errors are corrected equally with respect to frequency. These correctors assume that luminance and chrominance nonlinearities are equal.

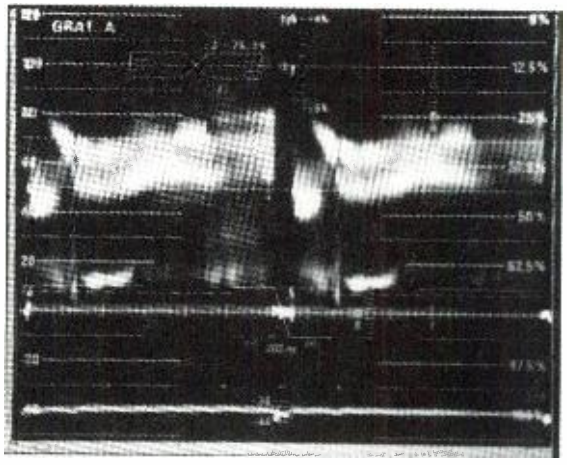
Luminance nonlinearity is the change in picture brightness. A gain corrector affecting only low-frequency luminance can be implemented by first separating the signal into frequency bands and then recombining after amplitude precorrection.

Chrominance phase nonlinearity, called differential phase, is the change in chrominance phase as the corresponding portion of the luminance signal amplitude is changed. The effect on the picture is a change in hue of colors. The signal is split into two paths. One path has a 90° phase shift at 3.58 MHz chroma subcarrier frequency. The other path contains the diode gain breaks. Recombining the inphase and quadrature signal allows phase variations of ±10° independently of gain errors.



1. Observe the signal with the waveform monitor DC RESTORER OFF and in SLOW clamp mode. Mains hum, if present, will be evident in a 2 field display.

Fig. 10. AC Hum, field display.



2. The FAST DC RESTORER of the waveform monitor eliminates hum on the display.

Fig. 11. Signal after clamping.

Modulator

FCC type accepted transmitters using IF modulation first became available in the early 1970s. Now it is a universal practice. The reason for its popularity is the ease at which precise IF signal processing can be implemented and the convenience of field adjustment. The modulator is usually a broadband, balanced diode mixer. It is configured for maximum rejection of the oscillator signal and biased so as to provide linear, low noise and low modulation capability. A schematic diagram of a typical balanced mixer is shown in Fig. 12. The video signal is offset to provide the proper modulation level. The video signal is used to control the attenuation of the

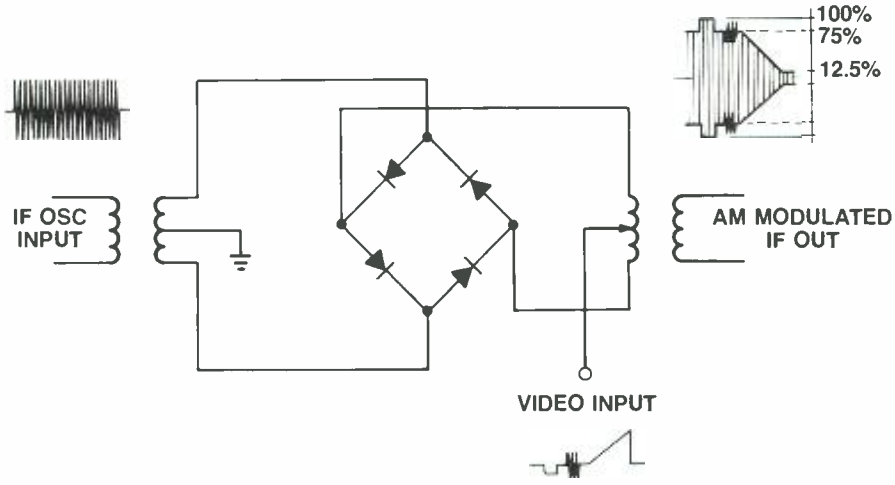


Fig. 12. Balanced mixer.

diodes. Peak of sync corresponds to maximum IF envelope output and white corresponds to minimum IF output.

The output of the modulator is a double sideband AM signal having the proper depth of modulation.

IF and Video Delay Compensators

Picture and waveform distortions can be caused by group delay errors in narrow band RF power amplifiers and tuned RF output systems. Group delay error is the nonuniform group delay over the bandwidth of the TV signal. In a bandpass filter, spectrum components on the edge of the passband are delayed more than components in the center of the passband. In general, the closer the amplitude roll-off frequency is to the visual passband, the higher the delay error.

Group delay impairments show up as color smear and halo effects on edges. On a waveform monitor the effects may be seen using the 2T and modulated 12.5T contained in the composite test signal shown in Fig. 7. Pulse responses may include exaggerated pre or post ringing on 2T and modulated 12.5T base line disturbance. The multipulse signal shown in Fig. 13 may also be used.

The multipulse signal consists of a gray flag (80 IRE), 2T pulse, and five sine-squared pulses modulated with five discrete frequencies (consisting of one 25T pulse and four 12.5T pulses). The multipulse may be used to measure linear distortion in TV systems, such as gain/frequency distortion (frequency response) and delay/frequency distortion (group delay).

The modulated pulses contain two spectra of information, the low frequency and the high frequency, as illustrated in Fig. 14. These modulated

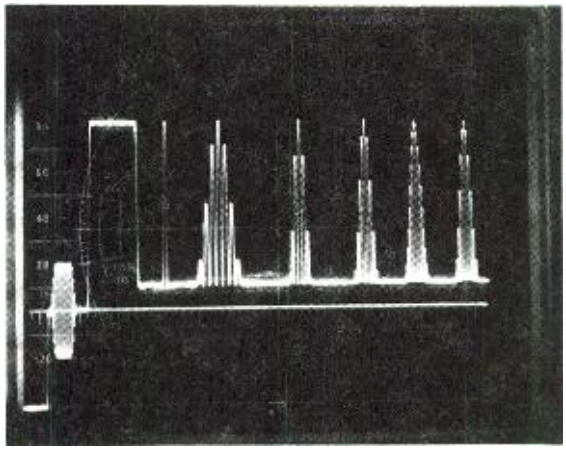


Fig. 13. Multipulse.

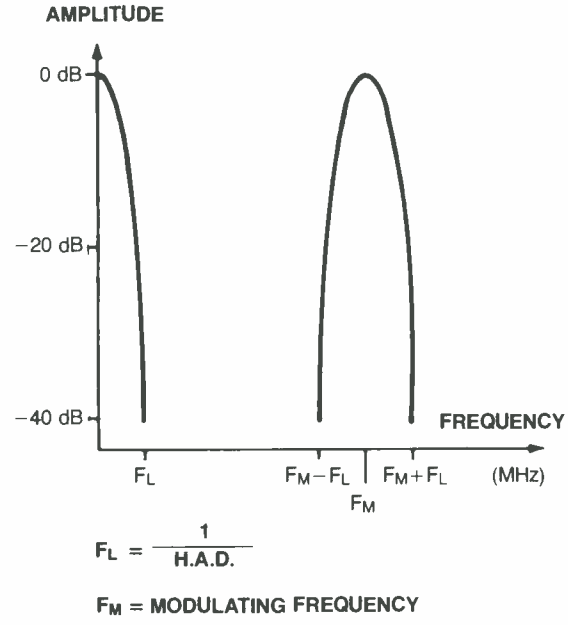


Fig. 14. Energy spectrum for modulated pulses.

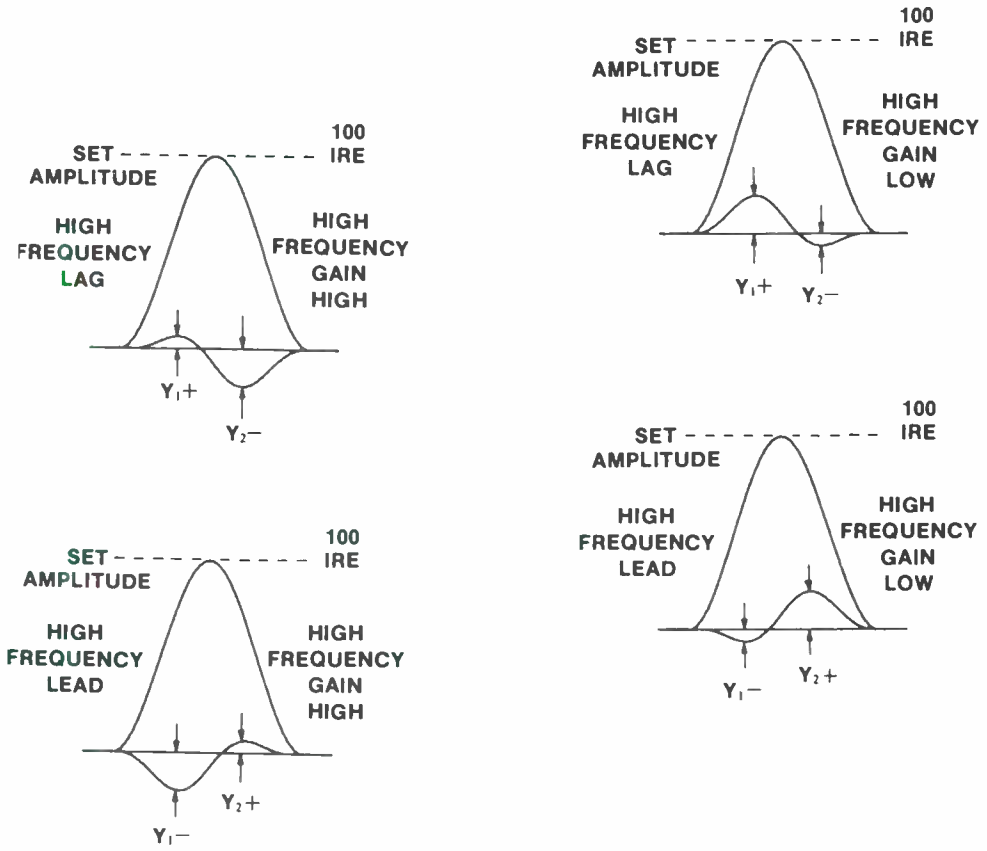


Fig. 15. Modulated sine-squared pulses with gain and phase errors.

pulses are useful for measuring group delay errors. If the low-frequency spectrum and the high-frequency spectrum are delayed equally, the results will be a symmetrical modulated pulse with the same shape as the input. The gain/frequency distortion will alter the base line flatness but will not change pulse symmetry. Delay errors will result in an asymmetrical pulse baseline. Combinations of delay and gain errors are shown in Fig. 15.

Low-frequency group delay and amplitude errors are referred to as short time waveform distortions. Fig. 17 shows typical distortions of a 2T pulse.

A method of quantifying these distortions is to use the waveform graticule shown in Fig. 16. This graticule was arrived at empirically and represents constant perceptible distortion levels. It shows that overshoots closer to the desired pulse are not as perceptible as ringing further away.

The desired K factor graticule, i.e. 2%, is overlapped on a waveform monitor and the group delay corrector is adjusted until the 2T waveform lies entirely within the graticule. This technique is often preferred to swept group delay measurements because the results are in terms of perceptibility.

If the group delay error affects only the high frequency side of the passband, precorrection can be accomplished at video. This is the case for most visual-aural RF notch type diplexers and FCC receiver equalizer curve. In the case of the notch diplexer, a pair of cavities resonant at the aural frequency are inserted between two 90° hybrid couplers. Refer to Fig. 79. The presence of the tuned circuits near the upper edge of the visual passband can cause significant group delay error.

Another source of group delay is the tuned circuits of the high power tetrode or klystron am-

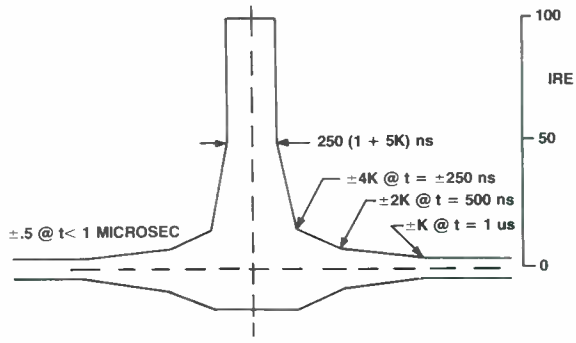


Fig. 16. 2T sine-squared pulse graticule.

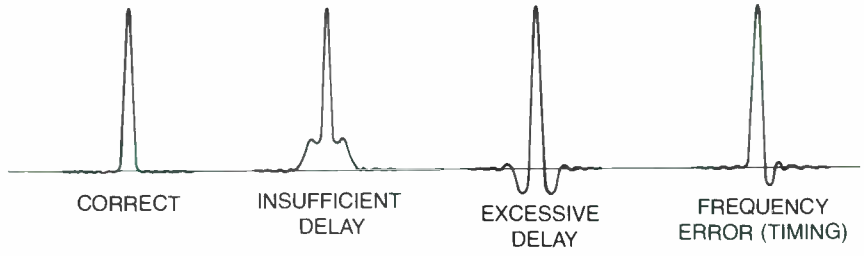


Fig. 17. Typical distortion of a 2T pulse.

plifiers. Finally the FCC requires the TV transmitter to predistort group delay according to the curve shown in Fig. 18.

The delay shown in Fig. 18 is a characteristic delay curve the FCC requires all visual transmitters to have. The purpose of it is to compensate for the delay error caused by discrete LC aural notch filters in early TV receivers. The theory was that it would be far cheaper to group delay compensate one transmitter than every TV set. The notch filter in TV receivers is necessary to prevent the aural carrier from mixing with the detected video and chroma subcarrier signals and producing visible spurious beats.

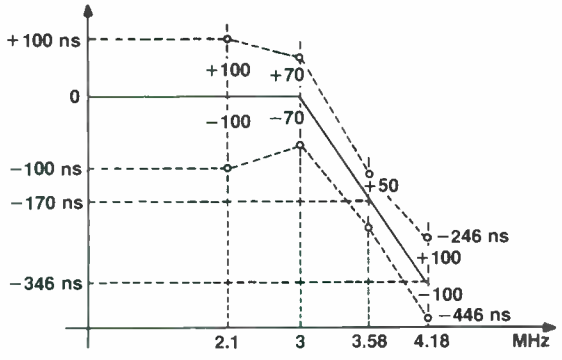


Fig. 18. Predistorted group delay curve.

Group delay predistortion is accomplished at video or IF. The techniques used are similar in concept. Both active and passive equalizers are employed. IF group delay correction is necessary to correct group delay errors associated with the lower sideband below visual carrier. Above visual carrier both IF and video correction is effective.

Passive Group Delay Equalizer

A common form of a passive video delay equalizer is shown in Fig. 19. It provides a flat frequency response and a nonlinear group delay which peaks at the resonant frequency of the circuit. This type of circuit is referred to as a passive all-pass network.

Without going through a detailed analysis of the circuit much can be understood by examining the all-pass at frequencies well below and above resonance. At low frequency the network can be approximated by a low-series inductive reactance due to L1. Here the output voltage leads in phase near zero. At high frequency well above resonance the circuit can be approximated by a series capacitive reactance due to C1. At high frequencies the output lags in phase near zero or more correctly 360°.

The output amplitude is a constant. The phase of the network is plotted in Fig. 20. The slope of the phase change is defined as group delay. The steeper the slope the higher the maximum group delay. A plot of the group delay is shown in Fig. 21.

Active Group Delay Equalizer

As in the passive type the network has a constant amplitude frequency response and a nonlinear phase response. The action of an active allpass network can be best explained using the simplified schematic of Fig. 22. If the voltage e_1 and phase were plotted as a function of frequency, it would trace out a circle with maximum

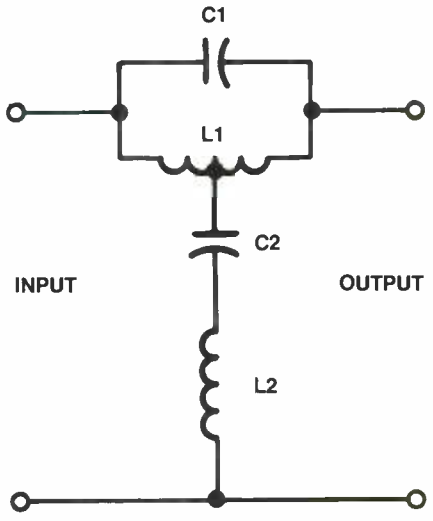


Fig. 19. All-pass network.

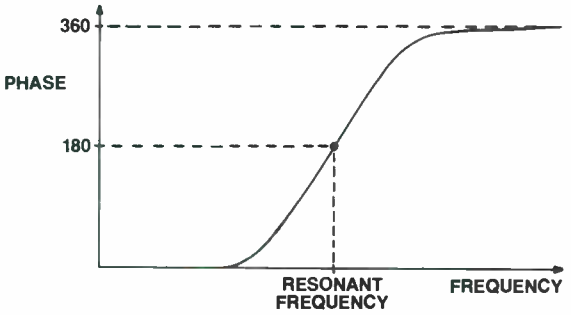


Fig. 20. All-pass phase.

amplitude and zero phase at resonance. Voltage e_2 on the other hand has a constant amplitude and phase. For the case when e_1 maximum is equal to twice e_2, the e_3 output of the summing amplifier A1 has the characteristics of an ideal all-pass network. The output amplitude is constant, the resonator tuning determines the frequency of maximum group delay and the Q determines the magnitude of delay.

For the case that e_1 is larger than twice e_2, the output will have an amplitude ripple peak at resonance and conversely if e_1 is smaller, the output will have a dip at resonance.

Vestigial Sideband Filter

The FCC requires that the radiated TV signal suppress a major portion of the lower sideband. In addition, on the high frequency side the signal must be contained within 4.75 MHz of the visual carrier. Originally, the bandshaping was performed at the output of the transmitter. With the advent of IF modulation the filter has moved to low-power stages and at first was built using discrete inductors and capacitors. More recently transmitter manufacturers have selected solid state filters using Surface Acoustic Wave (SAW) technology.

The term Surface Acoustic Wave (SAW) refers to the propagation of elastic waves on the surface of a piezoelectric crystal. The propagation is roughly the speed of sound, and therefore called acoustic. A time varying voltage on a metalized transducer is used to induce a deformation on the surface and produces a electromechanical wave. The deformations produce local electric fields which travel along with the mechanical wave, and interact with metal electrodes, which convert the mechanical wave back to a time varying voltage. The length of the electrodes, the spacing and the number determine the wave shaping properties of the filter.

The electrodes act like tapped delay lines, as illustrated in Fig. 23. The electrodes are designed to amplitude scale and delay the signal. The output is selectively attenuated depending on the time delay and signal frequency relationship. This type of filter is called transversal because the attenuation is controlled by delay lines rather than resonators. The transversal filter was invented in the early forties and used coax cables as delay lines.

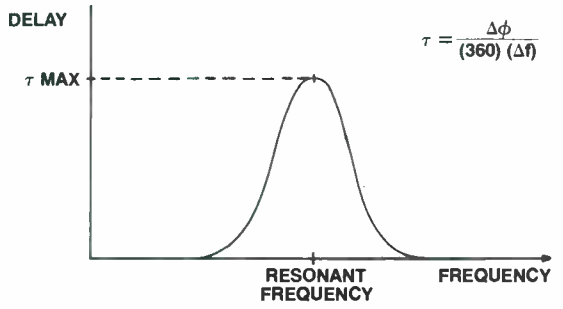


Fig. 21. All-pass group delay.

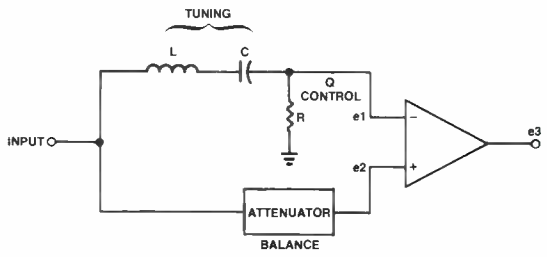


Fig. 22. Active all-pass network.

Today, surface acoustic wave transducers provide the same function. The wavelength of a 37 MHz IF acoustic signal is approximately .003 inches.

This small size allows the filter to be very small and compact. Because the transducers are only on the surface, photographic masks can be used to accurately control the physical dimensions of the transducers. The photographic mask lends

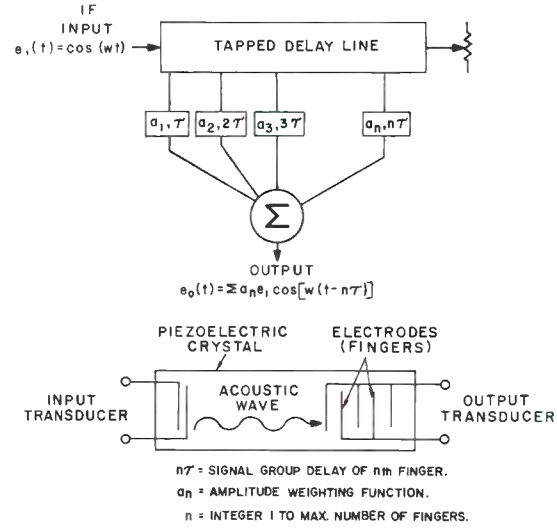


Fig. 23. Saw filter.

itself to modern manufacturing techniques and insures a reproducible filter with a permanent attenuation and group delay.

A characteristic of the transversal filter is that group delay can be set independently of the amplitude characteristic. This is not true of discrete LC filters where basic physical laws couple group delay and bandwidth. The independent nature of group delay and bandwidth allow the manufacturer to provide ideal pulse response without the need to use group delay equalizers. The FCC group delay characteristics shown in Fig. 18 can also be built in.

Although the FCC does not require attenuation of visual signals in the aural passband, video signal frequency components can cause interference called visual to aural crosstalk. Reduction of visual to aural crosstalk is very important because of the adoption of stereo sound and other subcarrier broadcast services. High resolution cameras and character generators can produce spectral components at 4.5 MHz and beyond. Without sufficient attenuation these signals can cause distortion, especially in aural subcarriers which are more sensitive to visual crosstalk. SAW filters then are able to perform many functions simultaneously, i.e. bandwidth shaping, group delay equalization, and video to aural crosstalk reduction.

Common distortion products associated with SAW filters are due to spurious signal reflections and direct feedthrough. These distortions cause time echoes displaced either before or after the desired responses. In the frequency domain these echoes show up as ripples in the passband. Ripples are related to spurious time echoes as shown in Fig. 24. A given time echo will contribute uniquely to the amplitude, phase and group delay characteristics by the addition of a ripple component in the passband. The amplitude of the ripple is proportional to the echo level, and its period is the reciprocal of the time displacement.

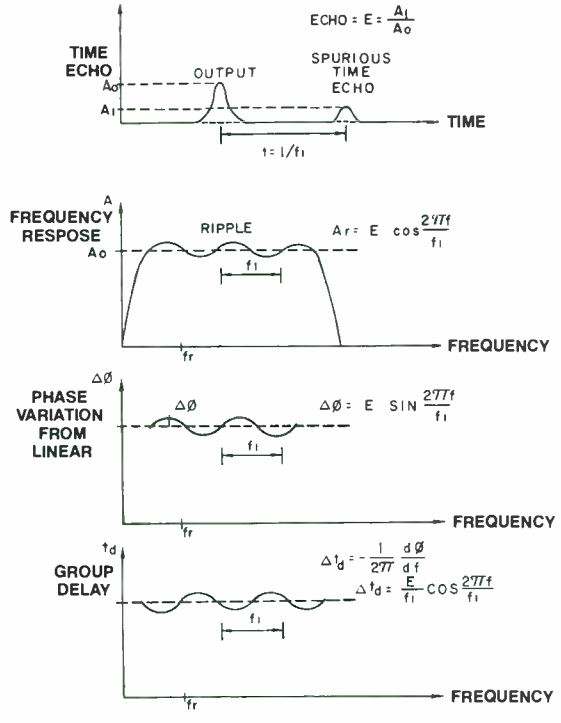


Fig. 24. Response, phase, and delay ripples caused by time echoes.

The group delay characteristic will vary sinusoidally with the same period as the passband ripple. Its magnitude however, is a function of both echo level and inversely proportional to time displacement, and therefore not a sure test of signal distortion. The group delay ripple for long delayed echoes will give peak-to-peak values which have no correlation with conventional signal distortion estimates. For that reason fast peak-to-peak group delay errors that occur closer than the reciprocal of the filter time delay can usually be ignored.

A better test is to measure group delay distortion using the pulse waveforms in Figs. 7 and 13. The 2T preshoot, overshoot, and dissymetry can be used to gauge low-frequency group delay error. Modulated Pulse baseline S curve is a result of group delay error at the modulated carrier and the peak excursions of the S curve can be used to access high frequency group delay.

IF Linearity Precorrection

It was pointed out in the section on Video Precorrection that amplitude and phase nonlinearities are sometimes corrected at video. The alternative is to provide correction at IF. There are advantages to correcting at IF in that since most distortions are caused in the high power RF amplifiers after vestigial sideband filtering, a corrector placed after the vestigial sideband filter can more accurately predistort the modulated signal in a manner consistent with the sideband energy. This is especially true of chroma distortions. 3.58 MHz chroma has only a single sideband information at RF and thus has 6 dB less energy than the luminance signals. The RF power spectral density is altered by the vestigial sideband nature of the TV signal. An ideal diode detector frequency response of the NTSC modulated signal is plotted in Fig. 25. Here it is seen that beginning at .75 MHz the video begins to fall to −6 dB. For video signals lower than .75 MHz, the RF is double sideband and has twice the peak RF voltage.

Intermodulation products are caused in high power amplifiers by nonlinear amplitude and/or phase transfer characteristics. As the power output increases towards saturation amplitude compression begins and in general the phase begins to lag as well due to electron crowding in the

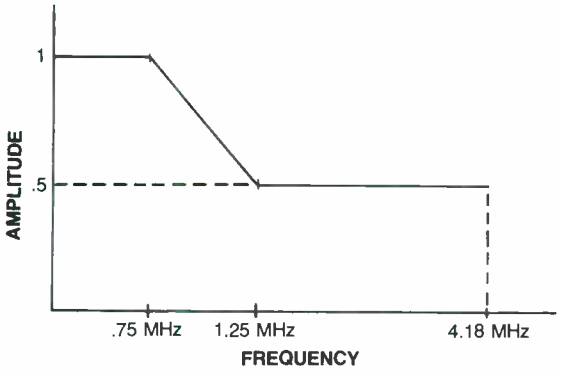


Fig. 25. Frequency response using ideal diode detector.

amplifier device. The nonlinear amplifications give rise to mixing products which occur at sum and difference frequencies around the visual carrier. The amplitude compression distortions produce spectral components which are in phase with the modulation signal. Correctors for compression distortion are usually similar in concept to video differential gain correctors. The linearity correctors generally use biased diodes to modify gain as described earlier in the video processing section. Implementation, however, is generally more difficult because for given diode bias the peak-to-peak IF envelope amplitude requirement is twice that of video. In addition, since the susceptibility to reactance drift varies with frequency, the design and manufacturing tolerances for IF correctors are several orders of magnitude more stringent than video correctors.

A basic gain expansion circuit is shown in Fig. 26. The signal is normally attenuated a fixed amount by using a resistive L-pad. The diodes are normally reverse biased by equal, but opposite polarity, dc voltages. Reducing the dc voltage amplitude permits the diodes to conduct on the signal peaks. This inserts additional resistance in parallel with the series arm of the L-pad thereby decreasing the attenuation. Varying the resistance in series with the diodes provides for a variable gain expansion.

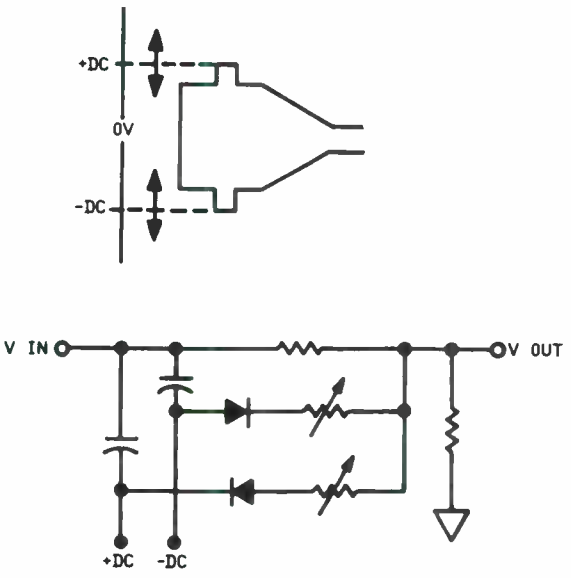


Fig. 26. Basic gain expansion circuit.

The phase distortions produce Incidental Carrier Phase Modulations (ICPM) which are bessel type spectral components in quadrature with the modulation signal. For a given level dependent phase shift the amplitude of the spectral component will increase directly with the video frequency. The spectral amplitude frequency relationship is consistent with phase modulations. In other words fast video amplitude changes such as a step or pulse will cause larger phase spectral components than slow changes. Receivers make this condition worse by not detecting the lower sidebands below .75 MHz. The receiver then responds to the sidebands as if they were amplitude single sidebands and produce spikes. The faster the rise time on the signal the more high frequency energy is present resulting in edge distortions.

The picture impairment is similar to simultaneous group delay and differential phase errors in that edges are less sharp and color changes with brightness. On a waveform monitor, overshoots are visible on trailing edges and rounding on leading edges. These overshoots vary in severity depending on how close the power amplifier is driven towards saturation.

Audio impairment is produced by ICPM in receivers employing intercarrier detection. Intercarrier receivers use an AM or synchronous detector to produce a 4.5 MHz aural IF signal. Any phase modulation present on the visual carrier is then transferred to the aural IF carrier. In the L + R or monaural baseband audio the increasing amplitude frequency effect of ICPM is nullified by de-emphasis to some degree. With the advent of multichannel sound, however, the distortion is more pronounced at the subcarrier and pilot frequencies. To counteract the effects of ICPM and other noise sources on subcarriers an elaborate audio companding system has been adopted which greatly reduces the potential interference. Although the audio companding process reduces the effects of ICPM, ICPM correction is an important aid in delivering clear, low-noise audio to intercarrier receivers.

ICPM correctors can be grouped into two types, ones using a phase modulator and the other operating on the signal directly. The phase modulator type uses video to vary the IF or master oscillator phase with the opposite phase characteristics of the nonlinear amplifiers. A block

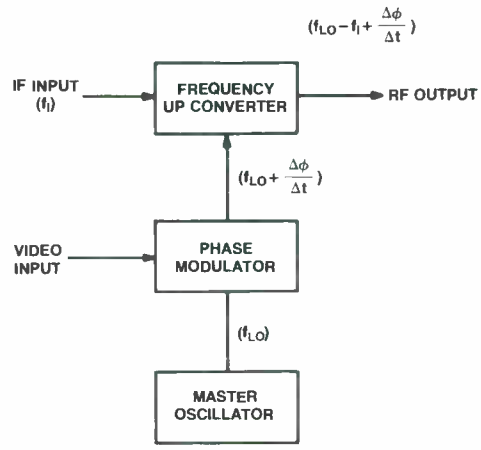


Fig. 27. Master oscillator phase modulator block diagram.

diagram of a master oscillator phase modulator is shown in Fig. 27.

ICPM correctors operating directly on the IF signal can be implemented several ways. Direct correction at IF is similar in concept to baseband phase correction. In both cases the video is split into two paths which are in phase quadrature. In the IF corrector the entire channel is in quadrature, whereas in the video corrector only the chroma band is in quadrature (Fig. 28).

One implementation is to modify the quadrature signal gain function with level dependant diode breaks. This can be done using the same techniques as in the linearity corrector.

RF Generator

Transmitters employing IF modulation generate the following frequencies; visual IF, modulated aural IF, and a common master oscillator for translating visual and aural IF to final carrier frequencies. The oscillator schemes have been implemented with either digital synthesizer techniques or crystal oscillators. An advantage of the synthesizer is that only one crystal which may operate at a single standard frequency for all TV channels is required. The multiple crystal approach, however, involves simpler circuitry.

The two commonly used IF frequencies are 37 MHz and 45.75 MHz. There are many reasons for selecting one IF frequency or the other. One advantage of 37 MHz is that the temperature drift sensitivity of most IF components such as the SAW filter is related directly to carrier frequency. Thus the lower IF has a 12 percent less drift sensitivity than components at 45.75 MHz. On the other hand, 45.75 MHz is a common demodulator IF which can be useful for IF troubleshooting, and temperature drift may be minimized at either IF by maintaining the filter at a stable temperature.

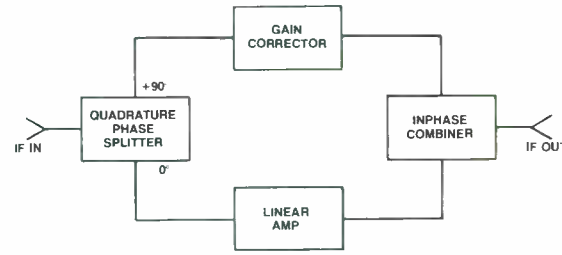


Fig. 28. Direct IF ICPM corrector.

The important performance characteristics of an oscillator is its low-phase noise, low sensitivity to frequency drift with time and temperature, and resistance to mechanically induced phase and frequency shifts called microphonics.

In replacing a crystal it is important to follow the recommendations of the oscillator manufacturer to insure proper operation. Synthesizer maintenance must be properly performed to prevent inadvertent phase noise and spurious frequency generation.

AURAL EXCITER

BTSC Multichannel Sound System

The combination of dbx companding and the Zenith Multichannel Television Sound Transmission System (referred to as the BTSC—Broadcast Television Systems Committee—System) provides high-fidelity stereo performance for all viewers within the present range of TV signals (grade A and B areas).

The introduction of TV stereo and SAP into the spectrum requires that the person or persons maintaining the entire aural transmission chain from audio input to transmitted RF fed to the antenna be aware of the BTSC system. The following paragraphs offer an overall view of the BTSC system.

The transmission spectrum of the BTSC system is graphically illustrated in Fig. 29. A total system block diagram is presented in Fig. 30.

Except for the stereo subcarrier center frequency, the system is similar to that used for transmitting stereo FM in the United States with the pilot frequency being the video horizontal-scanning frequency of 15.734 kHz ($1f_H$).

To keep the signal compatible with mono television sets, the L + R signal is transmitted in the same spectrum space previously occupied by the mono audio signal. Stereo information is encoded in the L − R channel which will only be decoded by stereo compatible television sets while mono sets will ignore the L − R subcarrier. The stereo set uses the L − R signal to reconstruct the original left and right audio signal by adding and subtracting the L + R and L − R signals.

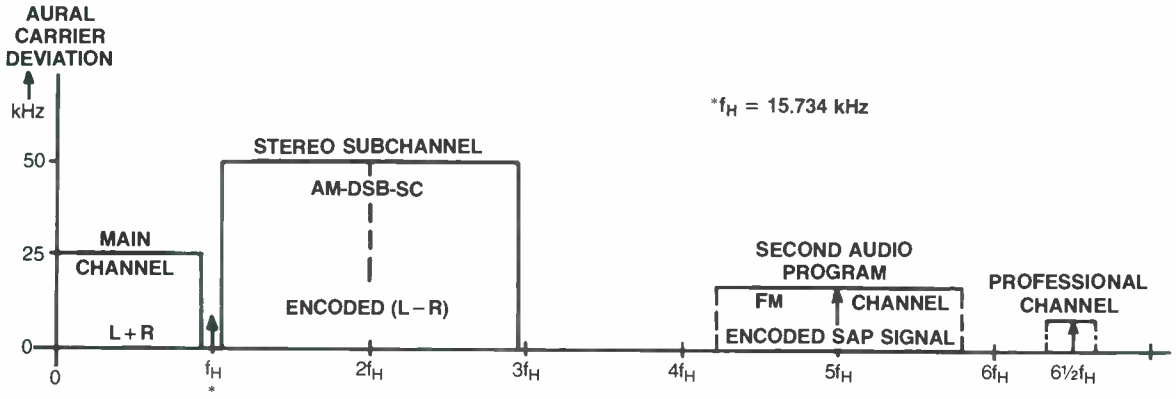


Fig. 29. BTSC system frequency spectrum.

The main channel aural carrier modulation consists of an (L + R) audio signal with a pre-emphasis of 75 microseconds. The (L – R) audio signal is subjected to compression according to a companding system that complements the expansion in the receiver. The compressed L – R signal causes double sideband, suppressed carrier amplitude modulation of a subcarrier at 31.468 kHz ($2f_H$). The audio bandlimits of both pre-emphasized L + R and of the encoded L – R are 50 Hz and 15 kHz.

The main channel (L + R) peak deviation is 25 kHz. The stereophonic subchannel (L – R) peak deviation is a maximum of 50 kHz. When L and R are statistically independent, the peak deviation of the main channel and the stereophonic subchannel combined is also 50 kHz when full interleaving exists. When L and R signals are not statistically independent or when (L + R) and (L – R) signals do not have matching pre-emphasis characteristics (as is the case when (L – R) is compressed in the BTSC system) the combined deviation of the main channel and stereophonic subchannel is also constrained to a maximum of 50 kHz peak deviation.

A CW pilot carrier of frequency $1f_H$ is transmitted with the main carrier deviation of 5 kHz.

The subcarrier for the Separate Audio Program (SAP) channel has a frequency of $5f_H$ (78.670 kHz) and is frequency locked to $5f_H$ in the absence of modulation. The SAP audio signal is subjected to compression identical to that of the L – R signal. The resulting SAP modulating signal is bandlimited to 10 kHz and frequency modulates the SAP subcarrier to a peak deviation of 10 kHz. The RF deviation or injection of this subcarrier is 15 kHz.

The professional subchannel has a subcarrier located at approximately $6.5f_H$ and modulates the aural carrier by 3 kHz peak deviation.

Total peak deviation allowed for the aural baseband is 73 kHz.

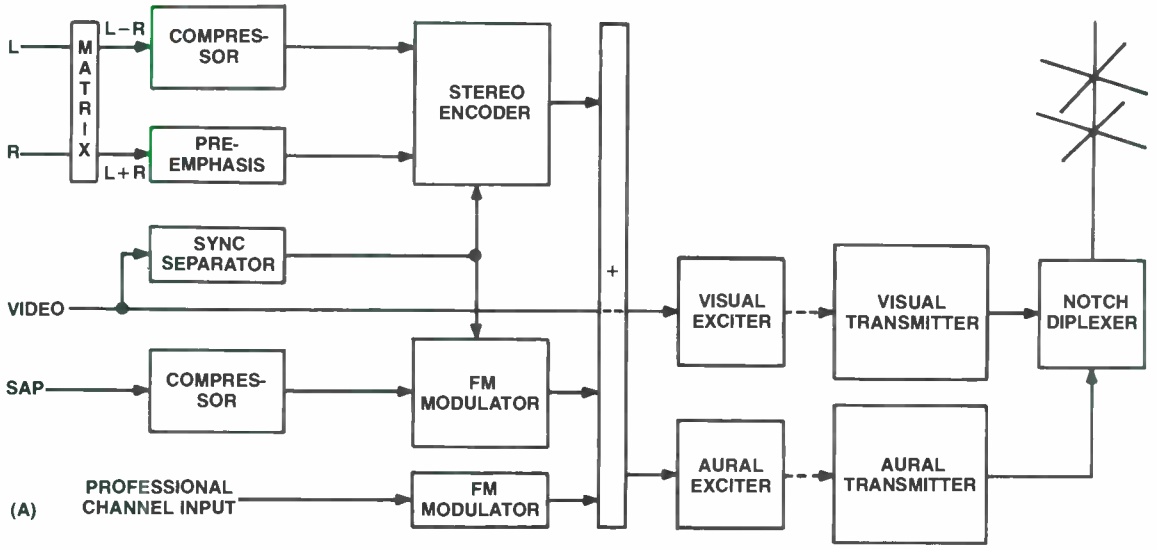


Fig. 30. Block diagram of BTSC system.

Stereo and SAP Noise and the Need for Companding

FM transmission systems like the BTSC system have a receiver parabolic noise characteristic, which means that they have increasing noise at higher frequencies. Because the stereo subchannel is at a higher frequency than the L + R signal (the L + R signal contains only frequencies up to 15 kHz, while the modulated subchannel bandwidth extends from about 17 kHz to 46 kHz), the L – R signal contains much more noise when demodulated.

To improve the signal to noise, the L – R modulation level can be increased, but this technique is limited. Increasing the modulation level too much will produce crosstalk from one channel to the other. In the BTSC system, 6 dB more L – R modulation is allowed than for L + R. The result is that the subcarrier adds approximately 15 dB of noise to stereo reception as compared with no companding, even under ideal reception condition.

To make matters worse, when transmission and/or reception conditions are impaired (transmitter ICPM incidental carrier phase modulation, multipath, etc.), buzz or hum can be introduced into the audio. This would further degrade the stereo signal-to-noise ratio as compared to mono if no companding system were used, especially in grade B reception areas. The SAP channel's subcarrier is located at a frequency of 78.67 kHz, so more noise is introduced because of the FM parabolic noise curve. Also the SAP subcarrier is an FM subcarrier which makes it additionally subject to buzz beat, an intermodulation of the picture with the audio that causes a particularly obnoxious type of non-harmonically related distortion.

Companding

Companding is defined as a process in which compression is followed by expansion. For noise reduction, the signal is compressed before the noise exposure (before the transmitter) and expansion afterwards (in the TV receiver). In the BTSC system, the dbx TV system of companding is used and will be explained in the paragraphs that follow.

The dbx TV noise-reduction system was designed to aid the BTSC multichannel sound TV transmission system in delivering a clean, noise-free audio signal into the home. Specifically the system was designed to:

- Provide significant amount of noise reduction even in poor reception areas (grade B or worse).
- Preserve input-signal dynamic range without headroom loss or transient overshoots.
- Prevent the stereo subcarrier from interfering with the overall transmitted power levels (AM-interleave effects).
- Reduce buzz due to ICPM.

The system was designed to compand only the L – R and the SAP channels. The L + R signal is transmitted without companding to ensure compatibility with the mono TV sets still in use. The same companding process is used for both the L – R and SAP channels.

Masking

All audio noise reduction systems work on the principles of masking. This principle can be simply stated as follows:

If a desired program signal (music or speech) is loud enough and broad enough in its spectral content, then the ear's attention will be captured by this signal rather than by the noise of the transmission medium.

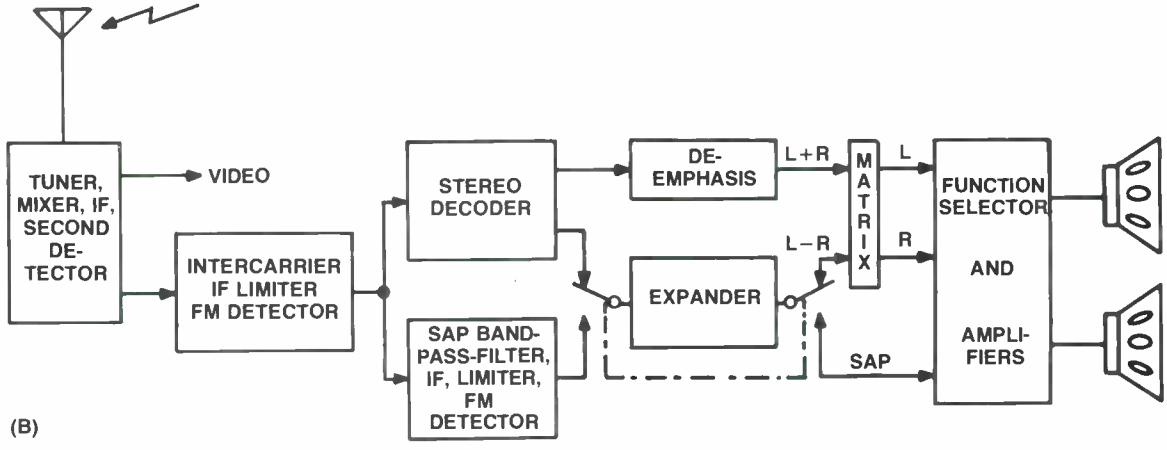


Fig. 30. (continued)

The noise-reduction system must encode (compress) the audio signal so that it will consistently mask the noise of the channel during transmission and then decode (expand) the transmitted signal to recover the original audio. And in the decoding process, all the audible noise should be eliminated. This requires that:

- The level of the transmitted audio is high relative to the background noise.
- The audio spectrum must be conducive to masking.

The background-noise spectrum of the BTSC stereo subcarrier is parabolic, having a 3-dB/octave rising characteristic, while the SAP subcarrier has a 9-dB/octave rising characteristic. Proper masking of the noise in the presence of signal takes place only if the transmitted signal spectrum contains substantial high frequency content, especially in the case of the SAP channel. If the program material itself could be relied upon to have sufficient high frequencies, then the compander would only have to keep amplitude levels high through the transmission channel. However, most program material has its dominant energy at low frequencies.

The simplest way to transform such program material into a signal conducive to masking is to apply fixed pre-emphasis to the signal before transmission. This pre-emphasis changes the spectrum of the average program material (containing mostly low frequencies) to be more evenly balanced between highs and lows. In the TV receiver, the program signal is de-emphasized, which restores correct tonal balance and reduces the audibility of the high frequency hiss at the same time.

In dbx TV, three processes are used to achieve the desired noise masking; pre-emphasis, spectral companding and wideband amplitude companding.

Pre-emphasis

In dbx TV two pre-emphasis networks are used. One is essentially the same as 75 microseconds (actually 72.7 microseconds). The other is 390 microseconds, but the rising frequency response created by this pre-emphasis is curtailed at 30 microseconds. The frequency response curve of the complete pre-emphasis has a very steep section between about 2 kHz and 5.5 kHz, which helps dbx TV overcome the large amounts of noise present in grade B reception. In the TV receiver, a corresponding de-emphasis restores the correct tonal balance to the program material and reduces the audibility of the hiss picked up in transmission.

Unfortunately, audio program material is inconsistent in its spectral balance and its level. With fixed pre-emphasis alone, two problems remain. First, some audio signals contain predominately high frequencies and the pre-emphasis would boost them too much, causing overmodulation. This is called lack of headroom—insufficient room for the peaks of the program to be transmitted cleanly. Second, some audio signals would be too low in level and too lacking in high frequencies to properly mask the channel noise, even with the strong pre-emphasis used in dbx TV.

Spectral Companding

In order to help make the audio more consistent in its spectral balance before transmission, a second stage, in which the pre-emphasis adapts its characteristics to suit the signal, is used and is called spectral companding. The spectral compressor (in the encoder) monitors the spectral balance of the input signal and varies the high frequency pre-emphasis accordingly. When very little high frequency information is present, the spectral compressor provides large high frequency pre-emphasis. When strong high frequencies are present, the spectral compressor actually provides de-emphasis, thereby reducing the potential for high frequency overload. The resulting encoded signal is therefore dynamically adjusted to consistently contain a substantial proportion of high frequencies before transmission, providing masking of the channel noise.

Spectral compression uses a variable pre-emphasis/de-emphasis stage and varies the gain of a voltage controlled amplifier (VCA) embedded in a frequency selective network. When the VCA gain is low, no signal appears at point B in Fig. 31. The only transfer from the input to the output must go from point C to the output, which passes through the de-emphasis network. This attenuates the high frequencies.

On the other hand, when the VCA gain is high, the response between point A and the output is essentially flat (like an op amp with a closed feedback loop). The signal at point C is small compared to the signal at point B (due to the high VCA gain), so the output signal is essentially the same as that at point A, which is the input signal after pre-emphasis. This provides gain to the high frequencies.

At intermediate VCA gain settings, the response varies smoothly between these two extremes, with flat occurring at unity (0-dB) gain.

The VCA gain is controlled by an rms level detector which senses the amount of high frequency energy at the output of the compressor. The bandpass filter center frequency is about 10 kHz.

When high levels of high-frequency energy are detected, the VCA gain is high, and de-emphasis

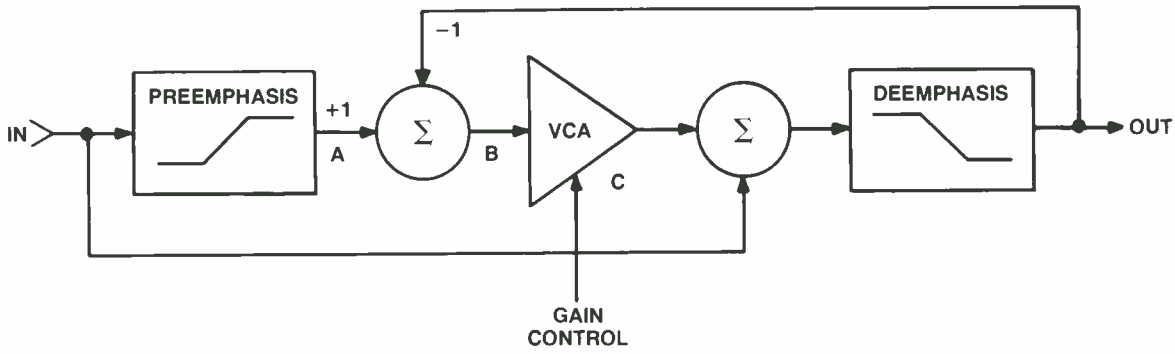


Fig. 31. Variable preemphasis/deemphasis network.

results, reducing high frequencies. When low levels of high-frequency energy are detected, the VCA gain is low, and pre-emphasis results, boosting high frequencies. In effect, the range of spectral variation at the output is reduced, "compressing" the spectral dynamic range.

During reception by a TV set, the spectral expander (in the decoder) will restore the high frequencies to their proper amplitude.

By using the spectral compressor, two simultaneous requirements are met:

- The system is extremely forgiving of high background noise environments because the spectral shaping of the input signal is adjusted according to the needs of the input signal to provide high masking at all times.
- Headroom is maintained throughout the frequency range because extreme pre-emphasis is used only when it is really needed.

Wideband Amplitude Companding

Neither the spectral compander nor the fixed pre-/de-emphasis will help reduce noise when the signal is very low in level, especially if the signal has little high frequency content. This is where the wideband compander is used to adjust the level of all frequencies simultaneously to keep the signal level in the transmission channel high at all times.

The wideband compressor reduces the dynamic range of input signals by a factor of 2:1 in dB. Not only are small signals raised in level but large signals are reduced. The output level tends toward about 14% modulation which has three benefits:

- The signal is consistently above the noise floor.
- The signal is consistently below 100% modulation, reducing AM interleaving effects.
- Headroom is maintained for transient peaks to overshoot the nominal level at the compressor output without causing overmodulation.

The wideband amplitude compressor works by controlling the gain of a VCA in response to an rms level detector, which senses the low and mid frequency energy level at the output of the compressor.

Transient Protection

A clipper or limiter is incorporated into the noise reduction compressor and is set to operate at 100% modulation to prevent large transients from causing excessive modulation of the transmission system.

To keep the effects of clipper operation from being audible, the amount of clipping is kept small. This is accomplished by:

- Setting the unaffected level point of the wideband compressor to substantially below the point that would cause 100% modulation in the transmission channel.
- Allowing the wideband and spectral compressors, which precede the clipper, to operate quickly enough to let only brief overloads reach the clipper.
- Placing the static pre-emphasis before the clipper, further reducing the transient overload duration.

Aural Transmitter Requirements

To ensure that the transmitter is not the limiting factor in stereo reproduction, it is desired that the transmitter be as transparent to the incoming signal as possible.

Baseband audio (stereo, SAP and profession channel) include components out to 105 kHz. Emphasis is placed on phase linearity, low distortion, minimization of any amplitude ripples, or roll-off over the audio passband to achieve optimum stereo separation and to minimize cross talk between the stereo channel and the SAP channel.

All errors in phase linearity or amplitude response within the aural transmitter tend to be cumulative. Separation degradation can be caused

by amplitude roll-off or departure from phase linearity.

For stereo, modulated oscillator performance requires flat modulation sensitivity vs frequency characteristics up to 47 kHz (with a desirable flatness out to 120 kHz to allow for SAP and Pro channels).

Intermodulation and harmonic distortion products which, in monaural operation lie above 15 kHz, now lie in the stereo channel or the SAP channel and will degrade stereo separation or crosstalk into the SAP channel. In addition, IM products generated by stereo subchannel will now lie in the main channel.

All modern transmitters are IF modulated. To insure these low-level stages do not contribute any group delay or amplitude roll-off, wideband amplifiers should be used. As the signal is up converted to the RF aural carrier frequency, the FM of the local oscillator signal should be checked. The residual level of FM produced by the LO should be 10 dB better than the modulated oscillator noise. Synthesized LO sources should be checked for reference frequency spurs which may show up as FM noise.

All RF amplifiers should be viewed from the point of obtaining a flat symmetric amplitude response and a minimized group delay across the passband. Since FM modulation and demodulation is a nonlinear process there is not a one-to-one correspondence between RF amplitude/phase response and baseband stereo separation and crosstalk. Measurements indicate that a 2.5 MHz, 3 dB bandwidth is sufficient to achieve excellent stereo and SAP performance. No longer can amplifiers be tuned just by maximizing efficiency without compromising stereo performance or crosstalk, unless the stage is designed to operate that way. The amplifiers must be swept and frequency analyzed to insure the passband is sufficiently wide to pass the stereo signal and that its passband shape is symmetric about the carrier frequency.

Klystron amplifiers have previously been adjusted with all cavities, excluding the penultimate, synchronously tuned on the aural carrier. The cavities must be stagger-tuned to achieve the required 2 MHz 3 dB bandwidth.

The notch diplexer is possibly the most critical element in the aural chain with regard to stereo separation. If correct tuning of the notch diplexer itself is not properly maintained, stereo separation will be degraded and crosstalk between the mono, stereo and SAP channels will occur. Hybrid diplexers do not present any degradations to multichannel sound.

In summary, these major changes were incorporated and must be maintained in the aural portion of the transmitter:

- Wideband low distortion audio stages with high S/N are employed to insure negligible distortion in the baseband signal.
- Low distortion wideband modulated oscillators with improved noise performance and PLL techniques are used so that the quality of TV multichannel sound will approach that of the FM broadcast service.
- The bandwidth of IF and RF stages is wide. Power bandwidth tradeoffs may need to be made to achieve optimum stereo performance. Where feasible, the TV station might consider 20% aural power to increase its stereo coverage area. This may compensate partially for the degradation in S/N due to the increased bandwidth of the stereo signal.

Visual Transmitter Requirements

ICPM

There is no defined level of ICPM for a given stereo performance level since the signal to buzz ratio is highly dependent on the picture spectral components. Refer to the EIA Recommended Practices for the current recommendations on ICPM limits.

Video components at 4.5 MHz should be minimized prior to being injected into the transmitter.

Video sidebands translated to the intercarrier appear at nf_H in the audio passband. If the 4.5 MHz intercarrier is maintained precisely, the buzz caused by the ICPM transferred to the intercarrier will be minimized.

Overmodulation causes the intercarrier to disappear and thus the local oscillator in the TV receiver has nothing to which to lock. This produces buzz in the receiver. This may be prevented by the use of a luminance clipper.

Antenna reflections cause multipath effects in the receiver and a loss in stereo separation. Therefore, it is extremely important to minimize the aural VSWR across the passband.

Monitoring TV Multichannel Sound

Assurance of having a high quality aural signal is perhaps the most important reason for having a monitor. An aural monitor provides a means of maintaining constant loudness from various program sources. Periodic maintenance and proof of performance are other important reasons to have a monitor that demodulates the RF signal and separates the components in the composite signal for analysis.

An ideal modulation monitor should consist of, but not be limited to, the following functions:

- Demodulates the composite signal from the aural carrier.

- Separates the components in the composite signal for measurements.
- Capable of off-air monitoring.
- Covers all VHF and UHF channels.
- Suitable for professional performance use.
- Contains a precision expander.

UHF KLYSTRONS

The klystron is a device for amplifying signals at microwave radio frequencies. The high-velocity electron beam emitted from the cathode passes through the anode and into the RF interaction region, as shown in Fig. 32. An external magnetic field is employed to prevent the beam from spreading as it passes through the tube. At the other end of the tube, the electron beam impinges on the collector electrode, which dissipates the beam energy and returns the electron current to the beam power supply.

The RF interaction region, where the amplification occurs, contains resonant cavities and field-free drift spaces. The first resonant cavity encountered by an electron in the beam (the input cavity) is excited by the microwave signal to be amplified, and an alternative voltage of signal frequency is developed across the gap.

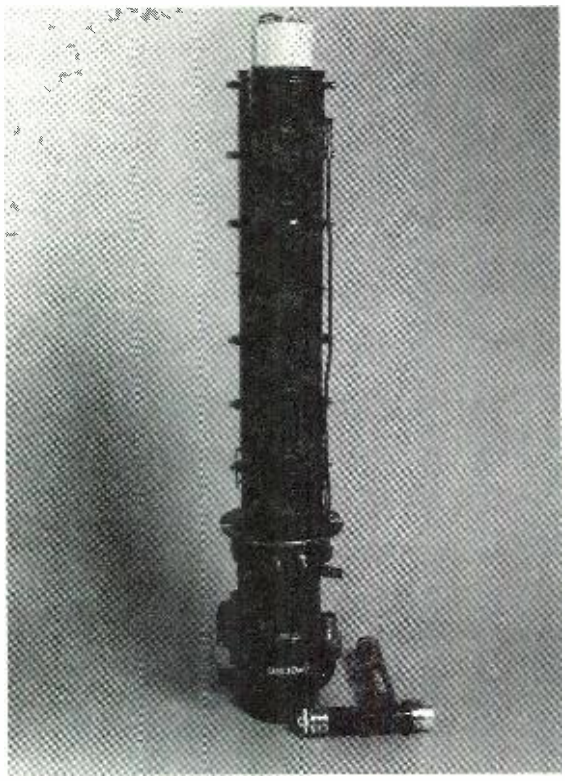


Fig. 33. Varian 110 kW VKP 7853 integral cavity klystron and output coupler.

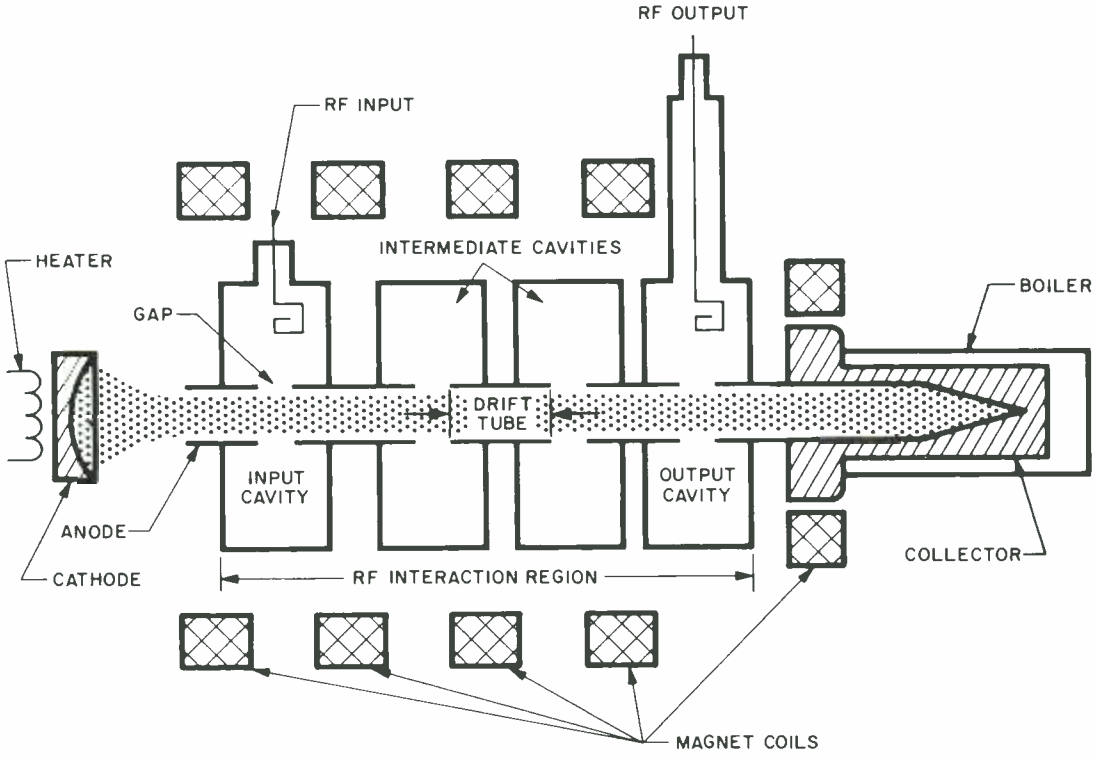


Fig. 32. Principal elements of a klystron.

Since electrons approach the input-cavity gap with equal velocities and emerge with different velocities, which are a function of the microwave signal, the electron beam is said to be *velocity modulated*. As the electrons travel down the drift tube, bunching develops, and thus the density of electrons passing a given point varies cyclically with time.

The RF energy produced by this interaction with the beam is extracted from the beam and fed into a coaxial or waveguide transmission line by means of a coupling loop in the output cavity. The dc beam input power not converted to RF energy is dissipated in the collector.

The cavities can be included in the vacuum envelope as shown in Fig. 33 or can be mounted external to the klystron as shown in Fig. 34.

All cathodes have optimum ranges of operating temperature. The operating temperature of the cathode must be high enough to prevent variations in the heater power from affecting the electron emission current (beam current) in the klystron. However, the temperature of the emitting surface must not be higher than necessary, since excessive temperature can shorten emission life. In Fig. 35, Ef_2 refers to filament voltage and Eb is the beam voltage.

Perveance and the Mod Anode

Perveance is a function of the geometry of the cathode-anode structure. The modulating anode voltage controls beam current which can be calculated using the following equation:

$$I_b = K E^{3/2}$$

K = Perveance constant of the klystron
I_b = Beam current amperes
E = Beam voltage

Fig. 36 shows the relationship between beam current and voltage described in the above equation. Two examples for using the graph are given. In example A, if a modulating anode of 4000 volts with respect to the cathode beam voltage produces a beam current of 0.6 amperes, the in-

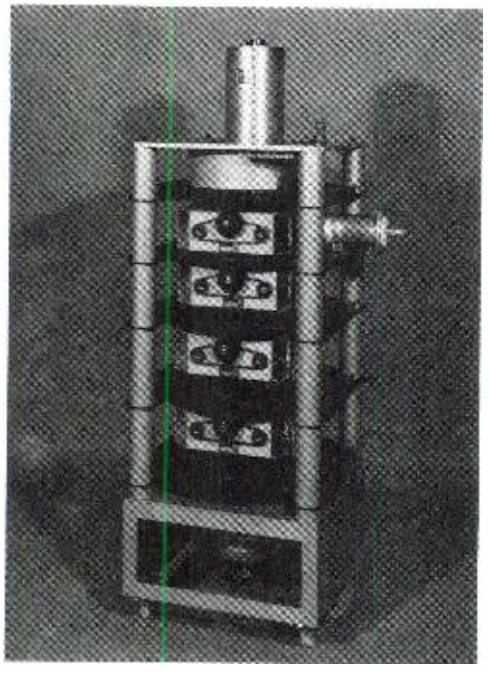


Fig. 34. EEV 58 kW K4251 external cavity klystron assembly.

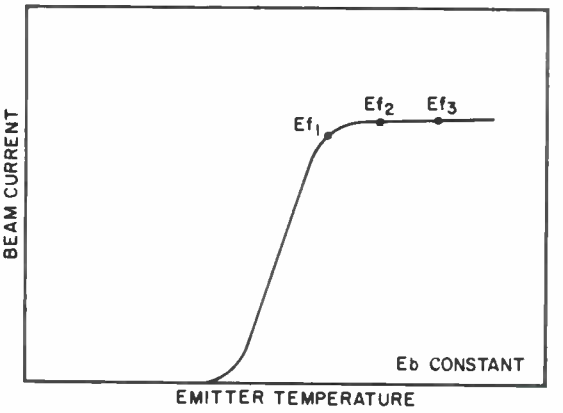


Fig. 35. Beam current variation with emitter temperature.

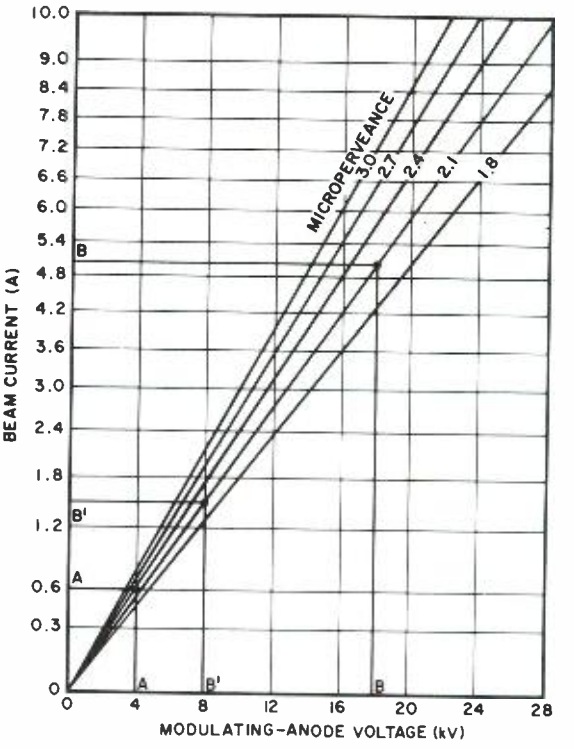


Fig. 36. Beam current variation with modulating-anode voltage.

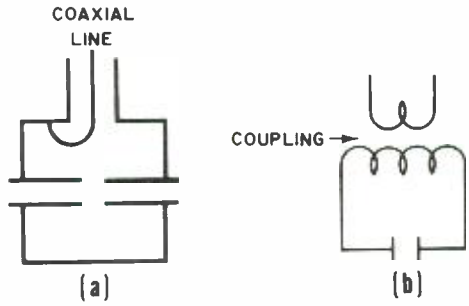


Fig. 37. Loop coupling and equivalent circuit.

tersection point lies on the 2.4 microperveance line, and the perveance is expressed as $2.4 \times 10^{-6} A/V^{3/2}$, or 2.4 micropervs. Operating condition B illustrates a rather practical television transmitter situation in which a common beam supply of 18 kilovolts is used to power both the visual and aural klystrons. At 18 kV, the visual tube operates at a beam current of approximately 5.0 amperes if the modulating anode is connected (through an isolating resistance) to the body of the tube, and the perveance is $2.1 \times 10^{-6} A/V^{3/2}$, or 2.1 micropervs. Since the aural output power required is much less, the dc input power can be reduced from that required to operate the visual tube. Points B′ indicate that if the modulating anode is supplied with only 8 kV (through a voltage divider) then the intersection with the 2.1 microperv line yields a beam current of only 1.5 amperes, thus accomplishing the necessary reduction of input power for aural service.

Magnetic Field

Electromagnetic coils are placed around the klystron to develop a magnetic field along the axis of the RF circuit which controls the size of the electron beam and keeps it aligned with the drift tubes.

Cavity Tuning

The resonant frequency of each of the cavities of a klystron can be adjusted to the operating frequency of the transmitter. This can be done in two ways:

- The inductance can be changed by changing the volume of the cavity. (External cavities)
- The capacitance of the drift-tube gaps can be changed. (Integral cavities)

Cavity/Transmission Line Coupling

Fig. 37 illustrates magnetic-loop coupling, where the RF energy is fed through a coaxial line with its center conductor inserted into the klystron cavity. The end of the center conductor is formed into a loop. This forms a simple one-turn transformer which couples RF energy into or out of the cavity through a coaxial transmission line.

Effect of RF Drive Power on RF Output Power

Fig. 38 shows RF output power as a function of RF drive power applied to the tube. From this curve, we see that when the RF drive power level is low, the RF output power is low. As the level of RF drive power increases, RF output power increases until an optimum point is reached. Beyond this point, further increases in RF drive power result in less RF output power. Because of these effects, two zones and one point have been labeled on the curve. In the zone labeled "Underdriven", RF output power increases when the RF input power is increased. The point labeled "Optimum" represents the maximum RF output power obtainable. Klystrons are said to be saturated at this point, since any further increase in RF drive only decreases the RF output power. The zone formed at the right side of saturation is labeled "Overdriven". To obtain maximum RF output power from a klystron, sufficient RF drive power must be applied to the tube to reach the point of saturation on the curve. Operating at RF drive levels beyond the saturation point will only overdrive the klystron, decrease RF output power, and increase the amount of beam interception at the drift tubes (body current). In TV service, klystrons are *always* operated within the underdriven zone of Fig. 38 unless beam current pulsing is used, which will be discussed later.

Fig. 39 shows how RF output power changes with various levels of RF drive power applied to a klystron under different tuning conditions. The RF power at Point A represents the drive saturation point for a synchronously-tuned tube. Point B shows a new point of saturation that is reached

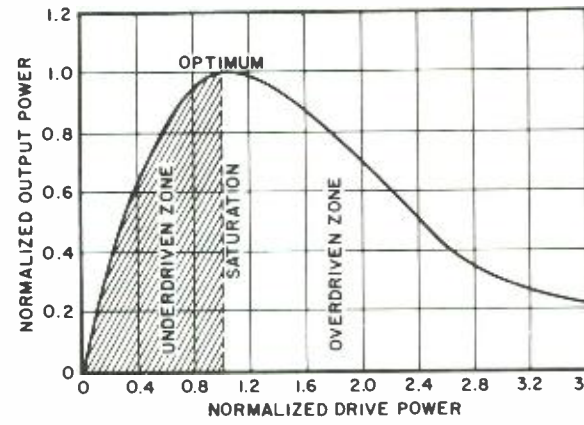


Fig. 38. RF output power as a function of RF drive power.

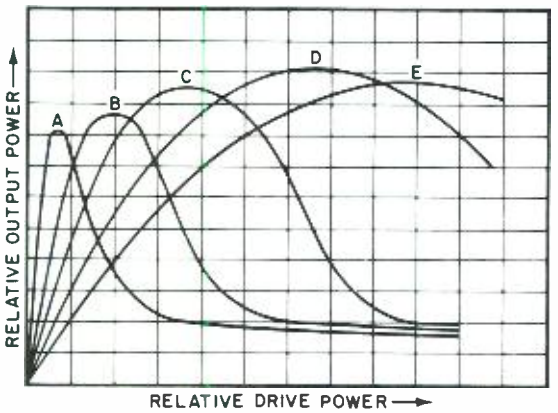


Fig. 39. Output power variation with drive power under different tuning conditions.

by tuning the penultimate (next to the last) cavity to a somewhat higher frequency. By tuning the penultimate cavity still further, Point C is reached. There is a point, Point D, where increasing the penultimate cavity frequency no longer increases RF output power; instead, it reduces the output power, Curve E.

Power Calibration

At UHF frequencies power is best measured by the calorimetric method. Dummy load water flow, input and output temperature can be accurately measured. Average power is then calculated:

P_{ave} = .264 × ΔT × GPM

ΔT = Change in water temperature from input to output of load in degrees C.

GPM = Gallons per minute of water flow through the load.

NOTE: For systems using special coolants other than pure water, an appropriate correction factor must be used.

Klystron Efficiency

Peak efficiency is calculated as follows:

dc input =

average beam current × beam voltage

Peak efficiency =

$$\frac{RF \text{ power out (peak of sync for visual)}}{dc \text{ input}}$$

This is a measure of the klystron stage only. Total transmitter or plant efficiency would include the power consumed by the magnets heat exchanger blower, pumps, and control circuits.

Some typical efficiencies are illustrated in Fig. 40.

For NTSC visual service with video set at blanking (no setup), 75% modulation, the peak power equals 1.68 × average power, or P_{ave} = .595 × Peak.

Proper measurement of sync to blanking ratio is essential to establish an accurate calibration of power. *Note:* Attempting to operate a klystron at more than its rated power by only a few percent can result in a number of difficulties (ie. sync type oscillation, nonlinearity, etc.) as well as wasting electrical energy.

Tuning

There are a number of methods of tuning klystrons. They are:

- Synchronous tuning for maximum gain.
- High efficiency tuning for aural services.
- Broadband aural for stereo service.
- Visual service with fixed beam current.
- Visual service with pulsed mod anode voltage.
- High efficiency visual tuning for integral cavity klystrons employing the variable visual coupler.

It is best to consult the transmitter manufacturer for specific data regarding tuning with the accessories and mode of operation required.

External Cavity Klystron Tuning Considerations

Some additional adjustments are provided on external cavity klystrons. The input coupling loop is adjusted for minimum reflected power. Individual cavities may be externally loaded to lower Q and increase bandwidth.

Magnet coils for each cavity are sometimes controlled separately to optimize performance and minimize body current.

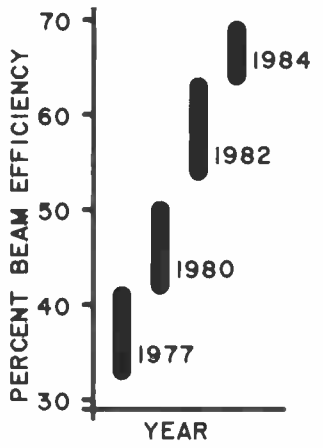


Fig. 40. Improvements of efficiency in UHF TV transmitters.

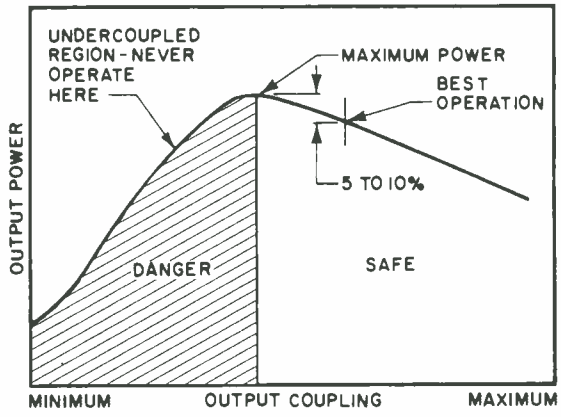


Fig. 41. Adjustment of output coupling control.

It is essential to operate with the output cavity slightly over coupled. Fig. 41 shows the relationship of output power to proper coupling loop adjustment.

Fig. 42 shows a typical response and cavity placement of an external cavity klystron tuned for visual service.

Mod Anode Pulsing

For a number of years klystrons were operated at maximum beam current. The mod anode was tied to ground through a resistor. Early model klystrons would draw approximately, 7.5 amps at 24 kV for 55 kW peak of sync visual operation. The development of more efficient klystrons allowed the biasing down of beam currents to near 6.3 amps for 55 kW. With saturation set at 115% of needed power, the klystron was operated in the more linear part of the curve, but still a lot of excess beam current was being consumed.

Operating the klystron at saturation will improve efficiency, but requires more linearity and phase compensation. By using a mod anode pulser to switch to a higher beam current during sync and back to a lesser current during video the average beam current is reduced. Refer to Fig. 43 block diagram of pulser.

Fig. 44 shows the horizontal line timing, modulation, and power output. Observe that sync is 8% of the duty cycle and line video is the remaining 92% of the transmitter signal.

Klystrons are high gain devices. In some applications as little as one watt is all that is required to drive a five-cavity klystron to 55 kW, a gain of 47 dB. Tuning for high efficiency and mod anode pulsing can reduce this gain by 13 dB or require 20 watts of drive.

Consider the following example of a typical 55 kW integral tube.

In static operation the tube is supplied with enough beam current to saturate at 115% power.

In pulsed operation only enough beam is supplied to saturate at 100% power during sync. The lower tip of burst causes 87.5% AM modulation.

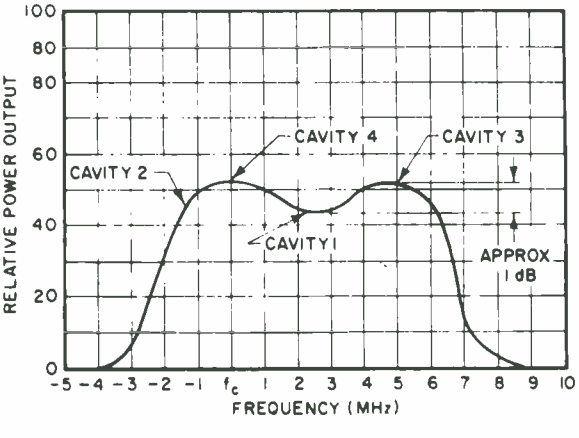


Fig. 42. Normal 4-cavity klystron tuning.

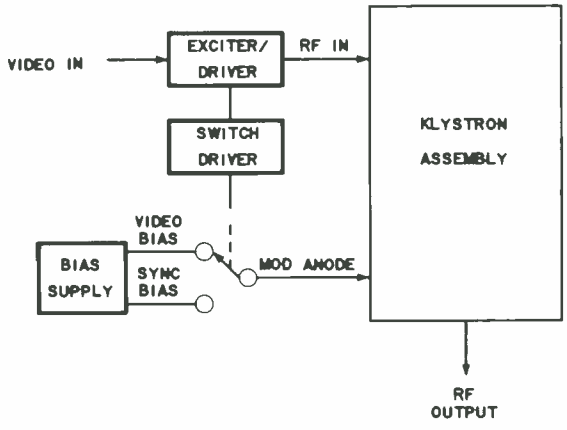


Fig. 43. Pulser block diagram.

Removing the lower sideband as in the case with vestigial filtering, the tip of burst represents 81.25% modulation. In order to prevent severe burst and back porch distortion approximately 6% modulation headroom is maintained. In other words the theoretical minimum beam current is increased to a practical level of about 87% corresponding to 76.6% of sync peak power. Refer to Fig. 45.

For Static Operation, Beam I is fixed with 24 kV 6.2A.

$$\text{dc Input} = 24 \times 6.2 = 148.8 \text{ kW}$$

$$\text{Peak Efficiency} = \frac{55}{148.8} = 37\%$$

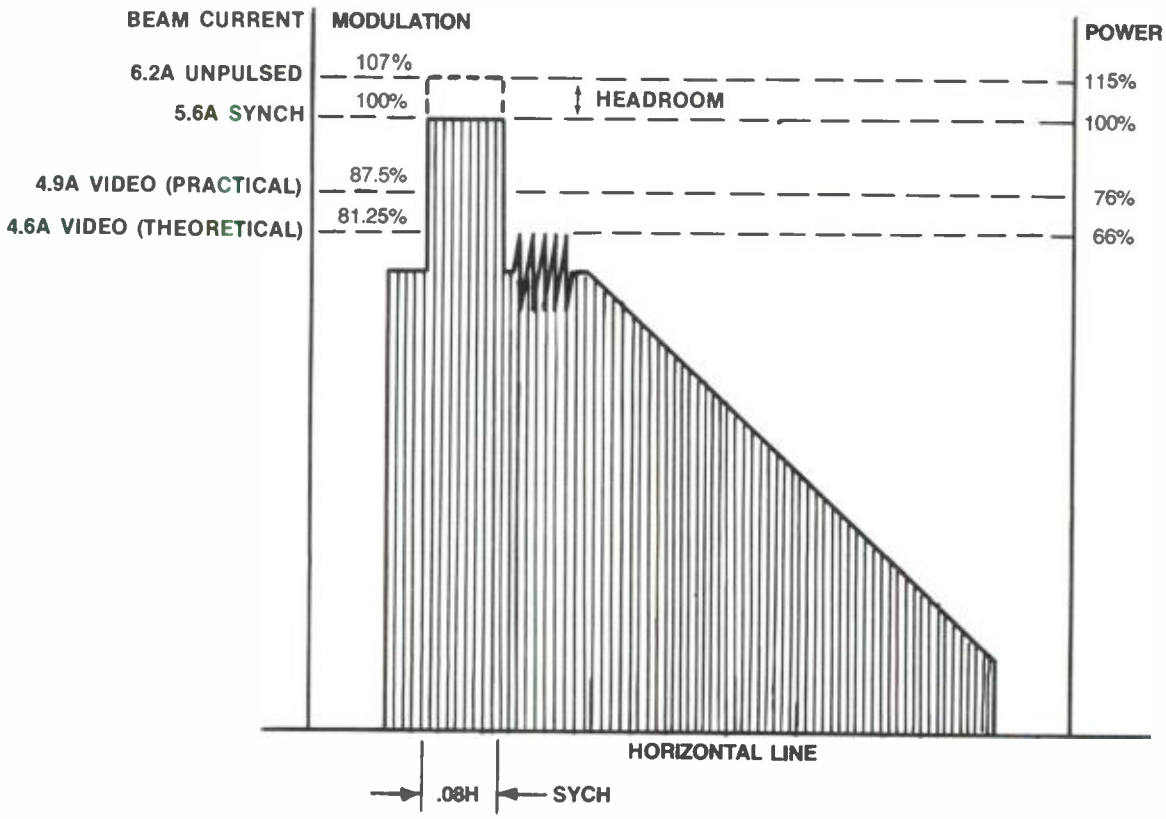


Fig. 44. RF envelope vs. beam current and power output.

For Pulsed Operation, DC Input is calculated as follows:

$$\text{DC Input} = \text{Beam Voltage} \times ((\text{Beam } I_{sync} \times \text{duty cycle}) + (\text{Beam } I_{video} \times \text{duty cycle})) = 24\ ((5.6 \times .08) + (4.9 \times .92)) = 24 \times 4.95 = 119 \text{ kW}$$

$$\text{Peak Efficiency} = \frac{55}{119} = 46\%$$

Both external and integral cavity klystrons have been successfully pulsed.

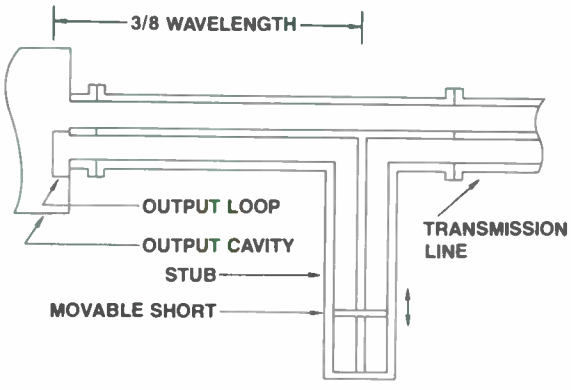


Fig. 45. Construction of Varian variable visual coupler.

Pulsing

During sync the klystron is operated at saturation which along with the change in beam current causes additional phase shift of the signal.

A phase modulation stage in the IF of the exciter is keyed by sync and adjusted to precorrect for incidental phase distortions caused in the klystron during pulsing.

Video signals are operating very close to saturation at burst and an additional range of differential gain and differential phase correction may be needed.

Modern exciters can fully precorrect these conditions. Refer to Figs. 48 and 49.

The practical limit of reduction of the video beam current is the point at which tip of burst

and back porch modulation begins to be suppressed.

Variable Coupler for Integral Cavity Tubes

The variable load coupler has a shorted transmission line stub which is tuned beyond a quarter wavelength to present a capacitive susceptance load to the output transmission line. This capacitance plus the transmitter load reflects back through an approximate 3/8 wavelength to present a substantially resistive load to the output coupling loop of the final klystron cavity.

The tuning procedure calls for the shorted stub to be pulled out by a quarter turn. This presents a higher impedance to the output cavity and raises the cavity Q. The new saturated power is then found by varying the drive power while observing power output on the transmitter power meter and the detected output waveform from an envelope detector. If saturated power increases, the procedure is repeated.

Even though the visual coupler presents substantially a resistive load to the output cavity, Q changes and slight reactance effects require that passband response be slightly retuned every few steps.

This incremental procedure is repeated until the beam efficiency decreases or until a tendency for sync tip oscillations from return beam electrons is observed.

Sync pulse oscillations appear as ringing on the sync pulse and are believed to be caused by secondary electron feedback enhanced by the reverse gain of the klystron cavities.

The S Klystron in Visual

The VKP-7550S "S" klystrons attain 52 to 54% beam efficiency under CW or unpulsed TV conditions. The S klystron can be sync pulsed to produce 63 to 69% beam efficiency in a TV transmitter.

Achieving high efficiency with the VKP-7550S series klystrons requires up to 50 watts of linear drive power, large amplitude linearity correction and high levels of modulating anode pulsing.

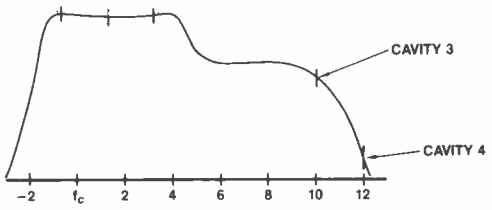
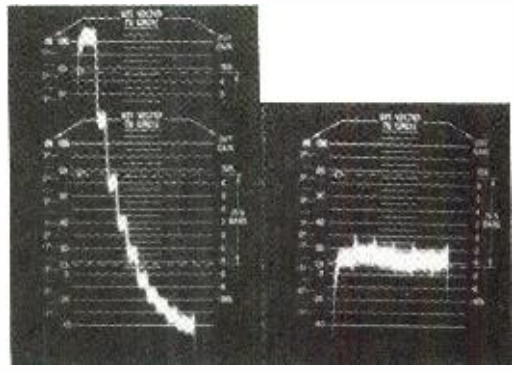


Fig. 46. High efficiency tuning of a 5-cavity Varian S series klystron.

Fig. 46 shows typical response and cavity placement of a five-cavity, Varian S series 60 kW klystron tuned for high efficiency. Figs. 47, 48, and 49 are actual visual performance waveforms showing large exciter precorrections necessary to achieve transparent output characteristics while achieving high efficiency.

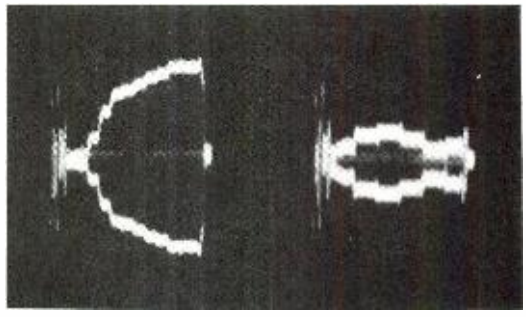
DIFFERENTIAL GAIN AT 70% EFFICIENCY, 60.6 kW



PRE-CORRECTED OUTPUT SIGNAL

Fig. 47. Differential gain at 69% efficiency, 60 kW.

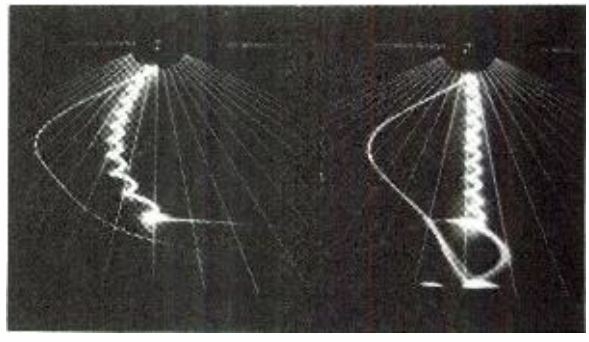
DIFFERENTIAL PHASE AT 70% EFFICIENCY, 60.6 kW



PRE-CORRECTED OUTPUT SIGNAL

Fig. 48. Differential phase at 69% efficiency, 60 kW.

INCIDENTAL PHASE AT 70% EFFICIENCY, 60.6 kW



PRE-CORRECTED OUTPUT SIGNAL

Fig. 49. Incidental phase at 69% efficiency, 60 kW.

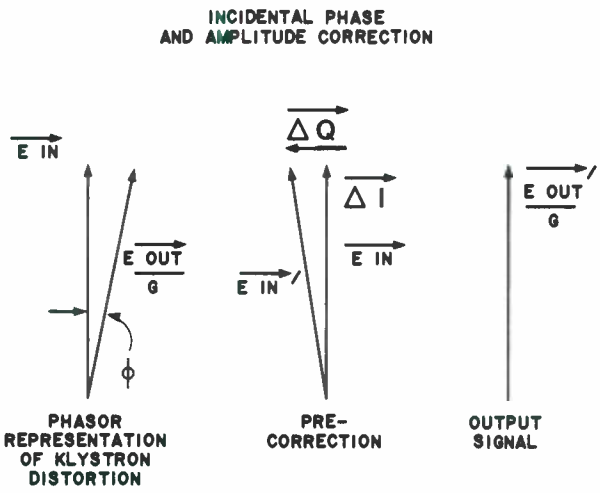


Fig. 50. Incidental phase and amplitude correction.

Tuning is as follows:

1st cavity	at	−1 MHz,
2nd cavity	at	+2 MHz,
3rd cavity	at	+10 MHz,
4th cavity	at	+12 MHz, and
5th cavity	at	visual carrier.

Precorrected Signal driving klystron shows 36% differential gain. Output Signal shows 3% differential gain. Vertical scale is 2%/div.

Precorrected signal driving klystron shows 13.5° differential phase. Output signal shows 1.5% differential phase. Vertical scale is 1°/div.

Precorrected signal driving klystron shows −6° over video and +20° at sync.

Output signal shows +2° incidental phase.

Incidental Phase and Linearity Correction

With increasing RF drive level, klystron amplifiers exhibit a phase change in addition to an amplitude compression. This phase change is called incidental phase modulation (ICPM). Very little can be done to reduce ICPM by klystron tuning, selection of magnet current, etc. Unfortunately, incidental phase distortion increases rapidly near saturation of the klystron. For maximum efficiency, one must operate the tube at saturation at sync tip. In a pulsed transmitter, the color burst and black picture content are near saturation as well.

To combat this problem, ICPM correctors have been developed. These correctors generally operate at the exciter intermediate frequency and introduce a correction equal and opposite to the distortion produced by the klystron.

Fig. 50 illustrates first order klystron nonlinearities and the operation of the quadrature and linearity correctors. The desired TV signal is represented by an instantaneous phasor diagram as E_{in}. The output of the transmitter would ideally be an amplified version of E_{in}.

An instantaneous phasor diagram illustrates how first order klystron non-linearities are corrected by ΔQ, and an inphase linearity correction, ΔI.

However, the transmitter output E_{out} (divided by the nominal RF gain G is phase shifted by a phase error ϕ and compressed in amplitude. The signal in the exciter is precorrected to E_{in} by an amplitude expansion ΔI and a correction in quadrature ΔQ. When the resultant signal E_{in} is amplified, the output signal E_{out} will be replica of the desired TV signal.

TRIODES, TETRODES, AND TELEVISION TRANSMITTERS

Triodes and tetrodes are used in the RF power stages of television transmitters. High power levels for VHF television transmitters are usually obtained by a single ended vacuum tube.

Much written material about the vacuum tube is still available but most of it emphasizes receiving tube theory. This section will highlight some of the facts on high power gridded transmitter tubes. The parts of the power tube will be reviewed.

General

A vacuum tube uses its grids to control the flow of current through the tube. The Cathode emits the electrons which travel to the plate. The plate is more positive than the cathode. The grids control this flow of electrons, thereby controlling the plate current. They also modulate the electron stream causing the plate current to have the same waveform, depending on class of operation, as the grid voltage.

A Triode is a three element tube consisting of the following:

- A heated cathode which emits electrons.
- A control grid which modulats the electron stream in accordance with the dc and ac voltages impresssd between the control grid and cathode.
- A plate which accepts the electron stream. The plate is positive with respect to the cathode.
- Input signals, dc and ac are applied between control grid and cathode.
- Output signals, dc and ac flow to the tube output load impedance by way of the plate and cathode.

A tetrode is a four element tube which has a screen grid added between the control grid and plates.

- The screen grid acts as an electrostatic shield which helps to isolate the plate output signal from the control grid input signal.
- The screen grid is operated at a positive dc potential with respect to the cathode. This potential is much lower than the dc plate voltage.
- The screen grid is usually operated at ac (RF) ground potential.
- The tetrode has higher gain than the triode.
- The plate voltage has minimum effect on the plate current as long as the instantaneous plate voltage is greater than the screen grid dc voltage.
  1. The plate voltage is normally allowed to swing close to but not below the value of dc screen grid voltage.
- If the tetrode screen grid is not maintained at ac (RF) ground potential the tube can take on the characteristics of a triode.

The tetrode input bias and signal are applied between the control grid and cathode and are similar in performance to the triode.

The dc plate current flows from cathode to plate.

The output ac (RF) signal current path in the tetrode is *from the plate, through the load impedance, and returns through the screen grid.*

The Cathode

A power grid tube will have high peak and average current levels. Therefore, the cathode must emit many electrons. It must be hot and requires large heater power with low voltage and high currents. DC current is often used to reduce ac noise levels.

It is usually directly heated to provide quicker warm up with lower heater power. It will requires some type of cooling to remove excess cathode heat from the tube filament/cathode contacts and the tube socket.

The Grids

The voltages (dc, ac, and RF) of all grids are measured with respect to the cathode.

The grids can have current which are positive when the grid accepts electrons from the electron stream or negative when the grid emits electrons.

Grids can emit electrons and have negative grid current because they are located close to the white hot cathode. The grids are very hot and can have small amounts of thermionic emission (primary emission) or electrons emitted by being bumped off by other electrons (secondary emission).

As the tubes age, some of the cathode electron emitting coating may be deposited on the relatively cooler grids thereby increasing their tendency to emit electrons.

The control grid has a negative dc bias and an ac signal which drives the grid positive.

The instantaneous grid current can be negative when the grid is swinging maximum negative, zero when the grid is only slightly negative, or positive when the grid is positive.

The screen grid has a positive dc bias and is at ac ground potential. The instantaneous screen grid current is negative when the plate voltage swings maximum positive, positive when the plate voltage swings close to or below the screen grid dc voltage, and zero when the plate voltage is between these extremes.

Both grids have instantaneous positive, zero, or negative currents that follow the voltage swing. The average of these currents is the dc grid current.

Since both dc voltage and current are present in both grids, the grids can dissipate power. The control grid also has ac (RF) voltages and currents present so that ac power dissipation in grids must be observed.

The dc plate power, E_b and I_b, that is applied to the tube is either converted to ac (RF) output power or dissipated as heat. This heat is developed in the plate and must be removed by air or water cooling.

Below 30 MHz, RF amplifiers use lumped components to resonate the tube input and outputs. At VHF and UHF frequencies several problems make the use of lumped components impractical.

The Transmission Line Cavity

As frequency increases, lumped component resonant circuits get smaller and smaller to reduce L and C, larger in diameter to reduce skin effect, closer to the tube to reduce the effects of stray L, and there is great difficulty in predicting exactly what values of R, L, and C a component or circuit may have.

These problems can be managed in low-power circuits but with high power circuits arcs and shorts due to high dc and RF voltages become a problem. Larger size and spacing of components is a good start towards arc and short prevention, but this is in opposition to the smaller size and spacing dictated by the high frequency operation. Also in high power circuits, the unpredictability of the circuit values of R, L, and C make it difficult to control the vitally important parameters of dissipation, efficiency, and reliability of operation.

One solution to the above problems is the resonant transmission line cavity amplifier. In this type of amplifier the tube becomes part of a resonant transmission line. The elements of these tubes are arranged to look like concentric coax-

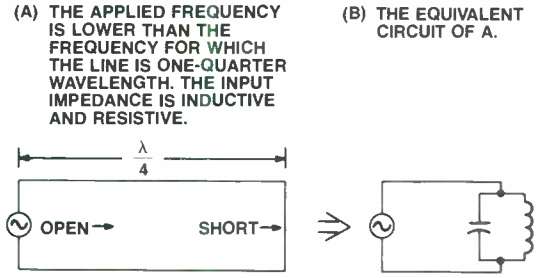


Fig. 51 Shorted quarter wavelength line.

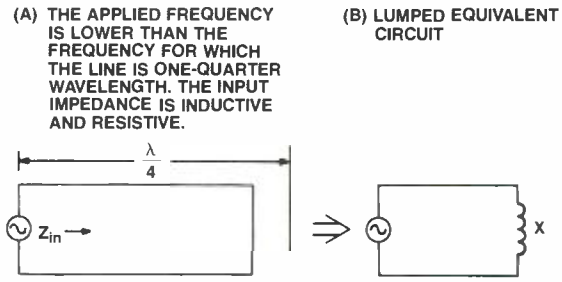


Fig. 52. Shorted line less than one-quarter wavelength.

ial transmission lines. The design of these tubes stresses low interelectrode capacity and low-distributed inductance. The stray interelectrode and distributed capacity and inductance of the tube becomes part of the resonant transmission line. The resonant transmission line is physically larger than the equivalent lumped constant $L-C$ resonant circuit operating in the same frequency. This larger physical size aids in solving the high power operation problems of skin effect losses, prevention of arcs and shorts, and reliable and predictable operation. A commonly used transmission line cavity amplifier uses a quarter wavelength transmission line as its resonant element.

The Shortened Quarter Wavelength Line

A shorted quarter wavelength transmission line has a high (almost open), purely resistive input impedance. Electrically it looks like a parallel resonant circuit (refer to Fig. 51). If the applied frequency is changed slightly so that the shorted line is no longer one quarter wavelength long, the input impedance drops and no longer remains purely resistive.

The Shortened Transmission Line less than a Quarter Wavelength Long

When operated at a frequency below that for which the shorted line is one quarter wavelength long, the physical length of the line at the new lower frequency will be less than one quarter wavelength. The impedance will be lower and the line will look inductive. Refer to Fig. 52.

The Shortened Quarter Wavelength Cavity

In Fig. 53, shorted transmission lines are used to resonate the inputs and outputs of this amplifier. Notice that the length of the lines are less than a quarter wave length but the tubes shunt input and output capacity and its series lead inductance will electrically lengthen and resonate the transmission lines. The input is shown inductively coupled, but it could just as easily have been capacitively coupled to the cathode. The input could also have a lumped constant resonant circuit or a transmission line resonant circuit since its power level is low. The output coupling is capacitive, but it also could have been inductive.

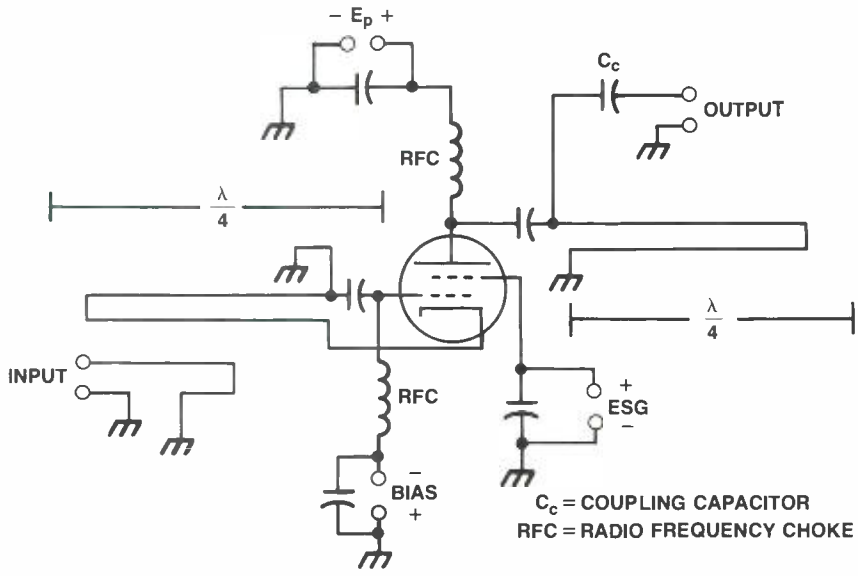


Fig. 53. A shorted quarter wavelength transmission line amplifier.

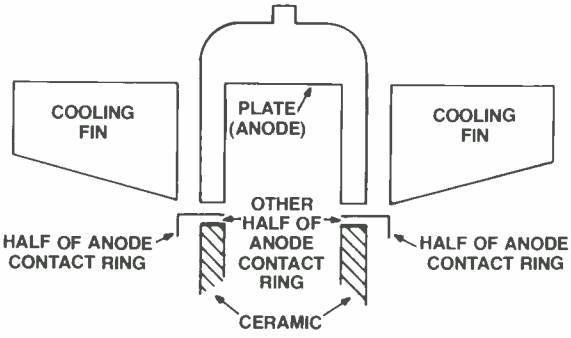


Fig. 54. Cutaway view of the anode structure.

The construction of the tube lends itself to transmission line tuning techniques.

Coaxial Line Feature of a Tetrode RF Power Amplifier Tube

The Anode (Plate)

The plate resembles a copper cup with the plate contact ring welded to the mouth and the cooling fins silver soldered or welded to the outside of the cup (refer to Fig. 54 and Fig. 55).

The contact ring is bonded to the base ceramic spacer through a strain isolation ring. This ceramic spacer is the same ceramic that is shown above the screen contact ring in Fig. 56.

The Screen Structure

The screen grid consists of many vertical supports fastened to a metal base cone. The other end of the metal base cone fastens to the screen contact ring. The inductance of the individual vertical supports is reduced by building the screen grid of many of them in parallel. The vertical supports are held rigid by horizontal rings welded to them and a metal cap on the top of the assembly. The screen contact ring, metal base, and metal base cone also functions to reduce lead inductance and RF resistance due to skin effect (refer to Fig. 56).

A cutaway view of the plate circuit and the screen circuit in Fig. 57 shows a concentric construction that resembles a coaxial transmission line.

Consider that the output RF current is generated by an imaginary current generator between the plate and screen grid. The RF current travels along the inside of the plate structure on its surface (skin effect), through the ceramic at the bottom of the anode contact ring, around the anode contact ring, across the bottom of the fins, and to the band around the outside of the fins. From here it flows through the plate bypass capacitor to the RF tuned circuit and load, and returns to the screen grid. The return current travels through

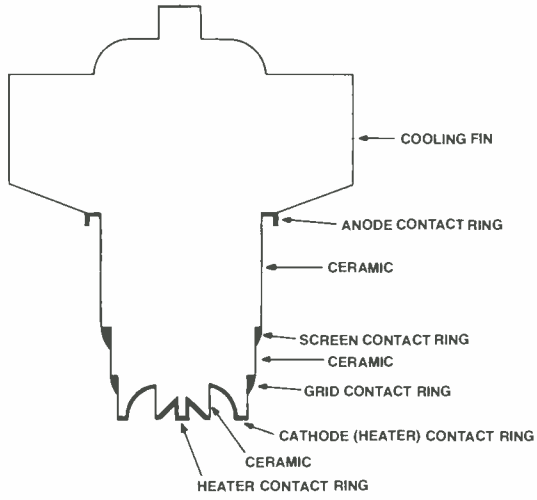


Fig. 55. Cutaway view of the exterior of a RF tetrode.

screen contact ring, up the cone, and up the the screen bypass capacitor, then through the screen grid to return to the imaginary generator. The screen grid has RF current returning to it but due to its low impedance, the screen grid is at RF ground potential. The RF current generator appears to be feeding an open ended transmission line consisting of the anode (plate) assembly, and the screen assembly. The RF voltage developed by the anode is due to the plate impedance (Zp) presented to the anode by the resonant circuit and its load.

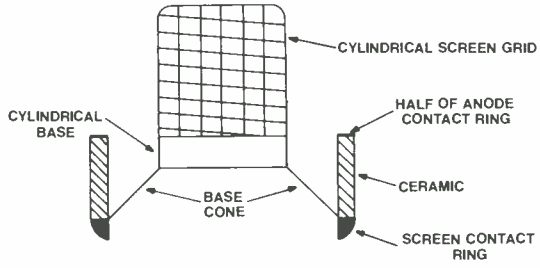


Fig. 56. The screen grid assembly.

The control grid assembly and the cathode assembly are also cylindrically constructed and concentric. The control grid assembly is constructed similarly to the screen grid and is slightly smaller than it. Fig. 58 shows the screen grid, control grid, and the cathode assemblies as they are placed in the tube.

Fig. 58 also shows the current path of an RF generator feeding a signal into the grid/cathode assembly resembles a transmission line terminated by the RF resistance of the tube's electron stream. The outer contact ring for the cathode heater is the inner conductor of this transmission line.

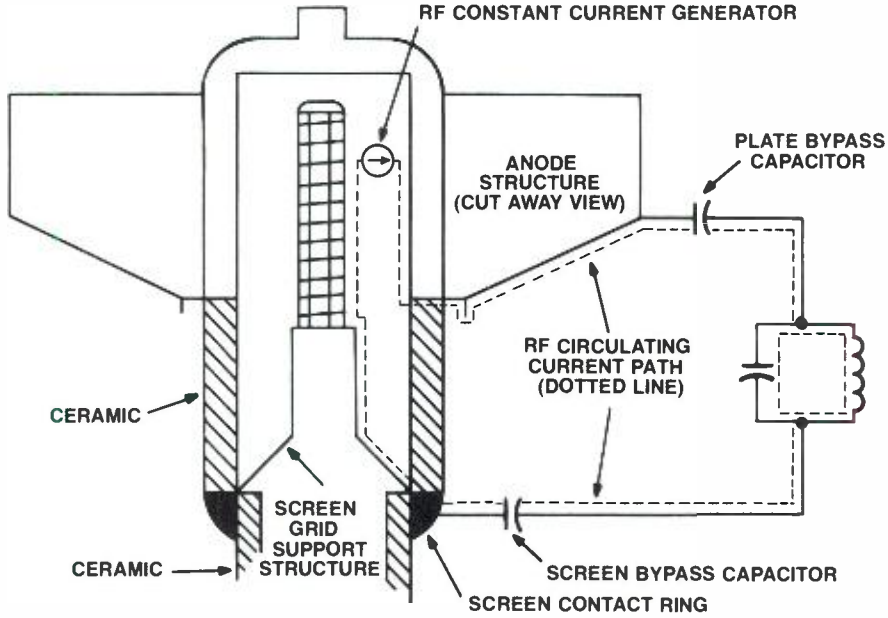


Fig. 57. Showing the plate and screen assembly and RF circulating current path (dotted line).

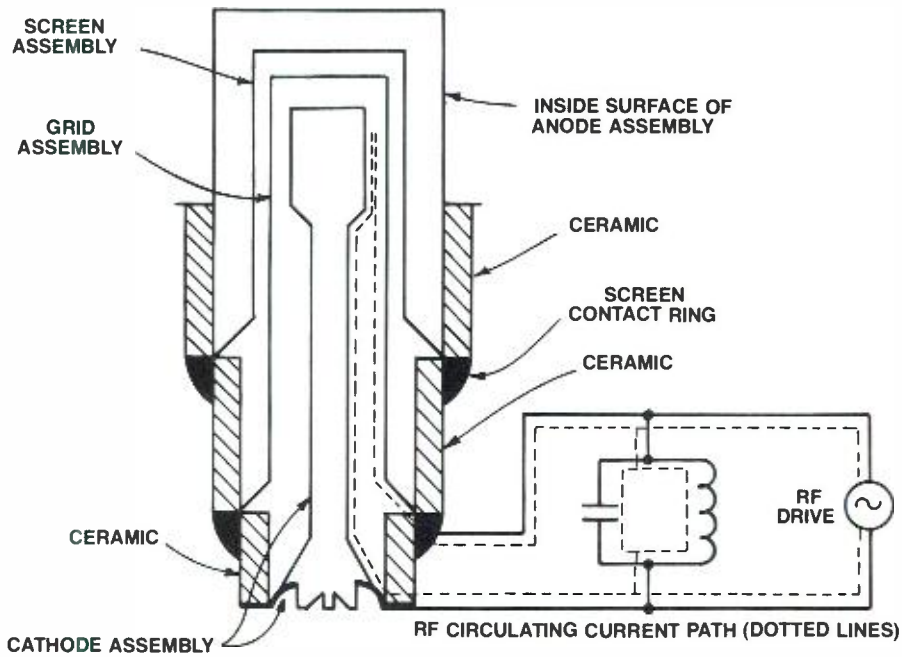


Fig. 58. Showing details of assembly of grids and cathode components and the simplified RF input circuit (bias circuit not shown).

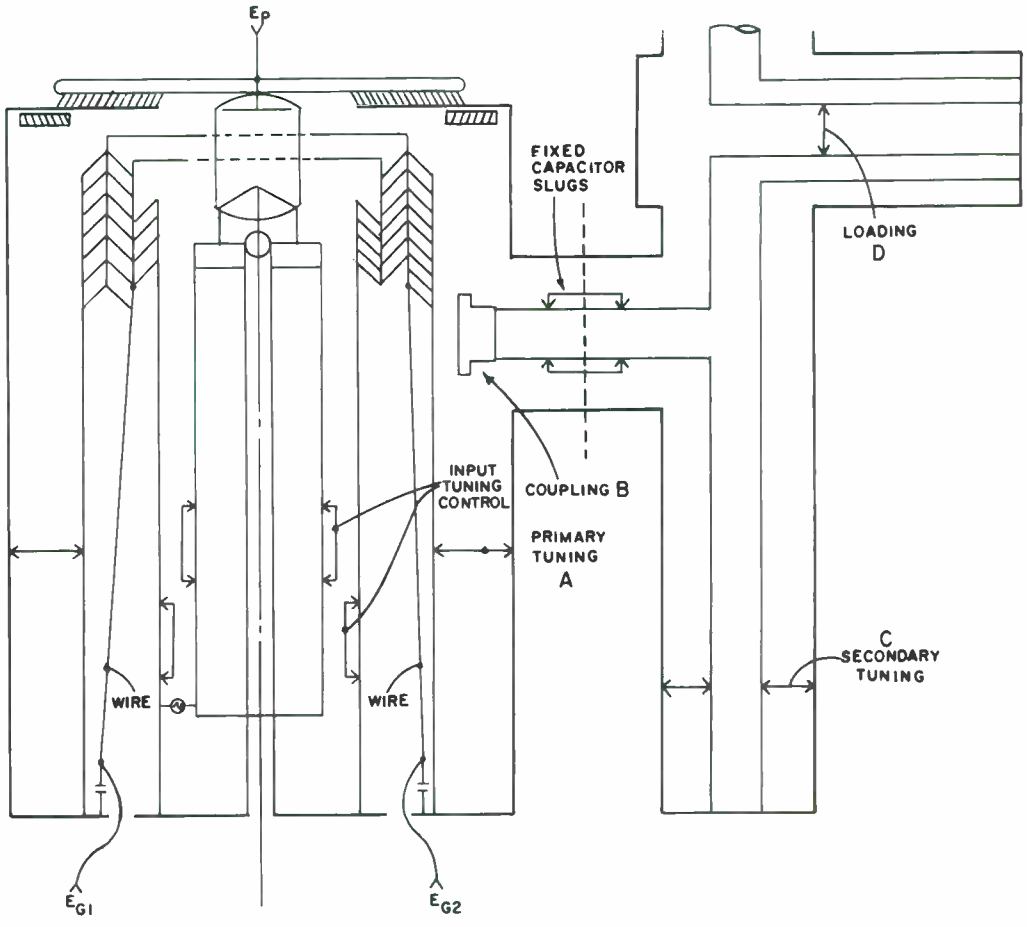


Fig. 59. High band coaxial transmission line cavity amplifier for TV use.

Double-Tuned Tube-Type Power Amplifiers Used in TV Transmitter Applications

State-of-the-art VHF television RF power amplifiers use tetrode tubes because of their high gain, good linearity, good efficiency, and high power advantages. A double-tuned output circuit is used to achieve proper bandwidth and efficiency.

As an example, the double-tuned overcoupled amplifier shown in Fig. 60 should not be thought of as an amplifier and a socket into which a tube is placed. The tube is an integral part of the cavity. The internal electrical properties of the tube will determine the amplifier gain and power han-

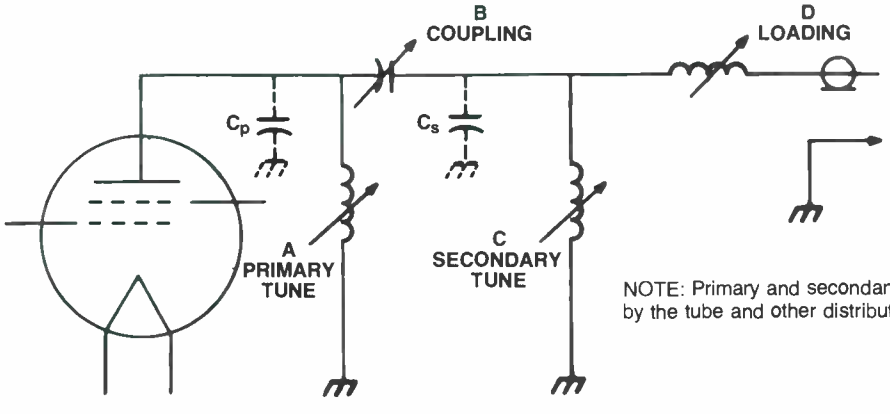
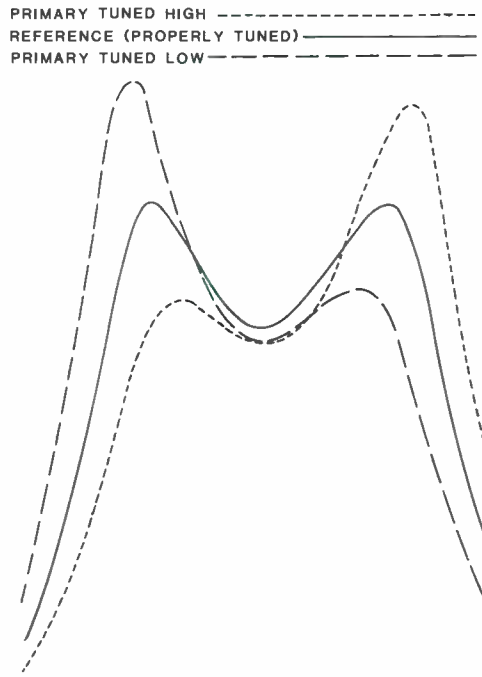


Fig. 60. Double-tuned power amplifier.



NOTE: As the primary tuning is rocked the response tilts and shifts.

Fig. 61. Primary tuning.

dling capabilities. It will also dictate the dimensions and functions of the circuitry.

All double-tuned overcoupled visual power amplifiers have four controls to accomplish output tuning.

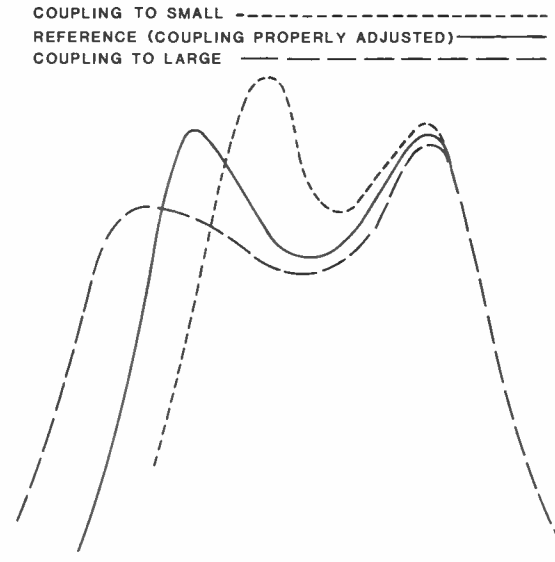
Effects of Tuning an Overcoupled P.A.

Plate Tune (Primary tune): Resonates the plate circuit and tends to tilt the response and slide it up and down the bandpass (refer to *A* on Fig. 60, also Fig. 61 and Fig. 59).

Coupling: Sets the bandwidth of the PA. Increased coupling increases bandwidth and lowers the PA efficiency. When the coupling is adjusted, it can tilt the response and change the center of the bandpass necessitating the readjustment of the plate tune control (refer to *B* on Fig. 60, also Fig. 62 and Fig. 59).

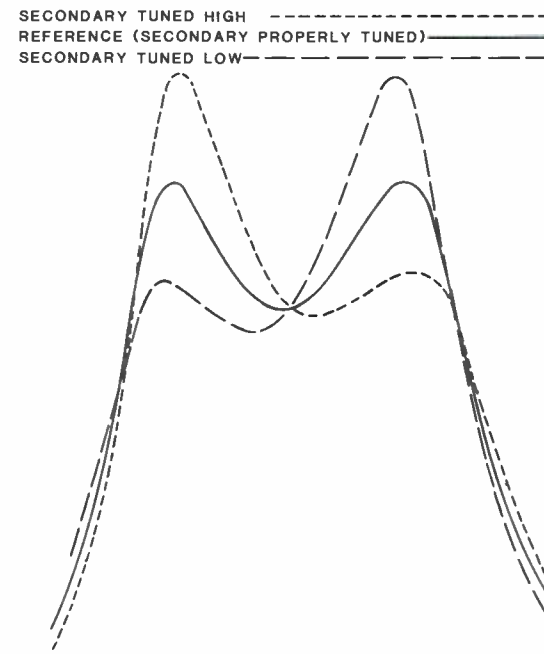
Secondary Tune: Resonates the secondary cavity and will tilt the response if adjusted. Generally it will not slide the response up and down the bandpass as will the primary tune (refer to *C* on Fig. 60, also Fig 63 and Fig. 59).

Loading (Secondary load or output load): This control determines the depth of saddle or value of ripple in the response. Heavier loading (maximum *C* or minimum *L*) creates a haystacked response and light loading creates excessive ripple. Adjustment of the loading control usually tilts the response and changes bandwidth. This necessitates readjustment of secondary tune and



NOTE: When coupling is adjusted, the upper end of the response remains constant and the upper end of the bandpass moves thus changing the bandwidth. Also the response is tilted and the center of the bandpass is shifted. This makes necessary the adjustment of the primary and secondary tuning to center and flatten the bandpass.

Fig. 62. Coupling plate loading.



NOTE: As secondary tuning is rocked, the response tilts, but it tilts in the opposite direction to the primary. Thus, the secondary and primary tuning can be changed together to shift the response up or down in frequency.

Fig. 63. Secondary tuning.

coupling. In some cavities, primary tune may also have to be readjusted. The coupling control will also effect the value of ripple, but its greatest effect will be on the amplifiers bandwidth (refer to *D* on Fig. 60, also Fig. 64 and Fig. 59).

NOTE: As loading is decreased, the amount of ripple is increased (greater depth of saddle) along with a tilt of response. The response tilt can be corrected by adjusting the secondary tuning. Likewise, as loading is increased, the value of ripple decreases. Again the response tilt is corrected by adjustment of secondary tuning.

When the loading control is changed and the response is corrected by the adjustment of coupling, secondary tune, and primary tune, the plate impedance of the amplifier is changed.

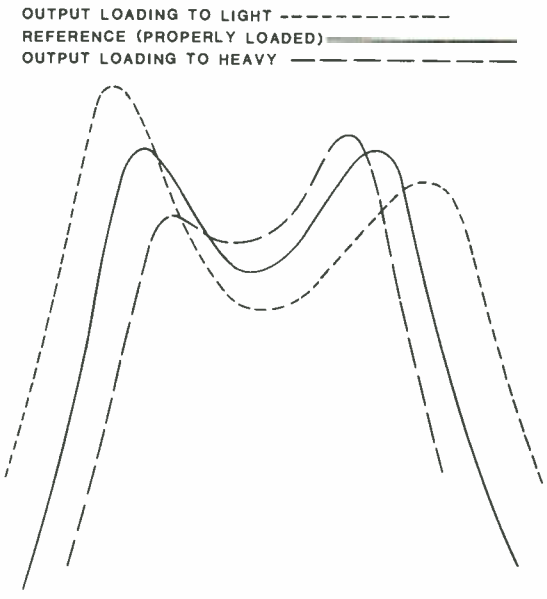


Fig. 64. Loading adjustments.

Heavy Loading	Smaller Ripple	Lower Plate Impedance	Higher I_p and Positive I_g Lower Gain	Lower Positive I_{sg}
Light Loading	Larger Ripple (Saddle) (Saddle)	Higher Plate Impedance	Lower Ip and Positive Ig Higher Gain	Higher Positive I_{sg}

Tuning for Power

Sweep the entire transmitter into the station load at 100% power. If tuning of any part or all of the transmitter is in doubt, check the following. Watch the response, reflected power (VSWR), I_p, I_{sg}, and I_g. If total response is not right, check each stage, starting at the exciter, to be sure each stage is flat and has the correct bandpass. The final amplifier should be the narrowest of all stages.

After the transmitter sweep is completed and the overall response has the proper bandwidth, transmit a black picture that is video set at blanking, 75% modulation, operate into the station load and check for the following:

1. Check for proper sync level at the transmitter output and adjust at the visual exciter linearity corrector as necessary.
2. Watch for excessive plate dissipation.
   Plate dissipation = $(E_p) \times (I_p)$ − (average rf power out)

   Where: E_p = dc Plate Voltage
   I_p = dc Plate Current
3. Check for excessive screen current. The screen current will increase rapidly at higher power if the PA is lightly loaded. Very light loading can cause sync compression.
4. Watch for excessive grid current if PA is loaded too heavy. It can cause sync compression.
5. Check the amplifiers output efficiency. It can also be a guide to proper operation of the stage. The efficiency at VHF typically will range from 41% to 45%. At UHF the range is somewhat lower.

$$\text{Efficiency} = \frac{P_o}{E_p I_p}$$

Where: P_o = Average RF output power

Solid line —Transmitter overall response
Dotted line—The part of PA response outside of the transmitters bandpass.

Fig. 65. Nonsymmetrical response caused by the amplifiers outside the transmitters bandpass. Solid line is transmitter overall response. Dotted line is the pat of PA response outside of the transmitters bandpass.

6. It is assumed that the RF output power is measured by an accurately calibrated rf wattmeter or by a calorimeter. If the wattmeter is not accurate, the amplifier dissipation and efficiency may be in doubt and the tube life will be shortened.

If the wattmeter reads low, 100% output power will be difficult to obtain. The amplifier might be trying to produce more than its full rated power. The symptoms would be high I_p, high dissipation, and sync compression. These are the same symptoms that improper tuning could yield.

If the wattmeter reads high, power will be easy to obtain and efficiency will appear high.

Plate dissipation might appear low and in reality be high. This will become apparent by a blackened anode.

A calorimeter is the most accurate way of measuring power but is not always practical. If the wattmeter is to be calibrated, send the thruline section, the slugs, and the meter (with the meter cable) together with information giving your frequency and power to the manufacturer for calibration.

The power measured on a calorimeter or on the wattmeter is average power. To find peak power use this formula:

$$\text{Peak Power} = \frac{\text{Average power}}{0.595}$$

If a large value of plate current is required to make power, it indicates that the plate voltage is not swinging very far.

The low plate voltage swing is also indicated by the low screen current. Remember that positive screen current flows only during the time that the plate voltage swings close to the screen voltage.

The low-swing of plate voltage along with the high swing of plate current indicates a low plate impedance (heavy loading).

$$Z_p = \frac{e_p \text{ (The swing of plate voltage)}}{i_p \text{ (The swing of plate current)}}$$

To make the amplifier more efficient and bring plate dissipation down, the plate impedance must be increased. To increase the plate impedance, the amplifier loading must be decreased. Complete the following corrections:

1. Sweep the transmitter and decrease the PA loading.
2. This will cause the response to tilt. Correct this tilt by adjusting the secondary tuning.
3. Decreasing the loading will also cause the bandwidth (and saddle) to increase. This can be counteracted by decreasing coupling.
4. Changing coupling will cause the response to tilt. This can be corrected by adjusting the primary and/or secondary tuning.

The above procedure may have caused the PA response to slide up or down out of the bandpass. It will show up as a nonsymmetrical bandpass (See Fig. 65). It can be corrected by adjusting both primary and secondary tune simultaneously to center the response.

5. The transmitters overall response will have the same bandpass but will have slightly more ripple. The ripple content in the transmitters overall response should still be within the ¼ to 1¼ dB limits.

CAUTION: When changing loading, coupling, and primary and secondary tuning, it is possible to get the PA bandwidth too wide. The excessive bandwidth of the PA will be masked by driver narrow response. This excessive bandwidth will cause PA overdissipa-

tion. Refer to Fig. 67. Correct bandwidth is shown in Fig. 66.

Once again transmit a black picture into the station load. Switch the Vestigial Sideband Filter and the linearity corrector in and check sync level at the transmitters output. I_p and I_g should be lower and I_{sg} should be higher. The amplifier efficiency should fall between 41% to 45%.

This is a general tuning procedure given to illustrate tuning methods, control interactions and tube operating characteristics. It will work well with most double-tuned overcoupled power amplifiers. For specific tuning information on a given transmitter the manufacturers instructions should be followed.

External Air Systems for Transmitter Sites

Most electronic equipment which requires forced air cooling has the required blower or fan already designed into it. However, with equipment such as transmitters dissipating relatively large amounts of power, the air which has already passed through the equipment and has picked up heat must be removed from the immediate vicinity of the equipment. In order to prevent the hot air from being recirculated and thus providing a hotter environment than that which the equipment was designed for. In addition to the air removal requirement, provisions must be made for sufficient makeup air to replace that which has been circulated through the equipment and removed.

If the equipment user is to provide adequately for hot air removal and fresh air makeup, the following information from the equipment manufacturer must be known:

- Maximum and minimum environmental conditions which the equipment may operate in.

  Altitude: _____
  Max Temp: _____
  Min Temp: _____

- Total air through the transmitter

  CFM _____

- Pressure drop within the critical portion of the air circuit (across the transmitter tube) for example. (This is required for checking purposes after the system is built.)

  P (Inches H_2O) _____

- Air temperature rise through the transmitter: _____

- Air exhaust area: _____

The following facts must be known about the conditions at the site or transmitter location:

- Maximum temperature: _____
  (In the transmitter room.)

- Altitude above sea level: _____

First, the removal of heated exhaust air away from the transmitter will be dealt with. Equipment layouts usually provide for heated air to exit from the top surface of the cabinet. The size and location of this exhaust area is usually shown on a manufacturer supplied outline drawing. Most broadcast equipment internal air systems are designed to be operated into free space (0 inches of water back pressure) so any unpowered exhaust must have minimum loss. A good practice usually is no more than +0.1 inches H_2O pressure in the duct close to the exhaust area of the transmitter.

Any exhaust installation other than a large cross section duct (equal to the cross section of the transmitter exhaust port) with no bends, and with a long radius turn outside the transmitter building for weather protection will need an exhaust blower or fan.

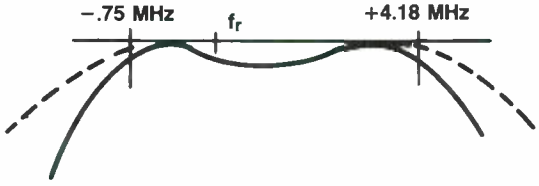
The following is an example of an exhaust duct design illustrating key cooling concepts:

From Manufacturers Specifications:

Air flow through transmitter = 325 CFM

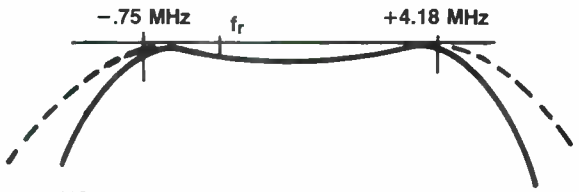
Air exhaust area = 3.4 ft²

$$\text{Air exhaust velocity} = \frac{325 \text{ CFM}}{3.4 \text{ ft}^2} = 94.5 \text{ ft/min}$$



NOTE: The driver bandwidth is the dotted line, and the PA bandwidth is the solid line. The solid line also represents the overall transmitter bandpass.

Fig. 66. Proper bandwidth.



NOTE: The PA bandwidth is the dotted line, and the driver bandwidth is the solid line. The solid line also represents the overall transmitter bandpass.

Fig. 67. Improper PA bandwidth.

The 94.5 feet per minute air velocity is extremely low which will allow a transition to a smaller diameter pipe if desired. Assume a transition down to a 10-inch diameter pipe, thus the following:

$$A = \frac{D^2}{4 \times 144} = \frac{100}{4 \times 144} = .545 \text{ ft}^2$$

$$V = \text{CFM}/A$$

$$V = \frac{325 \text{ CFM}}{.545 \text{ ft}^2} = 596 \text{ ft/min air velocity in a 10-inch diameter pipe.}$$

Where: D = Duct Diameter
A = Exhaust Duct Cross Sectional Area
V = Exhaust Duct Air Velocity

In a 10-inch diameter pipe air friction chart gives .06 drop per 100 feet of pipe with a flow of 325 CFM. Refer to friction loss in pipes chart Fig. 68. Assuming there is 20 feet of straight pipe to a roof, with two 90 elbows to turn the pipe down for weather protection, the total loss of the exhaust system may be estimated as follows:

Figure 71 shows loss is .06 inch/100 square feet.
Since 20 feet is .2 of 100 feet,
.2 × .06 = .012 drop in 20 feet of pipe.

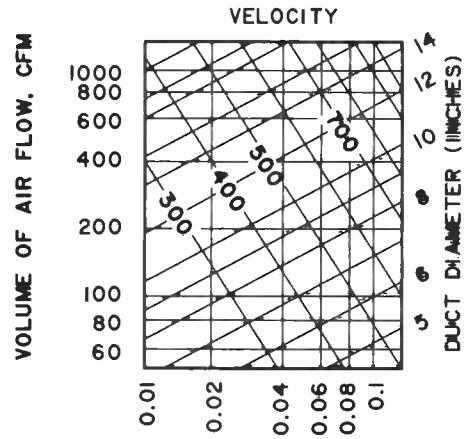
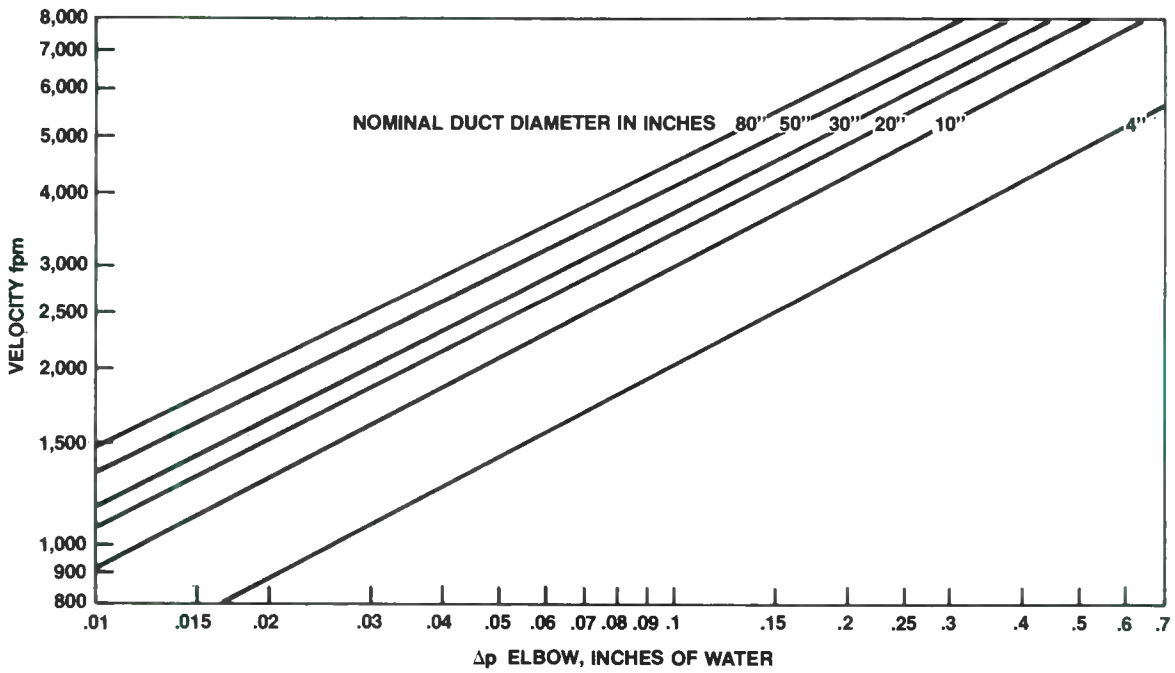


Fig. 68. Friction loss in pipes.

Considering the static pressure drop of two 90° elbows, to give a 180° bend in the pipe, it is found that a 10-inch elbow at 900 feet per minute gives less than .01 pressure drop, and we have only 600 feet per minute in our system. See pressure loss in a typical 5 gore round 90° elbow (Fig. 69). Adding the drops together, the result is as follows:

.012 + .01 + .01 = .032 total pressure drop.

Therefore, no exhaust fan is necessary.



"ZERO LENGTH" LOSS, ADD TO DUCT FRICTION CALCULATED FROM INTERSECTION OF DUCT CENTERLINES.

Fig. 69. Friction loss in 90° elbow.

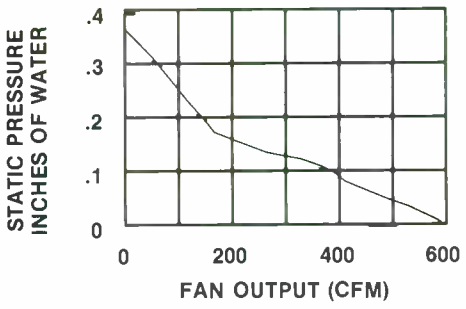


Fig. 70. Fan performance curve.

If the installer has a problem in exhausting the transmitter in this simple fashion, for example a roof exit is not available, and is required to add 2 additional 90° elbows and a straight run of 10-inch pipe 100 feet long. The pressure drop in the exhaust system will be as follows:

Friction loss in 20 ft of 10″ dia. pipe	=	.012
4 elbows × .01″ H_2O (est.)	=	.04″ H_2O.
Friction loss/100 ft. of 10″ dia. pipe	=	.06″ H_2O
		0.112 H_2O total loss in system.

Because the transmitter manufacturer recommends no more than a 0.1 inch H_2O loss in an exhaust system, good engineering practice indicates that an exhaust fan is required in this configuration. Searching through vendor catalogs for a fan results in the selection of a vaneaxial Caravel fan. Note that the performance curve on this fan (Fig. 70), indicates that it will deliver 325 to 330 CFM into 0.1 inch H_2O back pressure. This is sufficient to handle all of the air coming from the transmitter and overcome all of the estimated duct losses in this configuration.

It is also necessary to supply at least 325 CFM of air to replace the air circulated through the transmitter and exhausted to the outside of the building.

Because the transmitter only requires 325 CFM of air, it can probably be assumed that there would be enough leaks around windows and doors to supply this amount of air. However, if the installer wishes to insure an adequate amount of replacement air, a blower or fan may be installed in the wall of the building to supply the makeup air. Referring again to Fig. 70, examination of the curve shows that at 325 CFM delivery, this fan will develop a static pressure of 0.1 inch H_2O, which is sufficient to overcome the less than .01 inch H_2O pressure drop of a 10-inch diameter 90° elbow installed on the outside wall of the building for a weather hood, as well as a filter and bird screen to clean the incoming air.

20 ft of pipe	=	.012″ H_2O loss
2 elbows at .01 each	=	.020
		.032 total loss, maximum.

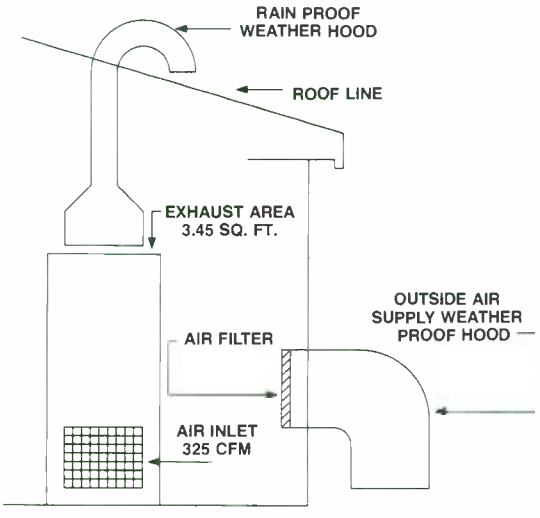


Fig. 71. Suggested intake and exhaust duct installations.

COMBINING CIRCUITS

Two different types of combining circuits must be considered:

1. Combining of sources with the same frequency
2. Combining of sources with different frequencies (visual and aural)

For combining of sources of the same frequency 90° 3 dB hybrid couplers have found

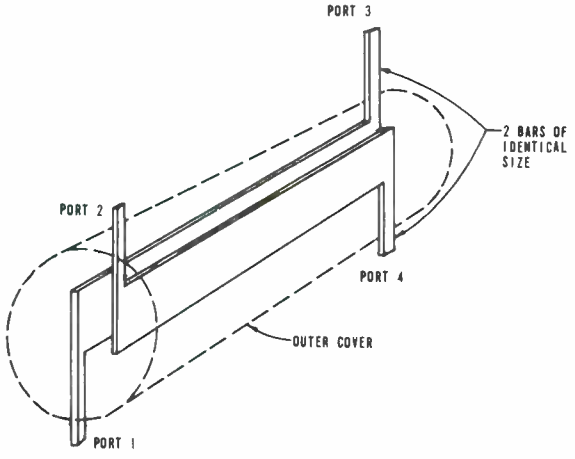


Fig. 72. 3 dB 90° hybrid coupler.

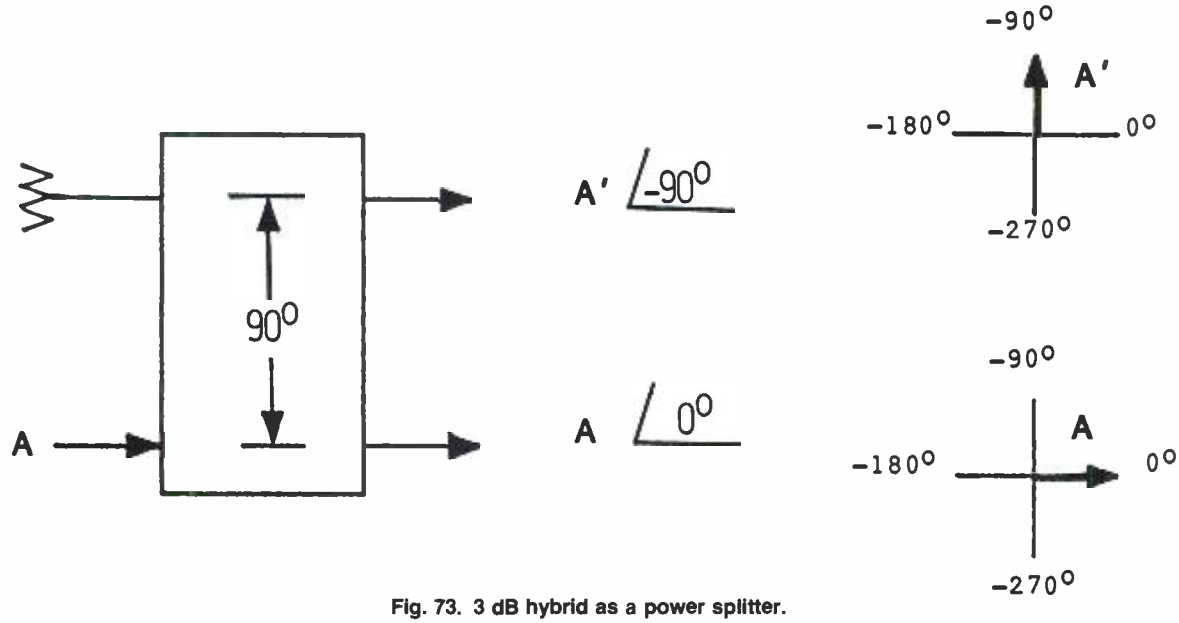


Fig. 73. 3 dB hybrid as a power splitter.

almost universal acceptance. Fig. 72 shows the physical model of a 90° 3 dB hybrid coupler.

A 3dB hybrid coupler consists of two identical parallel transmission lines coupled over a length equal or approximately equal to the quarter wavelength of the frequency to be acted upon and mounted in a common outer conductor.

The construction is symmetrical, i.e., both inner conductors have the same physical dimensions and have the same capacitance per unit length with respect to the outer conductor.

The 3 dB hybrid coupler can be used as a power splitter or as a power combiner. Fig. 73 shows the 3 dB hybrid coupler as a power splitter and Fig. 74 shows the 3 dB hybrid coupler as a power combiner.

One of the common uses of the 3 dB hybrid is to combine two frequencies that are close (Visual and Aural) in a back to back hybrid called a notch diplexer. The first step in building a notch diplexer can be shown by combining two 3 dB hybrids back to back as shown in Fig. 75. The input hybrid will act as a splitter while the hybrid at the output will act as a combiner.

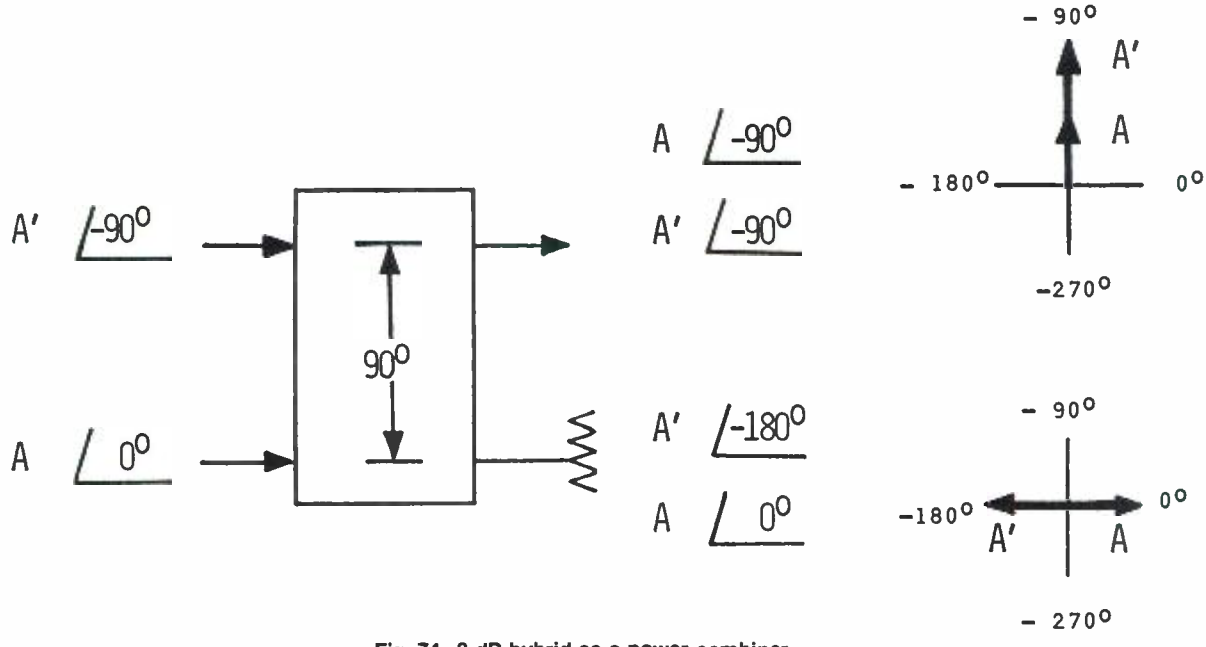


Fig. 74. 3 dB hybrid as a power combiner.

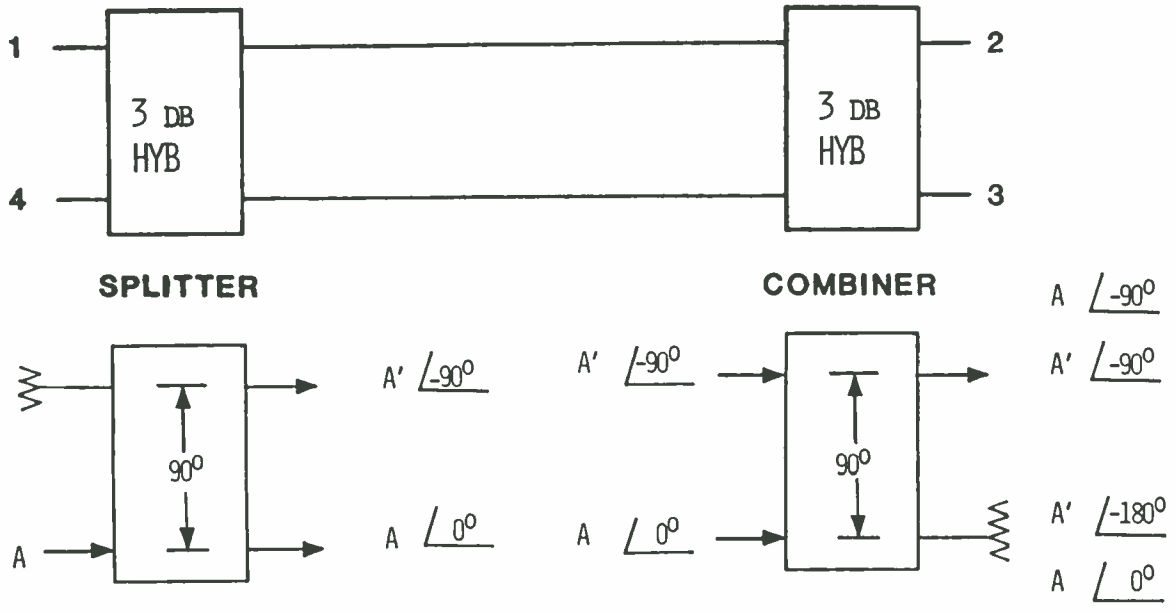


Fig. 75. Back-to-back hybrids.

If we now insert a Visual signal to location *A* in Fig. 75 we have the Visual signal appearing at the Antenna port as seen in Fig. 76.

If we now add the Aural signal as in Fig. 77, we can see that it is passed through the 3 dB hybrids but does not appear at the antenna port as required.

If we now add the Aural signal as in Fig. 77 but also add two high Q notch cavities tuned to the aural frequency, as depicted in Fig. 78, we can introduce a short to the aural frequency at the −3 dB output of its hybrid as seen in Fig. 79.

These shorts cause the aural signal, now split into two −3 dB components 90° out of phase by the 3 dB hybrid acting as a power splitter, to be reflected back into the 3 dB hybrid and where the 3 dB hybrid now effectively acts as a power combiner and passes the combined −3 dB aural signals to the antenna port along with the Visual signal. The Aural notch cavities are effectively not seen by the Visual signal since they are high Q cavities tuned to the Aural frequency.

Another use of the back to back hybrids can be seen in Fig. 80 which shows a single signal source driving a power splitter and dual amplifiers. This same arrangement can be used for Visual or Aural signals. Gain and phase adjustments are used to keep the signals out of the amplifiers (A1 and A2) at equal output power and 90° phase difference so that they can be properly combined by the power combiner with a minimum of reject load power.

A typical use of this system would be the driving of two Visual Power Amplifier chains in parallel with a single Visual Exciter. HY1 would be a low-power splitter while HY2 would be a high power combiner. A1/A2 would be the complete visual amplification chain consisting of multiple stages of solid state and/or tube amplifiers.

Differences in amplifier chain gain are compensated for by the attenuators AT1 and AT2 which vary the amount of input signal applied to the amplifier chains. Differences in phase are

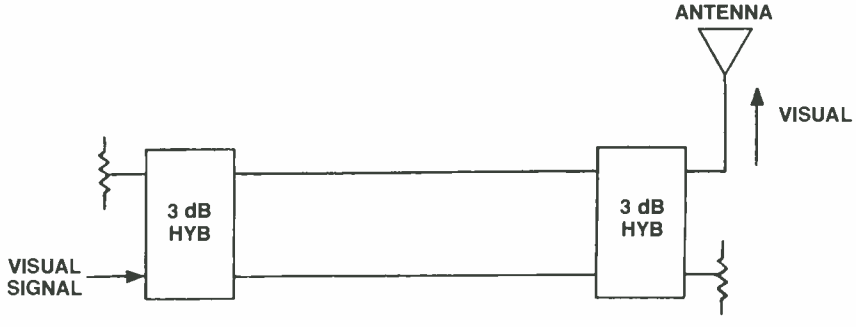


Fig. 76. Visual signal applied to back-to-back hybrids.

Fig. 77. Aural signal applied to back-to-back hybrids.

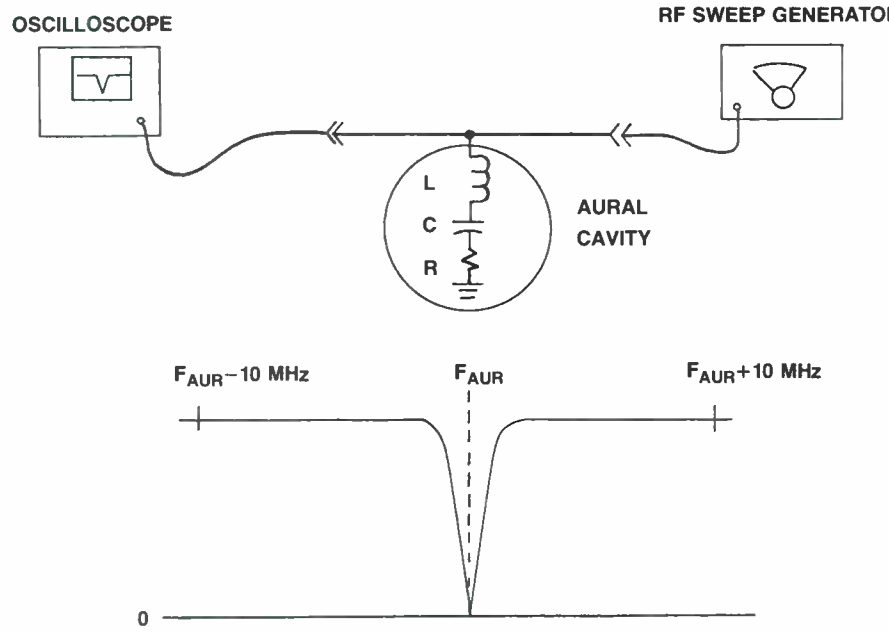


Fig. 78. Aural notch cavities with LC series resonant components and resistor (R) representing non-infinite Q of cavity.

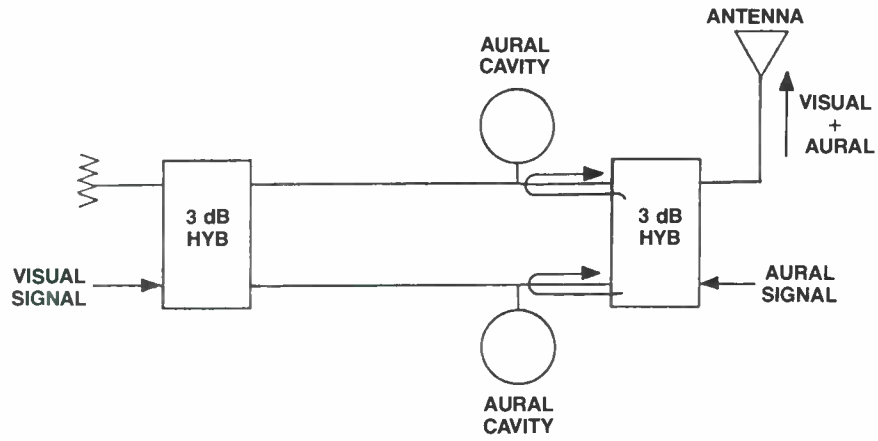


Fig. 79. Aural and visual signals applied to back-to-back hybrids with aural notch cavities to reflect aural signals back to antenna port.

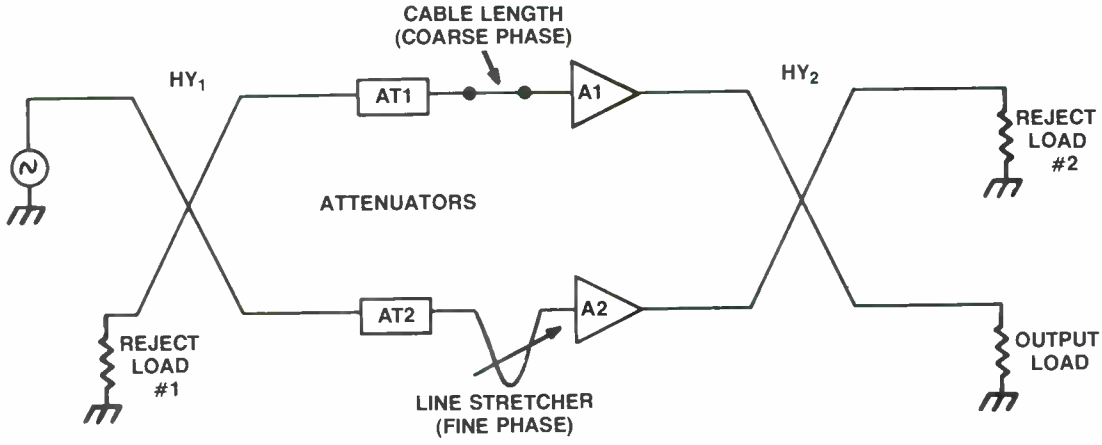


Fig. 80. Typical parallel amplifier with single signal source.

compensated for by the length of cable between the attenuators and the amplifier chain. Optimum phase and gain adjustments are determined by minimum power being dissipated by reject load number 2 and maximum power into output load as shown in Fig. 80.

Effective power transferred to antenna or load with respect to differences in phase or gain of amplifier chains can be seen in Figs. 81 and 82 respectively. As can be seen from these figures, a 60° error in phase will cause only a 25% reduction in output power and if one amplifier has only half the output power of its counterpart, a 3% reduction in power (in reference to the combined input powers) will result. (Transmitter A = 5 kW, Transmitter B = 10 kW, $K^2 = P_a/P_b$ = .5 which gives a K of .707 which equals approximately 3% in Fig. 84 or approximately 14.55 kW of useful power out of hybrid.) Worst case for gain occurs when one transmitter is not producing any output; in this case half of the remaining transmitter's output will be dissipated in the reject load and the other half will be applied to antenna.

A typical dual transmitter with notch diplexer can now be block diagrammed as in Fig. 83.

PRECISE FREQUENCY CONTROL

The limited number of available channels for TV Broadcasting makes it necessary to assign the

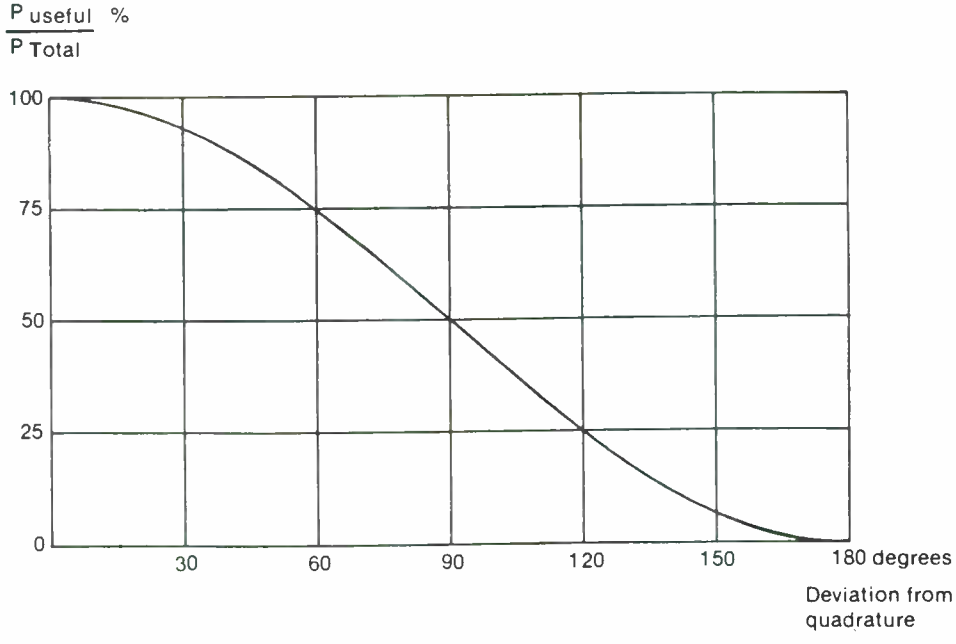


Fig. 81. Hybrid coupler phase sensitivity.

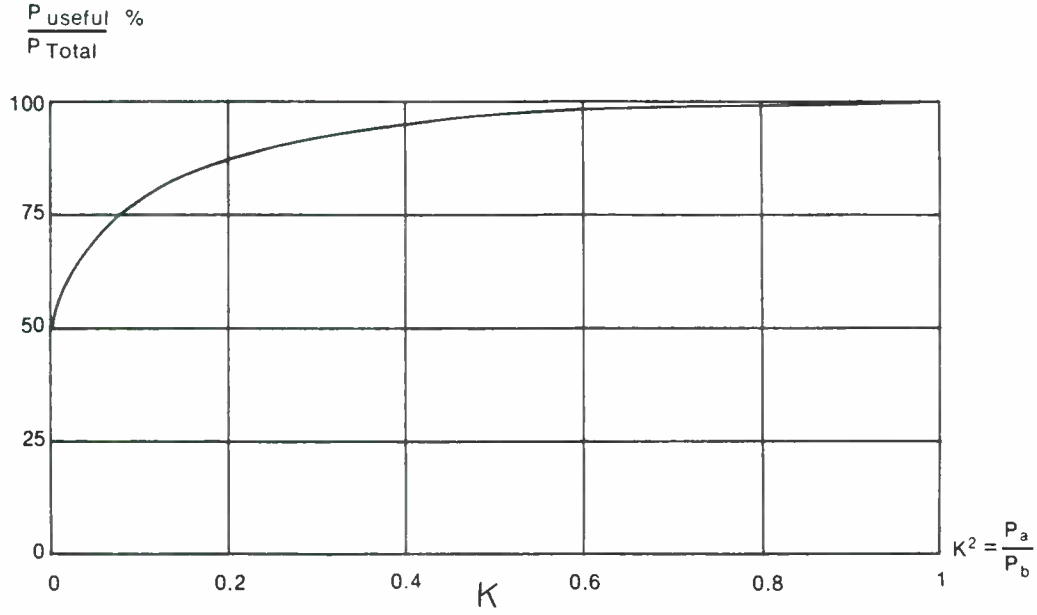


Fig. 82. Power imbalance in hybrid couplers.

same carrier frequencies to many stations. To avoid interference between stations operating on the same frequency (co-channel interference) geographical separation and radiated powers are carefully selected.

Nevertheless, considerable co-channel interference was encountered in many locations and investigation showed that additional means were available to reduce co-channel interference by making use of optical or perceptive elements in the system. In other words, steps were taken not to alter the strength of the interfering carrier but to choose operating parameters to reduce the visibility of the interference.

Considerable investigative work was done to lay the scientific and physiological basis and to define the parameters which need to be controlled to reduce the visibility.

It turned out, with horizontal and vertical sweep ratios fixed, the Visual carrier frequency of the interfering stations was the parameter which had to be controlled.

Co-channel interference between television stations appears to viewers as a horizontal pattern of alternating light and dark bars on the viewing screen—very much like the shadows cast by venetian blinds. It has been demonstrated for many years that the visibility of these bars varies cyclically as a function of the difference in frequency of the interfering carriers (Fig. 84). The interfer-

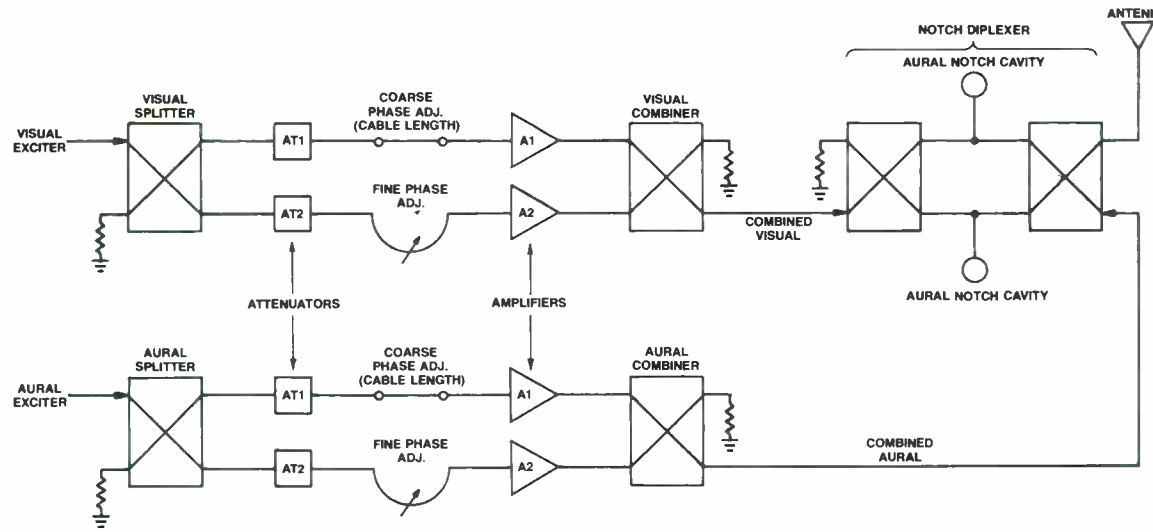


Fig. 83. Typical dual transmitter with notch diplexer.

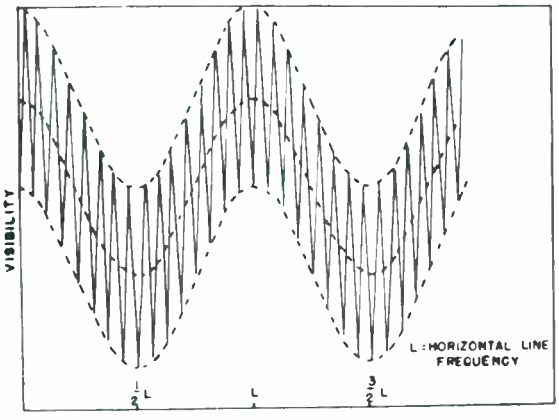


Fig. 84. Co-channel interference.

ence is most visible when the carriers were offset by multiples of the line frequency (15.734 kHz) and least visible when the carriers are offset by odd multiples of one-half the line frequency. In addition to the gross maxima and minima, fine grain maxima and minima occur when the frequency offset is a multiple of the frame frequency (29.97 Hz). Ideally, stations would be offset by odd multiples of one-half the line frequency to provide minimum interference visibility.

However, a third station in the same area would be offset from one of the other stations by an even multiple of the line frequency. Hence, maximum visibility of the interference. The 10 kHz offsets were chosen to provide approximately equal reduction of the interference patterns for any number of stations in geographical proximity, refer to Fig. 85.

Although it is not practical to utilize the gross minima occurring at odd multiples of one-half the line frequency, it was determined experimentally that utilizing the fine grain minima, occurring at even multiples of the frame frequency, would be very advantageous in reducing the visibility of co-channel interference.

The nearest even multiple (334th) of the frame frequency to the 10 kHz offset is 10,010 Hz. Since the carrier frequency tolerance is ±1,000 Hz, the precision offset is compatible with existing regulations. In a three station arrangement, the stations will be offset by 10,010 Hz and 20,020 Hz. Experiments indicated that changes in the frequency differences of ±5 Hz had a negligible effect on the reduction of the interference visibility.

To maintain the precision offset within ±5 Hz requires maintaining each visual carrier frequency within ±2 or 3 Hz.

Maintaining a television transmitter to such tight frequency tolerances requires some type of control system using an extremely stable frequency source.

In general, it is not practical to build into the visual carrier oscillator the required stability for precise frequency control. Most oscillators used in visual service have sufficiently short time stability for effectively locking to an external frequency standard. Fig. 86 is a block diagram showing

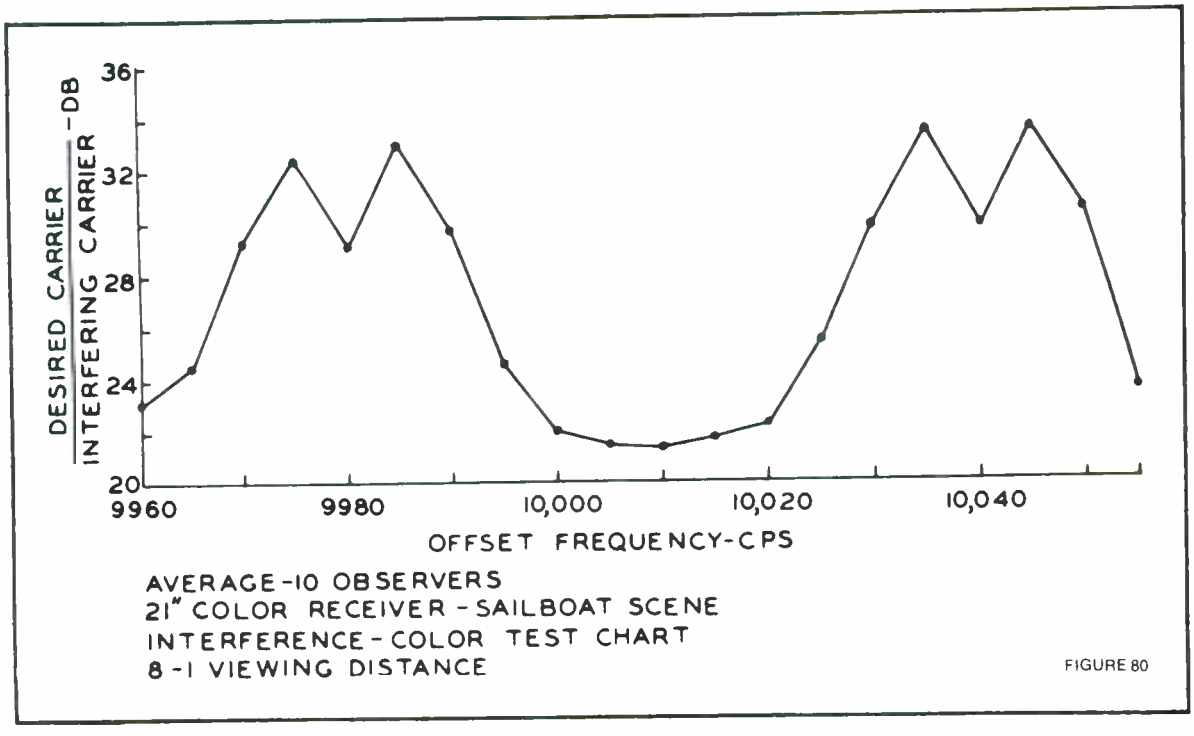


Fig. 85. 10 kHz offset pattern.

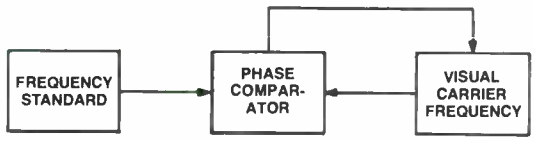


Fig. 86. Precision frequency control block diagram.

the visual carrier frequency in a phase lock loop with a frequency standard.

In exciters using two independent oscillators, the visual carrier feed to the phase detector is derived from mixing the oscillators together. For exciters using synsthesizers, the reference oscillator is fed to the phase detector.

By phase-locking the visual carrier to a stable reference oscillator, the Master Oscillator acquires the stability of the reference source. Sources which use an internal WWVB Receiver/Comparator to self-correct or an Atomic Frequency Standard can easily provide the stable reference source required. These reference sources allow a transmitter to be maintained within a few Hertz of a desired frequency indefinitely. Experimental results have indicated that frequency differences between transmitters can vary as much as ±5 Hz from the precision offset before co-channel interference becomes noticeably worse. This means that two television stations can minimize their co-channel interference without the requirement to frequently adjust the transmitter frequency.

One word of caution when working with any frequency standard. If power is removed from the standard and no backup power supply is incorporated either internally or externally, ensure that the standard has stabilized before making any adjustments. Also ensure that after any adjustment has been made, that a suitable time period has elapsed to allow the standard to settle before making any reading.

To ascertain the carrier frequency of a station operating under precision frequency control, assuming a measuring accuracy 10 times better than the quantity to be measured, leads to the following accuracy requirements:

VHF Low Band	$\pm 2.5 \times$	10^{-9}
VHF High Band	$\pm 1 \times$	10^{-9}
UHF	$\pm 3 \times$	10^{-10}

Frequency counters with the above accuracy and with NBS traceable calibration be used for making measurements.

PERFORMANCE MEASUREMENTS

In the age of deregulation, TV signal quality responsibility lies with the broadcaster. Over the past 10 years, critical signal performance parameters improved two to one. Transmitters led the improvement with the introduction of IF modulation, solid state SAW vestigial filters and sophisticated precorrection circuits. Precision demodulators followed with synchronous detection and SAW filters capable of near ideal detection. New test waveforms and digital signal synthesis provided accurate test signal generation. Home receivers adopted high tech circuits including comb filters for wider band luminance, stable SAW IF filters, high resolution display devices, and sophisticated LSI video processing circuits.

It is difficult to show the correlation between signal quality and audience ratings. The issue of viewer enjoyment is easier to demonstrate. Many scientific studies relating signal degradation to perceived quality have been made over the years. These empirical studies have been the basis for *K* factor ratings and TASO picture ratings.

The Electronic Industries Associates Standard RS508 takes into account the empirical quality factors and reflects a common denominator for new transmitter performance. This standard is a valuable reference document which describes parameters, standards and methods of measurements.

A thorough proof of performance at the time of installation is an invaluable record of normal operating performance. It also serves as verification of proper signal quality and emission standards. The number of detailed measurements required after the proof usually can be limited since several performance characteristics are a measure of the same impairment. Also some test waveforms are more useful for transmitter adjustment than others.

Measurements can be broken down into two categories as follows:

1. Frequency response.
2. Linearity.

Performance dependent on amplitude and group delay are sometimes referred to as linear distortions. That is, these distortions are not signal level dependent. In the time domain 2*T*, modulated sine-squared pulses and multiburst are used in identifying and correcting distortions. In the frequency domain, swept amplitude and group delay measurements can be used but are normally reserved for out of service testing.

Linearity performance includes distortions which are signal level dependent and are a function of the instantaneous luminance level and on the average picture level over several lines. For example; level dependent chroma gain and phase called differential gain and phase, respectively; luminance gain variation called low-frequency nonlinearity; and frequency response versus brightness which is the change in swept response with static luminance level. The nonlinear responses can also change as a function of average picture level. For this test the video waveform

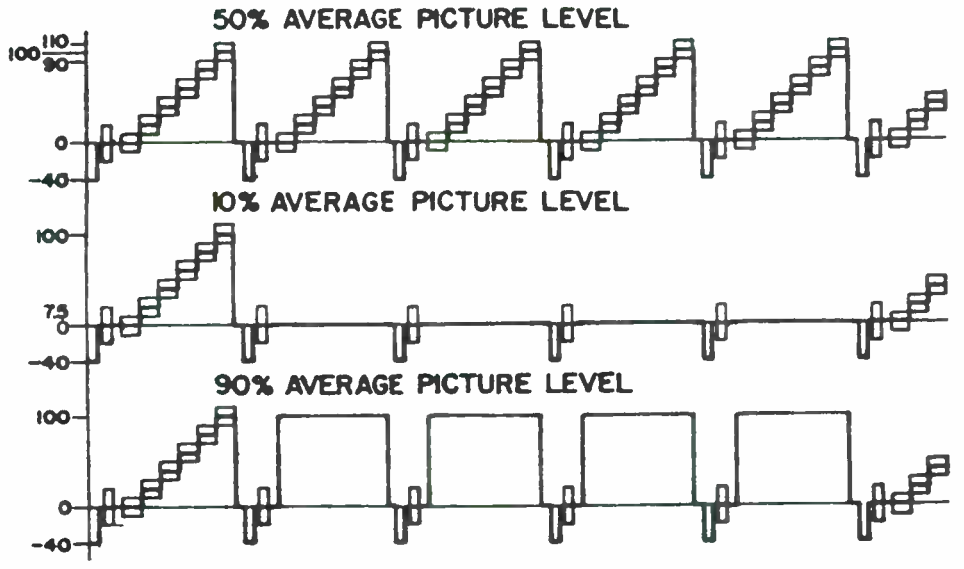


Fig. 87. Modulated staircase waveform.

is alternated with four lines containing a static luminance level. Fig. 87 contains a modulated staircase with three average picture levels.

Modern transmitters are designed for unattended operation for extended periods of time. A transmitter operating with adequate cooling, regulated power lines and properly adjusted, need only be checked in detail every three or four months or whenever a major component is replaced or repaired.

The following is a pretest check and a sequence of tests presented as a general guide for arriving at a properly adjusted transmitter.

Pretest Checks

- Test equipment.
- Input video.
- Output transmission line, station load, and antenna.
- AC mains input.
- Record meter readings, adjustment settings, and key performance parameters.

Transmitter Test Sequence

1. Exciter linear and nonlinear performance check.
2. Intermediate and driver linear amplifier performance check.
3. Swift frequency response.
4. Modulation depth (UHF pulser and sych ICPM adjustments).
5. Power output meter calibration.
6. Nonlinearity response checks. For example differential gain, differential phase, ICPM, etc.
7. Linear response checks for example, group delay, pulse tests, composite waveform *K* factors, etc.
8. Record meter readings, adjustment settings, and key performance parameters.

Many adjustments are interrelated and require returning to previous tests to verify proper performance. The sequence above is intended to minimize the adjustment iterations.

At the time of a periodic measurement and adjustment sequence, it is a good practice to record meter readings and adjustment settings before and after the test. These recordings will indicate normal setting range and can aid in getting the transmitter back to near normal in the event of mistuning errors during adjustments.

For off-air monitoring, a picture monitor is convenient for accessing gross video degradations quickly. Vertical interval test signals containing the composite waveform or other specialized test signals are useful for keeping track of depth of modulation, and fine grain linear and nonlinear responses. These test signals are displayed on a waveform monitor and vectorscope.

Records of transmitter meter readings and performance data are very useful in maintaining a transmitter at like new operating conditions. Maintenance logs should include date, time duration of outages, corrective action taken, and where possible, identify cause.

Equipment Needed

In order to make satisfactory measurements of video signals, a certain minimum of equipment is required. Measuring the output of a television

transmitter at baseband requires a demodulator. For greatest accuracy, this demodulator should provide a zero carrier reference pulse for determining percentage of modulation, and ideally will have both a synchronous and envelope detection mode. For most baseband measurements, a video waveform monitor is all that is needed, but to do a complete analysis of a system requires some additional equipment. The waveform monitor should include a provision for making measurements on vertical interval test signals (VITS) and provide filtering to allow separate examination of the luminance and chrominance components of color television signals. In addition to the waveform monitor, a vectorscope must be used for making certain measurements on color television system, particularly differential gain and phase measurements. The waveform monitor and vectorscope are all that are required to accomplish these measurements, but if a greater level of accuracy is desired in timing measurements, a conventional oscilloscope with an associated digital counter/timer would be a great asset.

RF Amplitude response as a function of frequency is the variation in gain over the frequency range of the channel. The use of a television sideband analyzer or other frequency selective voltmeter provides a suitable means to measure a television transmitter amplitude response versus frequency.

At one time or another, just about every component part of a video signal must be measured or adjusted. It is good engineering practice that each part of a transmission plant including studio, distribution, transmitter, and monitor equipment provides minimal distortion to the video signal. Furthermore it is not recommended that one part of the system correct for another part. The signal going into the transmitter should be a standard NTSC video signal.

The overall amplitude of the signal and each of its component parts have strictly defined levels, and the relationship between the parts is also critical. Refer to RS-508 for a description of specific electrical performance parameters and standard test methods.

REFERENCES

1. Electronic Industry Association. (To Be Published) RS-508 "Electrical Performance Standards For Television Broadcast Transmitters".
2. Electronic Industry Association. RS-462 "Electrical Performance Standards For Television Broadcast Demodulators".
3. Hans Shmid. "The Measurement Of Short-Time Waveform Distortion In NTSC TV Facilities" IEEE Trans. Broadcast, Vol 18, No. 3, Sept. 1971.
4. Charles Rhodes. "The 12.5T Modulated Sine-Squared Pulse For NTSC" IEEE Trans. Broadcast, Vol 18, Mar. 1971.
5. Pieter Fockens, Carl Eilers. "Inter carrier Buzz Phenomena Analysis And Cures" Transmitter Consumer Electric Vol 27, No.3, August, 1981.
6. C. Bailey Neal. "Frequency And Amplitude Dependent Phase Effects In Television Broadcast Systems" IEEE Trans On Consumer Electric, Vol 23, No. 3, August 1977.
7. T. M Gluyas. "Influence Of RF Output Systems On TV Transmitter Picture Quality" NAB Convention Record, April, 1972.
8. L. E. Weaver. "The Multipulse Waveform" Application Note No. 30, Tektronix Corporation.
9. W. A. Resch. "Visual Performance Characteristic Which Affect Multichannel Sound" NAB Convention Record 1982.
10. W. L. Behrend. "Effects Of Incidental Phase Modulation Of TV Transmitters Or Other Circuits, On TV Signals" IEEE Trans On Broadcasting, Vol 19, No. 3, September 1973.
11. C. J. Edgecombe. "The Television Performance Of The Klystron Amplifier" Radio And Electronic Engineer, September 1971.
12. A. Hans Bott. "Television Transmitters Chapter 19" NAB Engineering Handbook 6th Edition.
13. *TV/VIDEO Sync Primer And Product Note* Opt. 005-1, November 1981, Hewlett Packard.
14. Vol. XI Recommendations And Reports Of The CCIR, 1982. "Subjective Assessment Of The Quality Of Television Pictures" Report 405-4.
15. Varian Associates, INC. "Integral Cavity Klystrons for UHF TV Transmitters".
16. Varian Associates, INC. "External Cavity Klystrons for UHF TV Transmitters".
17. C. F. Smiley & G. L. Best. "Improved Efficiency Klystrons in UHF TV Transmitters" NAB Convention Proceedings, 1984.
18. Robert S. Symons. "Klystrons for UHF Television" Proceedings IEEE Vol. 70, #11 Nov. 1982.
19. Gregory L. Best. "Transmitter Conversion for TV Multichannel Sound" NAB Convention Proceedings, 1984.

20. Joseph C. Wu. "Monitoring TV Multichannel Sound" NAB Convention Proceedings, 1984.

21. Carl G. Eilers. "The Zenith Multichannel TV Sound System" NAB Convention Proceedings, 1984.

22. Leslie B. Tyler, Mark F. Davis, and William A. Allen. "The dbx TV Companding System for Multichannel TV Sound".

23. United Sheet Metal Bulletin 100-5-178 "Engineering Design Manual for Air Handling Systems".

24. Rotron Incorporated. "The Caravel Fan" Catalog Sheet E-3050C.

25. McGraw-Hill. Marks' *Mechanical Engineers Handbook.*

26. Andersen Laboratories, *Handbook of Acoustical Processing, Vol. I.*

27. A. G. Uyttendale, "Design Requirements and Operational Features of the Gates Dualtran RF Switching System," Harris Corp., Broadcast Products Division.

3.6

Multichannel Television Sound

Edmund A. Williams
Staff Engineer,
Department of Science and Technology
National Association of Broadcasters
Washington, DC

INTRODUCTION

Multichannel Television Sound (MTS) is a generic term for the process of adding subcarriers to the aural carrier of a television station. Some of these subcarriers are designed to be received by the general public and may be used for a variety of different purposes including stereophonic sound, second language, commercial communications, and data. Other subcarriers may be used for news crew cueing, transmitter telemetry or other digital or analog aural or data services. The subcarriers may or may not be related to the program on the video or aural portion of the television signal itself.

BACKGROUND

The addition of subcarriers to the aural carrier was approved by the Federal Communications Commission on March 29, 1984, in response to a petition for rulemaking from a television station interested in transmitting cueing instructions to remote news crews during live news events. In order to develop a standardized approach to the implementation of multiple sound channels, the broadcast industry, through the Electronics Industry Association (EIA) and its Broadcast Television Systems Committee (BTSC), established laboratory facilities and conducted transmission tests on several potential multichannel sound systems. The system selected by the EIA was a combination using the transmission parameters developed by Zenith Electronics Corporation and the noise reduction system developed by dbx, Inc. The combination is called the BTSC Multichannel Television Sound system after the EIA BTS Committee which conducted the laboratory tests. A chronological table of events for the development of MTS is shown in Fig. 1.

In response to the EIA's recommendation, the FCC, in their Second Report and Order

1. Provided protection to the transmission and reception of the BTSC system,
2. Produced an Office of Science and Technology Bulletin #60 containing the system's specifications, and
3. Permitted stations to implement not only the BTSC MTS system but any other system of subcarriers a station desired so long as no interference resulted to BTSC receivers or regular monophonic sound television receivers.

While not an absolute standard, the Commission's approach provides the next best thing—protection. Transmitter and receiver manufacturers are able to produce equipment operating with the BTSC system with full knowledge that there is a compatible, protected MTS system recognized by both FCC and industry. The industry has also developed a series of recommended operating practices some of which are

MTS CHRONOLOGY

- WCVB PETITION FOR RULEMAKING 1/21/77
- FCC NOTICE OF INQUIRY (DOCKET 21323) 7/1/77
- EIA MTS COMMITTEE FORMED 1/10/79
- FCC NPRM (NOTICE OF PROPOSED RULEMAKING) 11/20/79
- FCC 1ST REPORT & ORDER (CUEING) ... 6/30/81
- FCC FURTHER NPRM 7/28/83
- EIA CONDUCTS VOTE 12/22/83
- FCC 2ND REPORT & ORDER (STEREO) ... 3/29/84
- RECEIVERS SHOWN TO PUBLIC 6/4/84
- FIRST STEREO TEST BROADCAST 7/27/84
- FIRST FULL TIME STEREO BROADCAST . 8/6/84

Fig. 1. MTS Chronology.

summarized later in this chapter. Further, stations may also employ subcarriers for virtually any other purposes which do not interfere with the BTSC system or normal monophonic receivers operation.

It should be mentioned that while the multichannel sound system adopted for use in the United States is unique, multichannel sound transmission schemes were developed and adopted in at least two other countries before the FCC Order. In Japan, an FM subcarrier system for either stereo sound or a second language was adopted in 1977 and stations began transmission of this system in 1978. In 1981, West Germany adopted a two-carrier sound transmission system providing either stereo or second language. In comparison, the U.S. system, adopted in 1984, provides a combination of AM and FM subcarriers to transmit both stereo and second language simultaneously. Further, the US system permits other subcarrier arrangements which serve an individual stations requirements.

THE BTSC SYSTEM OBJECTIVES

1. The system must be compatible with existing monophonic television receivers.
2. The system must provide both stereo and 2nd language simultaneously.
3. There must be provisions for other professional use or station use subcarriers.
4. A noise reduction (companding) system must be employed in both stereo and second audio program channels.
5. Aural carrier deviation must be increased to accommodate the new subcarriers.

TRANSMISSION FORMAT

In order to understand the following description of the transmission format of the BTSC system with respect to the television aural baseband, the reader should refer to Fig. 2.

The design of the basic MTS system took into account several major considerations. Among these were such important factors as compatibility

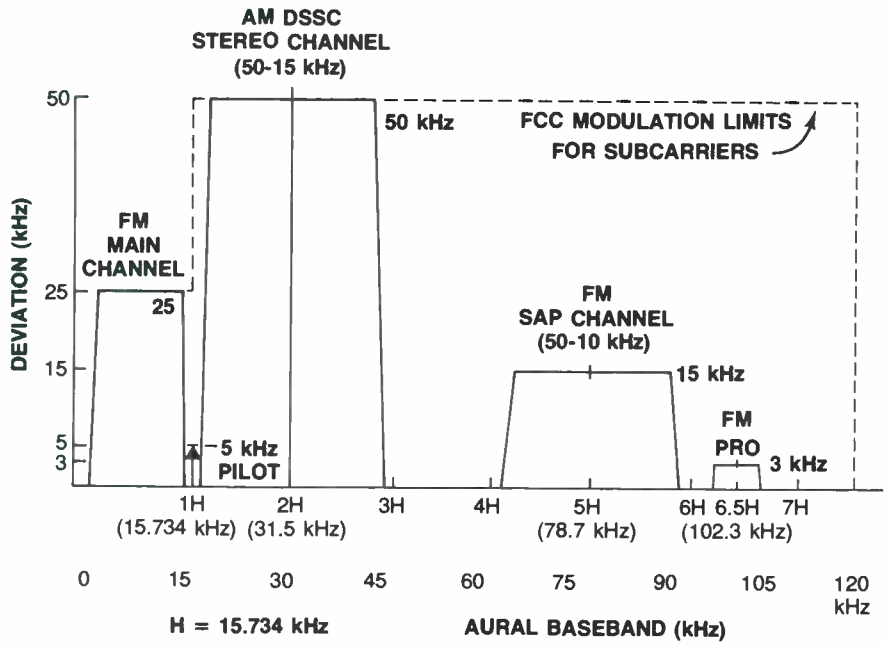


Fig. 2. BTSC MTS baseband.

with existing television receivers, ease of modification of transmitters, full sound fidelity, the ability of the MTS signals to pass through cable TV, master antenna systems, TV translators, the ruggedness to withstand substantial transmission impairments in the path between the transmitter and receiver. These factors influenced the design criteria with the result that the single carrier system with subcarriers was favored over a two-carrier system, and an audio companding or noise reduction system was required. Also, a seperate audio program channel for special programming purposes was provided.

Transmitting the stereophonic component in the form of a difference signal or left minus right (L – R) rather than any other mathematical derivation for the stereo matrix was based mainly on the U.S. FM broadcast model and its familiarity to broadcasters. For example, the West German system transmits the sum (L + R) signal on the main aural carrier and a plus right (+R) signal on the second carrier. Further, additional subcarriers for cueing, data, telemetry or other station related purposes may also be transmitted. Space for these professional use subcarriers is reserved in the aural baseband as well.

MONOPHONIC CHANNEL

The basic monophonic, or sum channel (L + R), is maintained at its present place in the aural baseband, remains at 25 kHz peak deviation, and uses the standard 75 microsecond pre-emphasis. All other subcarriers increase the overall deviation of the main carrier. Increasing the deviation of the aural carrier does not result in any degradation to the normal monophonic sound in existing receivers. Maintaining 25 kHz deviation for the monophonic channel also avoids the need to reduce the modulation level of the monophonic signal during MTS transmission which would mean lowering the signal-to-noise ratio of the aural channel and "loudness" of the sum channel compared to stations not operating with the BTSC system. Increasing deviation provides the "room" for the new stereo, separate audio program and professional use subcarriers to be added to the aural baseband successfully.

The fidelity of the main channel monophonic audio is maintained as before. But, because of the closeness of the sidebands of the stereo subcarrier, BTSC stereo encoder equipment incorporates sophisticated lowpass filters in the audio circuits to limit response of each audio channel to no more than 15 kHz. Nevertheless, the BTSC system is capable of providing audio quality essentially limited only by the quality of the main or monophonic channel.

STEREO SUBCARRIER

In contrast to the monophonic or sum channel which is frequency modulated and deviates the main aural carrier by 25 kHz, the stereophonic subchannel audio is placed on an amplitude modulated, double sideband suppressed carrier, subcarrier at a frequency of 2H or 31,468 Hz (twice the NTSC video horizontal scanning rate of 15,734 Hz.) The subcarrier is modulated with the stereophonic difference signal or left minus right (L—R). The maximum injection of this subcarrier is set to 50 kHz main channel deviation. The suppressed carrier signal is injected into the aural carrier during modulation. The injection level is related to the companding system algorithm. However, because of the nature of stereophonic sound, a form of interleaving between sum and difference channels takes place...which prevents the deviation of the main carrier from becoming the sum of the two components which would appear to produce a total of 75 kHz. Instead, the maximum rarely exceeds 50 kHz. This is because a "left only" or "right only" signal originating from the studio would produce only a 50% modulated signal in the mono channel and a similar level in the difference channel.

The difference channel also employs the noise reduction circuit which further controls the maximum level of modulation of the difference signal. The dynamic response characteristic of the compressor is shown in Fig. 6. The result of this combination of events produces no more than 50 kHz deviation of the aural carrier. Finally, most stereo encoder manufacturers incorporate some form of peak limiting device to prevent the stereo subcarrier, the monophonic channel, and perhaps the combined deviation as well, from exceeding the maximum 50 kHz except for occasional peaks.

The selection of 2H for the center frequency of the stereophonic subcarrier was based on its relationship with the horizontal frequency component of the video in both the transmitter and the receiver. Crosstalk from video signal circuits, power supply and RF paths in the transmitter generally occur at multiples of H and therefore may be cancelled or at least dealt with in the receiver without significantly affecting overall stereo audio quality.

The first harmonic of H (15,734 Hz), present to some extent in many transmitter and receiver audio circuits, is above the normal hearing range of most viewers and not normally audible. Receiver audio circuits may also employ notch or low pass filters to eliminate the H signal at the audio output. The second harmonic falls at 2H (31,468 Hz) which is the frequency of the BTSC stereo subcarrier. Because the subcarrier frequency is locked to the video sync, the harmonic and subcarrier remain in phase and no beat occurs.

Modulation of the 2 H harmonic by 60 Hz field rate components of the video signal can also occur in either transmitter or receiver. The resulting buzz can be effectively reduced by the use of high pass filters in the stereo subchannel at the receiver to remove unwanted audio below about 100 Hz. While this has virtually no affect on the stereo audio quality, it substantially reduces low frequency buzz and hum caused by the field rate modulation. Placing the stereo subcarrier at a higher multiple of H is not desirable due to the much higher noise levels encountered in that portion of the aural baseband. A higher subcarrier frequency would also have made the addition of the separate audio program channel more difficult as well.

Fig. 3 shows the noise level build-up in the aural baseband. This illustrates why it was important to place the stereo subcarrier as low as possible in the baseband as well as the need for the audio companding system. The noise increases at a rate of 6 dB for each doubling of the bandwidth. As a result the noise the stereo subcarrier would add to the received dematrixed sound is about 21 dB. This is reduced by 6 dB because the stereo subcarrier deviates the main carrier by 50 kHz compared to the main channel deviation of 25 kHz. The resulting degradation in signal-to-noise is only about 15 dB which is easily overcome by the noise reduction system.

The use of an AM modulated double sideband suppressed carrier, subcarrier also provides several other significant advantages over an FM subcarrier. AM subcarrier technology is well known and developed within the FM broadcast industry and circuit and performance refinements have been raised to near-perfect levels. Second, AM offers lower theoretical distortion levels than FM, given the amount of spectrum available for transmission. The bandwidth for the stereo subcarrier channel is 30 kHz.

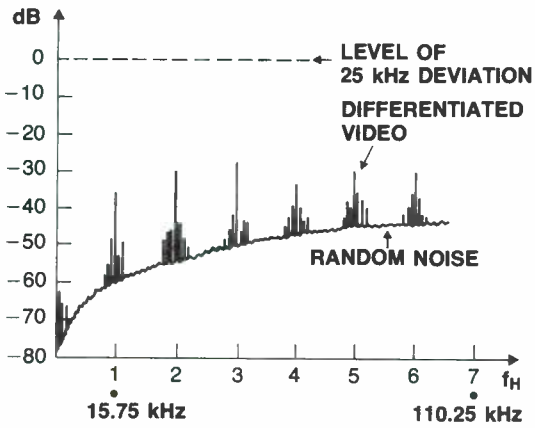


Fig. 3. Spectrum of noise on the received aural baseband. (Courtesty J.J. Gibson, RCA)

AM detection techniques are such that the distortion can be exceedingly low—on the order of 0.1% or lower. An FM subcarrier with enough deviation to produce the desired S/N and limited to only 30 kHz would produce higher distortion (1.5-3.0%) when detected. Calculations which prove this point may be found in the EIA MTS Report Vol 2B. And finally, further enhancements of the aural signal are possible through the use of quadrature modulation of the AM subcarrier for some future aural requirements such as a center channel or surround sound. Frequency response of the stereo subchannel is a good solid 15 kHz which properly compliments the main channel.

PILOT CARRIER

It was mentioned above that the stereo subcarrier is transmitted with its carrier supressed. In order for the AM detector to have a reference, a PILOT signal is transmitted at one-half the subcarrier frequency similar to the technique employed in broadcast FM transmission systems. The pilot is an unmodulated carrier at a frequency of 15, 734 Hz locked to the video horizontal sync rate. It modulates the main aural carrier to a deviation of 5 kHz ±0.25 kHz. The stereo encoder requires a feed from the companion video signal in order to obtain its frequency reference. It might be thought that receivers should not need the pilot and could use horizontal sync information obtained from the receiver video circuits. While this could be the case in some instances, there are receivers which do not process the video when decoding the stereo audio and would not have a reference to synchronize the stereo detector. The pilot also serves as a signal that BTSC is being broadcast and for the receiver to activate the stereo circuits.

A disadvantage with providing the pilot at H rate is that there may be some residual H components in transmitters and receivers which, under normal operating conditions, could cause false indications or even malfunction of stereo decoders in receivers. Problems of this sort must be solved by broadcasters and manufacturers by adequately shielding or isolating the H components of the video and video circuits from the audio circuits in transmitting and receiving equipment designs and modifications to existing equipment. For example, the level of 1H components from the visual transmitter 4.5 MHz above the visual carrier can be controlled by installing lowpass video filters, adjusting transmitter visual RF circuits or improving the 4.5 MHz rejection in the transmitter combiners or diplexers.

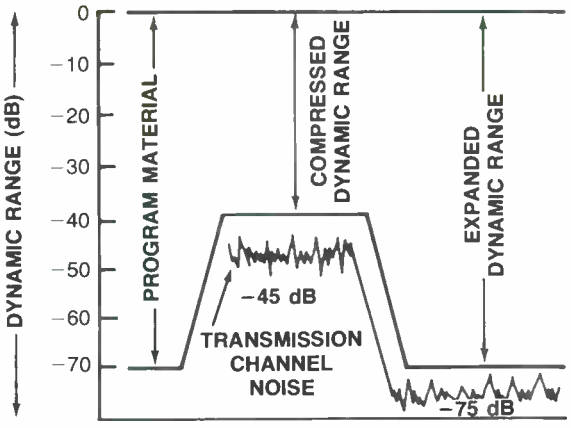


Fig. 4. Typical noise reduction action.

THE COMPANDING SYSTEM

Companding is a term used more frequently in the telecommunication industry to describe what broadcasters call noise reduction, a process which is well known to studio audio technicians. Its use is restricted to systems where there is control over both ends of the circuit. Examples include magnetic analog audio recorders, microwave and satellite circuits and telephone lines used for program transmission. Simply stated, noise reduction is compressing the dynamic range at the sending end and expanding the signal at the receiving end of the circuit. In the process of expansion the noise is reduced (see Fig. 4). Until the development of the BTSC MTS system, noise reduction techniques could not successfully be used for over-the-air transmission because a complementary expander is required in the receiver. MTS required the use of expanders in the receiver from the beginning of the service. As a result, MTS is the first broadcast service to use companding as an integral part of the transmission system.

Some FM broadcast stations employ a simple limited range compression arrangement for an over-the-air noise reduction system. But because few receivers are equipped with the corresponding expander, the compression must be held to about only 10 dB in order to avoid producing objectional side effects and becoming objectional to the listener.

Noise reduction is built into the BTSC MTS system from the beginning of the service and therefore a high performance system may be employed. Figs. 5 and 6 show how the compressor alters both the dynamic range and high frequency response of the program material according to the content. Dynamic range is reduced from 70 dB to about 40 dB. High frequency material is increased by as much as 30 dB at low levels but virtually not at all at high levels.

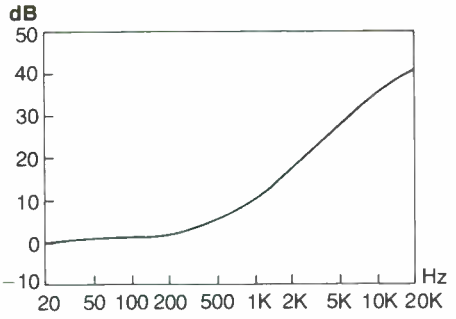


Fig. 5a. Fixed-preemphasis frequency response.

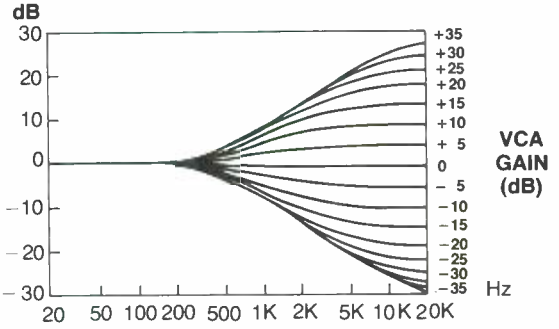


Fig. 5b. Spectral compressor, frequency-response range.

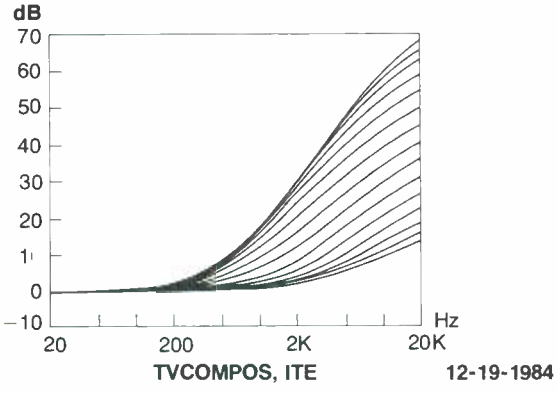


Fig. 5c. Frequency-response range of spectral compressor and fixed preemphasis.

Fig. 5. Spectral compression action. (Courtesy of dbx, Inc.)

The companding system employed by the BTSC MTS system was specifically designed to operate in the comparatively "hostile" environments presented by television transmitters, signal propagation, re-transmission systems (CATV, MATV, translators) and the receiver itself. Thermal and impulse noise, multipath distortion and buzz generated by transmitter and receiver all combine to present formidable obstacles for the companding system to overcome.

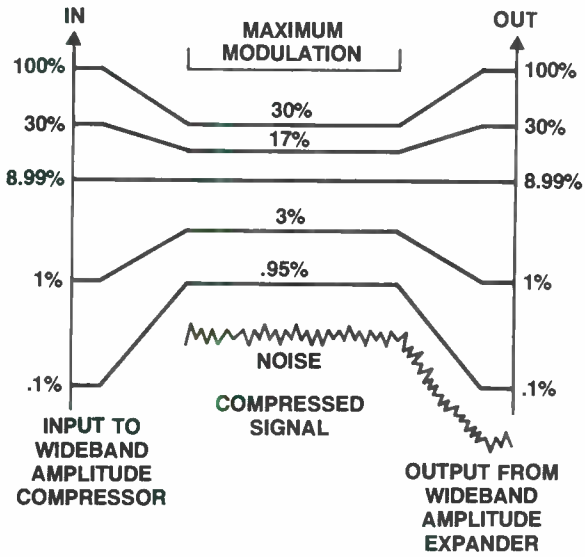


Fig. 6. Companding of (L-R) and SAP. (Courtesy of dbx, Inc.)

The companding system selected for the MTS employs a combination of fixed preemphasis, "spectral" compression, and amplitude compression. The fixed preemphasis combines the familiar 75 microsecond rising frequency response with a 390 microsecond network. The resulting curve is shown in Fig. 5a. By itself this extremely steep preemphasis curve would cause problems with high frequencies. To avoid this, a dynamic "spectral" compressor (variable preemphasis) circuit is employed to increase the gain of low level, high frequency material and reduce the gain of high level, high frequency audio. Only frequencies above about 200 Hz are affected. Fig. 5b illustrates the dynamic characteristics of the spectral compressor. A complicated algorithm involving both the fixed and variable preemphasis produces the sharply rising frequency response shown. Fig. 5c.

The third feature of the companding system is the amplitude compressor which reduces the dynamic range of the input signal by a factor of 2:1 for low frequencies, and 3:1 for high frequencies. In other words, a 40 dB dynamic range audio signal is reduced to 15 to 20 dB or less for transmission (see Fig. 6). In addition to dynamic range compression, the maximum input level applied to the stereo subcarrier is reduced below that required for maximum modulation of the subcarrier. This feature provides some headroom to accommodate instantaneous peaks without resorting to clipping. High level "transients" however are clipped to avoid severe distortion in the reconstruction of the compressed signal in the receiver expander.

The use of companders and noise reduction systems is gaining wide acceptance throughout the broadcast industry. Is is not unusual for a given program to undergo noise reduction processing 5 to 6 times by the time it reaches the viewer. The mis-tracking of a single companding system in the chain may result in substantial errors in the resulting sound which may be more objectionable than the problems the compander was designed to solve. It is essential therefore, that in order to prevent audible artifacts from occurring, only the highest quality systems be employed, properly operated and maintained.

THE SEPARATE AUDIO PROGRAM CHANNEL

Multichannel Television Sound transmission may include a second audio program (SAP) channel in addition to stereo. This SAP channel may be program related or not, as the station chooses. However, if not program related, viewers with the SAP option switch may wonder about the material if it is not related to the picture in some manner. Because it is designed for reception by the public, stations should avoid transmitting non-public material on the SAP channel unless the injection level of the subcarrier is kept below the receiver threshold.

The SAP channel subcarrier is located at 5H in the aural baseband as shown in Fig. 2. Although somewhat noiser at this location in the baseband than if it were placed at 4H, there is less chance for crosstalk to and from the stereo channel. The use of the noise reduction system on this channel provides adequate signal-to-noise ratios and, with the audio response limited to a maximum of 10 kHz, the performance of the SAP is quite good.

The SAP subcarrier is frequency modulated by program material to a maximum deviation of 10 kHz. The subcarrier injection into the main carrier is limited to a maximum of 15 kHz. That is, the subcarrier modulates (deviates) the main carrier by 15 kHz. The subcarrier frequency is locked to 5H when not modulated.

The injection level of 15 kHz by the SAP subcarrier into the main carrier is important. Receivers with SAP decoding equipment will detect the presence of the subcarrier and provide either automatic switching or at least an indicator lamp to the viewer. The receiver decoder will normally be set to activate the SAP circuits when the injection level exceeds about 7.5 kHz. Below this level the receiver will ignore the presence of a subcarrier. To use this portion of the baseband for some purpose other than for program related audio, a subcarrier with an injection of 3 kHz would probably be ignored by most SAP receivers but could of course activate the station's intended receivers. Obviously such a subcarrier could not

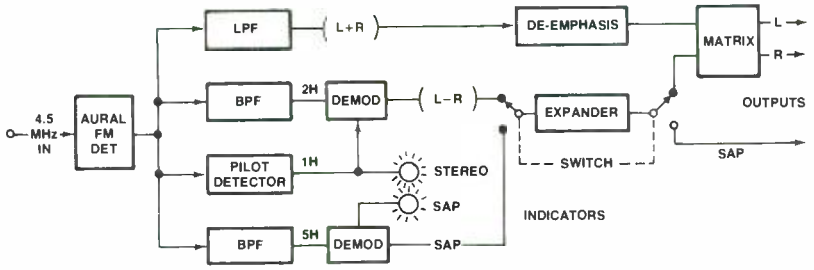


Fig. 7. Typical MTS receiver decoder.

be used at the same time as the regular SAP channel but could be used during stereo or monophonic operation. Fig. 7.

The same noise reduction scheme is used on the SAP channel as for the stereo subcarrier. This permits a single expander to be used in the receiver for either stereo or SAP. Most receivers will provide either stereo or SAP but not both at the same time. To make both available a receiver would need two expanders. Alternatively, the SAP output could be provided without expansion but the output would be highly compressed. The sound would be acceptable for most vocal material but may be objectionable for some music. While the use of a single noise reduction circuit helps the receiver, the broadcaster must deal with maintaining exact levels and performance for two compressors if both stereo and SAP are to be transmitted simultaneously.

OTHER SUBCARRIERS

In addition to providing for stereo and SAP subcarriers, the FCC also allows any other scheme of subcarriers which do not interfere with the operation of BTSC receivers or normal monophonic sound television receivers. When not transmitting stereo or SAP, broadcasters may elect to use the aural baseband for subcarriers for non-program related purposes. Virtually any kind of subcarrier incorporating digital or analog signals of program material or data may be transmitted using AM, FM or other modulation methods. Subcarriers may be placed in the aural baseband between 16 and 120 kHz. The maximum deviation of the aural carrier by other subcarriers is limited to 50 kHz. Any number of subcarriers may be used as long as their total modulation of the main aural carrier does not exceed 50 kHz. The total modulation of the main carrier including main channel sound and non-BTSC subcarriers may not exceed 75 kHz.

Stations should avoid placing other subcarriers within ±15 kHz of the SAP frequency (5H or 78.671 kHz). If the SAP frequency is to be used for non-program related material, the injection level of the subcarrier should be kept below the SAP threshold of the receiver or about 3 kHz deviation. The use of a single subcarrier with 50 kHz deviation should be avoided because of the potential of crosstalk into the main channel in some receivers unless extensive compatibility testing is conducted.

MODULATION SUMMARY

The FCC permits the BTSC specified multichannel sound signal to modulate the main aural carrier a total of 73 kHz. This is produced by the combined monaural and stereo subcarrier deviation of 50 kHz, the pilot subcarrier deviation of 5 kHz, the SAP subcarrier deviation of 15 kHz and the professional use subcarrier of 3 kHz for a grand total of 73 kHz. See Figs. 8 and 9.

Other subcarrier arrangements may modulate the main carrier by as much as 50 kHz. With the main channel at 25 kHz and subcarrier at 50 kHz, the total may not exceed 75 kHz deviation.

PERFORMANCE SPECIFICATIONS

In 1984 the FCC began a series of rulemaking procedures in which many of the technical rules in part 73 of the FCC Rules and Regulations were deleted if they described "quality" characteristics

SIGNAL	MONITORED PARAMETER
MAIN CHANNEL (L+R)	25 kHz PEAK DEVIATION
STEREO CHANNEL (L+R)	50 kHz PEAK DEVIATION
MAIN AND STEREO	50 kHz PEAK DEVIATION
PILOT CARRIER INJECTION	5 kHz PEAK DEVIATION
SAP MODULATION	10 kHz PEAK DEVIATION
SAP INJECTION	15 kHz PEAK DEVIATION
OTHER SUBCARRIER	3 kHz PEAK DEVIATION
TOTAL COMPOSITE	73 kHz PEAK DEVIATION

Fig. 8. Typical modulation monitor functions.

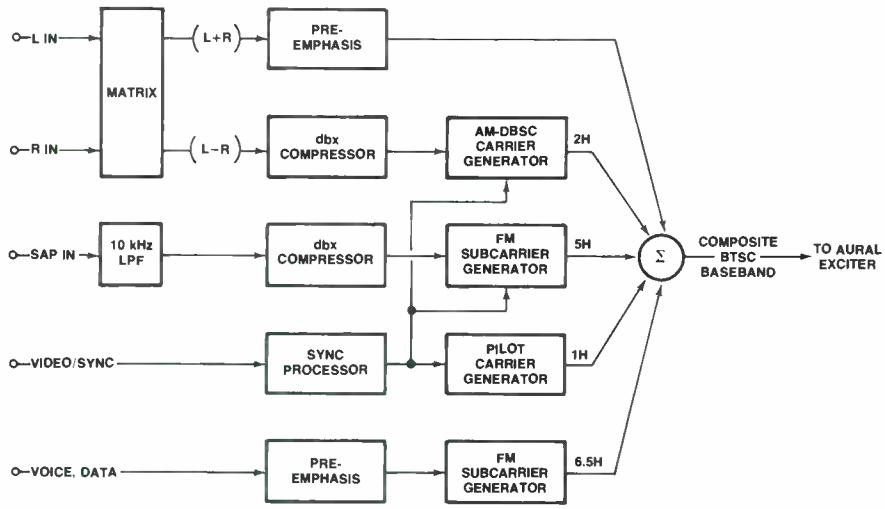


Fig. 9. Typical MTS transmitter encoder.

of the transmitted signal. Hence, the Rules requiring stations to meet certain distortion, frequency response and signal-to-noise performance levels have been eliminated in favor of marketplace pressures to maintain quality levels. Therefore, there are no rules which require minimum audio performance levels. Rules which act to control interference, however, have been maintained where needed.

The Rules which permit multichannel television sound are no different and the user must consult either the manufacturers specifications or the original laboratory test results to determine the sound quality capability of the TV stereo system. The FCC considers new services differently from well established radio broadcast systems that have a track record for quality. Because TV MTS is *new*, several quality specifications are included, not in the Rules themselves, but in a separate document—OST #60, a Technical Bulletin published by the FCC Office of Science and Technology. However, the implementation of MTS is relatively new and the broadcast and receiver industry have produced a series of recommended operating practices, many of which are cited in this chapter.

Because the transmission of stereo sound for television is technically similar to that of FM broadcasting, the reader is encouraged to review the chapter on FM broadcasting and stereophonic transmission elsewhere in this handbook for background information. Portions of the BTSC MTS system description are also contained in the Television Transmitter chapter.

Fig. 10 shows the general performance characteristics of TV MTS which should be achievable under ordinary conditions. While most of the performance objectives indicate the potential for high audio quality, the stereo separation figure may be of some concern to those familiar with the much higher performance of the FM stereo system. The 30 dB figure should be easily acheived in practice. However, it is relatively low because of the use of the companding system and the critical adjustments which must be made in the companding system and the more sophisticated circuits involved compared with the simpler circuits which can produce better than 40 dB separation in FM stereo operation. The tracking gains of the mono and stereo channels determines the relative separation between channels (see Fig. 15a). While it may be possible to maintain a difference of a few tenths of a dB in gain in the sum and difference channels in FM stereo transmission, it is extremely difficult to obtain better than about 0.5 to 0.8 dB in TV MTS. This is because the stereo channel is compressed by the noise reduction system by as much as 20 dB which magnifies the difference when received and decoded in the TV receiver. Improvements in circuit stability in the future may permit an increase in stereo

SIGNAL	RESPONSE	S/N	DIST
MAIN CHANNEL	50-15 kHz	>58 dB	<2.5%
STEREO SUBCHANNEL	50-15 kHz	>55 dB	<1.0%
SAP CHANNEL	50-10 kHz	>50 dB	<3.0%
PROFESSIONAL CHANNEL	100-3 kHz	>40 dB	<3.0%
STEREO SEPARATION	>30 dB		

(Grade B or better TV signal)

Fig. 10. MTS performance objectives.

separation, perhaps as much as 40 dB on a regular basis.

It should be noted that in actual operation there is no "stereo noise penalty" in TV MTS as there is in FM stereo. This is due primarly to the use of the noise reduction system. Further, there is no reduction in deviation of the mono signal during BTSC stereo transmission as there is in FM stereo operation. In FM stereo the main or mono channel must be reduced by 8 to 10% to permit the addition of the pilot subcarrier. This is not the case with TV MTS.

The crosstalk performance values are probably the single most important technical parameter with which the broadcaster must be concerned. Crosstalk less than those values shown in Fig. 11 will be caused by systems external to the stereo transmission equipment itself. Non-linearities in the TV aural exciter and power amplifier stages, combining networks, antenna switching components and the antenna itself constitute the main areas in the station where crosstalk can be generated. In general, the crosstalk into the stereo signals from the SAP will be less than crosstalk from the main channel into the SAP signal. As long as these levels do not become excessive, most crosstalk will be concealed by the companding system.

Other sources of crosstalk are multipath distortion due to poor VSWR of the transmission line and antenna, multipath during the propagation of the transmitted wave and improper matching of the antenna and receiving system. In general, the expander can conceal noise and crosstalk in the stereo and SAP channels by as much as 30 dB.

CROSSTALK	OBJECTIVES
MAIN INTO STEREO	>40 dB
STEREO INTO MAIN	>40 dB
MAIN INTO SAP	>50 dB
SAP INTO MAIN	>60 dB
OTHER SUB INTO MAIN	>60 dB
OTHER SUB INTO STEREO	>60 dB

Fig. 11. Crosstalk objectives.

INCIDENTAL CARRIER PHASE MODULATION

The control of incidental carrier phase modulation (ICPM) in the visual transmitter is the single most important performance characteristic of the transmitter that can affect the quality of multichannel sound. ICPM will cause buzz in intercarrier sound receivers. Intercarrier type receivers will be used for multichannel sound reception because of their high immunity to "common mode" phase modulation found in various systems in the path of the television signal before it reaches the receiver. Such common mode phase modulation can occur in TV translators, MATV downconverters, and CATV headend and set-top converter equipment. In intercarrier type receivers, the aural and visual carriers beat together in the video detector to produce the 4.5 MHz sound signal. Because common mode phone modulation affects both carriers, the phone modulation is factored out of the 4.5 MHz carrier.

On the other hand, phase modulation of the visual carrier in the transmitter which is independent of the aural carrier, will produce undesired phase modualtion of the 4.5 MHz in the receiver and the result will be the familiar buzz. Phase modulation in the visual transmitter can be caused by hum in the carrier frequency oscillator, nonlinearities in the IF and power amplifier stages, and especially the visual modulator. UHF transmitters which use klystron anode pulsers to achieve higher operating efficiencies may have phase modulation caused by the pulser modulating the visual amplifier power supply at a 60 Hz rate and a 15 kHz rate. The higher frequency is not heard by most viewers but the lower frequency is heard as a raspy buzz. Pulsing the visual amplifier may cause crosstalk through the common power supply into the aural amplifier. The resulting 15.734 kHz modulation, if high enough, may cause false indications of the stereo indicator on MTS television receivers as will high ICPM.

ICPM in visual transmitters should be adjusted to be less than 3 degrees during luminance and to less than 5 degrees during sync. See Fig. 12.

ICPM manifests itself as differential phase in the demodulated video. Measurement instrumentation requires a TV demodulator with both envelope and quadrature video detectors and a waveform monitor with proper graticules. After measuring ICPM or listening for buzz on a stereo television receiver to determine if ICPM is present, make the necessary phase adjustments and retune RF stages as appropiate. Adjustment of

DEGREES ICPM →	1°	2°	3°	4°	5°
BASEBAND BUZZ LEVEL IN dB BELOW 25 kHz DEV. ("WORST CASE")	−50	−44	−40	−38	−36
STEREO SBR dB	56	50	46	44	42
SAP BUZZBEAT THD dB	−49	−43	−39	−37	−35

NYQUIST SLOPE EQV. ICPM = { 2.4° AT (L-R) SUBC. / 6° AT SAP SUBC.

Fig. 12. Intercarrier buzz and buzzbeat levels. (Courtesy J.J. Gibson, RCA)

ICPM will affect video differential phase. Once ICPM is corrected, adjust video correction cirtuits to compensate for differential phase.

ICPM will be more noticeable on television receivers with multichannel sound capacity. Although some buzz may be heard in the main channel, the ICPM will affect the subcarriers to a greater extent. In addition, the improved audio quality in the new multichannel receivers will make any existing buzz more noticeable even when transmitting monaural sound. Therefore, broadcasters not contemplating multichannel transmission should investigate the ICPM condition of their transmitters with an ear toward improving the quality of the mono sound on both stereo and mono receivers.

COMPATIBILITY WITH EXISTING RECEIVERS

During the testing of the BTSC multichannel sound system considerable effort was spent evaluating the effect of a fully loaded BTSC system on existing monophonic television receivers. Extensive compatibility testing of a wide range of receiver makes and models, under extreme transmission conditions revealed virtually no significant degradation to either the sound or picture of the desired or adjacent channel, as noted by trained observers.

Modern monophonic television receivers should not experience any significant degradation when receiving a TV MTS signal. In fact there may actually be a noticeable improvement in the sound quality on a monophonic receiver due to the increased attention paid to the stereophonic sound signal production and processing and lower visual transmitter ICPM. This desirable side benefit should also offset the slight reduction in monophonic modulation level which will result when transmitting a mostly left or right channel sound. Because the main channel is the sum of left plus right, a right or left-only signal will produce 6 dB less modulation than the sum signal. However, producers seldom employ left or right-only signals and as a result the actual reduction will be something between 0 and 6 dB. It could be argued that these several dB could reduce the apparent "loudness" of the stereo station when compared to a monophonic station. The argument will cease as more television stations install stereo transmission facilities.

COMPATIBILITY WITH CATV SYSTEMS

During the testing of the TV MTS system considerable attention was paid to the ability of the MTS signal to pass through MATV and CATV systems. Cable headend, distribution and subscriber equipment was used to conduct the various tests. A concern that the upper adjacent visual channel might be affected by the wider MTS modulated aural carrier of the lower channel was not confirmed. In general, those CATV systems which process off-air signals in an RF mode (that is, not demodulated) will have little difficulty in successfully processing and passing an acceptable MTS signal through their system.

Cable systems with demodulating type headend and/or subscriber equipment may not be able to pass MTS signals without substantial degradation to the subcarriers due to the use of low pass filters in the audio portions of the demodulator facilities. However, it can be expected that equipment manufacturers will accommodate the BTSC system in future designs.

The BTSC MTS signal should also pass through most amplitude modulated link (AML) microwave systems used by many cable companies for wide area distribution of multiple channels without significant degradation.

COMPATIBILITY WITH TELEVISION TRANSLATORS

Television translators using heterodyne or direct RF conversion techniques should not cause significant degradation to MTS signals if the translator is properly maintained. However, some translators receive little attention unless they fail completely. In general, unless the picture and sound are severely degraded, or visible or audible interference is present due to improper operation of the translator, then the MTS signal will probably pass through the system with little degradation.

Remodulating type translators however, may require modifications to accommodate the MTS signal. A wider audio bandpass, to accept the subcarriers, and improved visual transmitter oscillator stability and low ICPM are some of the improvements required to properly retransmit the MTS signal.

Fig. 13 shows what kinds of transmission impairments may cause various audio impairments.

OPERATING PRACTICE

Fig. 2 shows the composite baseband signal that is used to modulate the aural carrier. In addition to the main, pilot and stereo subcarriers there is the SAP and professional use subcarriers which are discussed in other sections. The main channel contains the sum of the left and right or "sum" audio which may be received without

EFFECT / CAUSE	BUZZ	SAP BUZZ BEAT	NOISE & NOISE PUMPING	REDUCED STEREO SEP	DIST.	X-TALK
NON-LINEAR PIX	✓					
NON-LINEAR SOUND					✓	✓
MISMATCHES						✓
DIPLEX FILTER					✓	✓
ICPM	✓	✓				
MULTIPATH	✓	✓	✓	✓	✓	✓
WEAK SIGNALS			✓	✓		
CO-CHANNEL					✓	✓
MISTRACKING				✓		
REC. FILTERS	✓	✓		✓	✓	✓
FM DETECT	✓				✓	✓

Fig. 13. Effects of transmission impairments. (Courtesy J.J. Gibson, RCA)

degradation on ordinary monophonic receivers. The left minus right or difference channel is contained on a double sideband, suppressed carrier amplitude modulated carrier at two times the TV horizontal rate (2 X 15.734 kHz = 31.568 kHz). The subcarrier is suppressed to avoid wasting modulation capability. The energy in the sidebands however, is permitted to deviate the main aural carrier by as much as 50 kHz.

In order to properly decode the signal it is necessary to reinstate the carrier in the receiver on the exact frequency and nearly the exact phase as the original. To accomplish this a "pilot" signal is transmitted at a frequency of the TV horizontal rate (15,734 Hz). The pilot modulates the main carrier with a deviation of 5 KHz.

The pilot carrier also carries phase information with it for proper demodulation of the stereo subcarrier. The phase of the pilot carrier wave zero crossings in relation to the stereo subcarrier zero crossings should be within 3 degrees. No such tolerance is specified in the FM broadcast rules.

The pilot carrier must be protected from the main audio so as not to contaminate it upon reception which would degrade the ability of the receiver to produce high quality results. A fairly sharp low pass filter must be used in the transmitter to cut off audio frequencies above 15 kHz and provide a notch at 15.734 kHz.

Between 25 and 30 dB protection is considered adequate. Above 15.734 kHz the response should roll off rapidly to 50 to 60 dB in order to protect the stereo difference channel which contains sidebands between 16.5 kHz and 46.5 kHz. Fig. 14 shows the response of a typical low pass filter for use in television stereophonic sound transmission facilities.

The pilot is transmitted at a deviation of 5 kHz ±0.5 kHz. The receiver pilot detector threshold is nominally set to activate the stereo circuits at aural carrier deviation levels of about 2.5 kHz. To provide the receiver with an ample pilot level, it is essential that modulation products at 1H, from whatever source, be reduced to less than 1 kHz aural carrier deviation, or about 30 dB below maximum 25kHz deviation. In *monophonic* transmitters, the band in which the pilot would be located can easily be contaminated by:

1. Audio program material at 15.734 kHz;
2. Horizontal rate crosstalk from the visual transmitter; and
3. RF components from the visual transmitter passed through the aural and visual combining networks at the output of the transmitters.

For example, a simple matter of a studio microphone picking up the "screech" of a horizontal oscillator from a nearby video monitor can produce enough modulation at 1H to produce a false indication in a BTSC equipped receiver. Special

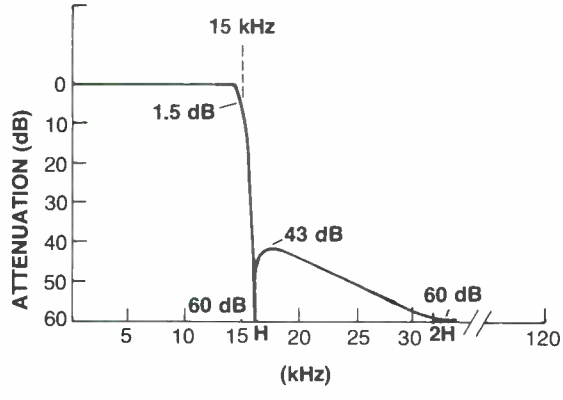


Fig. 14. Audio input low pass filter.

precautions are taken in transmitters designed specifically for multichannel sound operation to protect the pilot. Operators of monophonic transmitters should also check their facilities for residual 1H signals in either the aural transmitter or in the combining network at the output of the transmitters. Monophonic audio inputs to transmitters should incorporate a 15 kHz low pass filter.

For good stereo operation it is necessary that the left and right channels remain well separated before, during and at the end of the transmission chain. The amplitude and phase of the mono and stereo signals must be nearly identical and the phase of the pilot carrier must be maintained. Channel separation as a function of these three factors is given in the following equation:

$$\text{Separation in dB} = 20 \log_{10} \left[\frac{(\cos\theta + \frac{S}{M}\cos\phi)^2 + (\sin\theta)^2}{(\cos\theta - \frac{S}{M}\cos\phi)^2 + (\sin\theta)^2} \right]^{1/2}$$

Where:

M = the gain of the main (L + R) path and
S = the gain of the stereo (L − R) path
ϕ = the phase error of the reinserted 38kHz subcarrier that is twice the phase error of the 19kHz pilot carrier
θ = the difference in phase between the (L + R) and (L − R) paths.

The implementation of multichannel sound in a television facility which has not dealt with stereo or multiple audio channels in the past will find the experience to be a challenge. Virtually all audio equipment in the station will need to be reviewed, reworked, rewired, or replaced when adding new audio channels. Video tape machines, routing switchers, master control switching and monitoring, studio audio facilities and the STL will require close examination to determine how to implement extra sound channels. Video tape equipment with two sound channels may require new test procedures to determine that the phase relationships between channels is correct.

Studio to transmitter links will need additional channels for stereo and/or SAP audio. Consideration should be given to a composite BTSC signal for transmission over the STL. Special attention must be paid to audio processing. There will be a tendency towards maximizing the loudness of the signal rather than to moderate processing which will result in a more acceptable stereo sound quality.

Multichannel sound equipped television receivers have substantially improved audio system which will not require "loudness", but will emphasize audio faults now concealed by most television receivers. As a result, special attention must be devoted to the audio transmission facilities of all television stations, whether transmitting monophonic or multichannel sound.

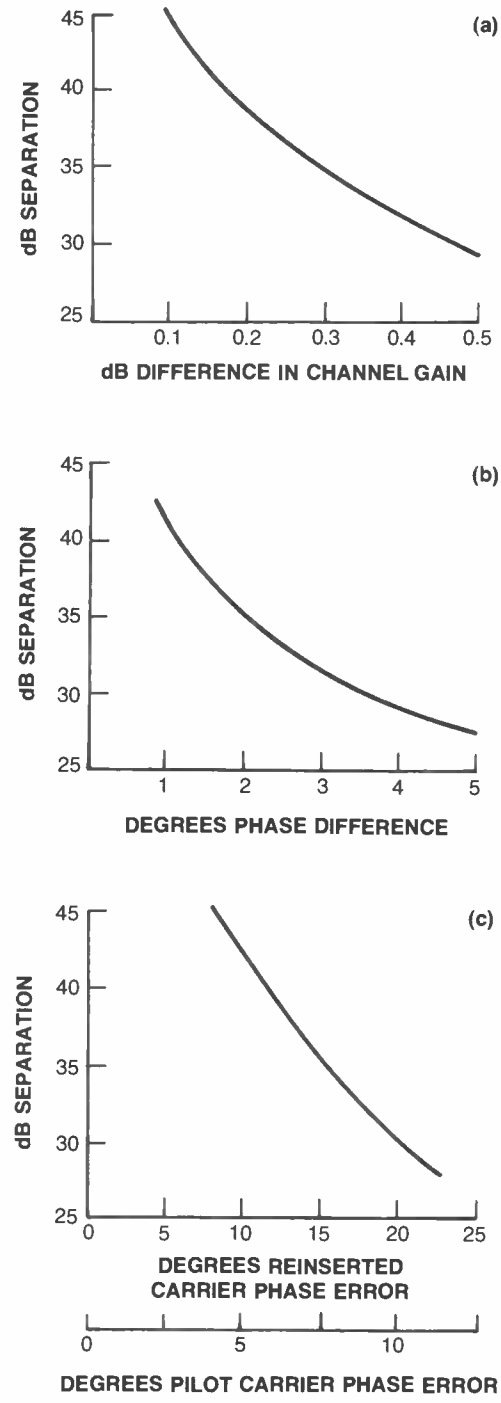


Fig. 15. Stereo separation versus (a) amplitude difference between main and stereo channels, (b) phase difference between main and stereo channels, and (c) error in phase of pilot or reinserted carrier.

3.7

Transmitter Control Systems

Fred A. Barbaria and Daniel L. Barnett
Moseley Associates, Inc.
Goleta, California

INTRODUCTION

One of the standard operating techniques used at broadcast stations is the remote control of transmitters. In 1953, the Federal Communications Commission (FCC) first authorized nondirectional stations up to and including 10 kW to operate by remote control. During 1957, the Commission, at the request of the National Association of Broadcasters (NAB), amended its Rules and extended remote control privileges to all types of standard AM and FM broadcast stations regardless of power or mode of operation. In 1963, the Commission, on its own motion, amended Part 73 of the Rules to permit the remote control of UHF television transmitting facilities. In 1971, again at the request of the NAB, the Rules were once again amended to permit the remote control of all television transmitting facilities regardless of frequency or type of operation. This enactment by the FCC permits remote control of all types of broadcast transmitters regardless of the service. In 1977, the FCC amended the Rules to allow control of AM (nondirectional) and FM stations with Automatic Transmission Systems. In 1984, the FCC amended the Rules to combine all classes of service under a uniform code and to relax the requirements of remote control. The history of FCC rule-making essentially has followed the history of transmitter plant reliability.

Several motives exist for using Transmitter Control Systems. The first is to allow unmanned operation at the transmitter site. Transmitter Control Systems allow an operator to activate and deactivate a transmitter from a distant control point. They relay required transmitter operating parameters to the control point. The systems allow the operator to make adjustments to the transmitter from the control point to ensure correct operation of the transmitter. Furthermore, the systems provide remote indications concerning security and environmental conditions at the unmanned transmitting plant.

The second motive for using transmitter control systems is to assist the operator at a control point in performing his duties correctly. Recent Transmitter Control Systems have digital displays, can be calibrated in engineering units, and have built-in power-to-linear and other conversions, allowing the operator to read the transmitter operating parameters directly, without interpolation or chart look-ups. In addition to displaying values, alarm conditions can be programmed into most transmitter control systems. For example, telemetry tolerance alarms can be provided to warn the operator that the transmitter is not operating within its specified limits. Status alarms can be provided by the system to notify the operator that something is amiss at the transmitter plant. To enhance system observation further, CRT displays may be used to provide an over-

view of the transmitter system. Diagnostics may be provided to the operator to help determine a cause of failure in the transmitter or the control system. Finally, automatic logging may be implemented to record routine information for trend analysis, and may initiate event-triggered logs to record transients and document emergencies of the transmitter plant. The log can also form the basis of a transmitter log to meet company or station requirements and can be provided to the FCC in the case of operating complaints against the station.

The third motive for using transmitter control systems is to automate certain functions of the operator. Automatic Transmitter Systems (ATS) provide the first of two methods for automation. These systems allow completely unmanned operation, providing a means to turn the transmitter on and off still exists. The ATS will monitor and adjust antenna input power for AM (or transmitter output power for FM) and modulation levels according to a rigid formula spelled out in the rules. The ATS will also take the transmitter off the air in case of failure or deviation from the acceptable operating limits.

Automatic Control Systems provide the second method of automation. These systems are intended to be adjuncts to standard remote control systems. Control ladders may be set up to perform sequences of action, and the systems may be used to perform trims, i.e. take action to keep particular telemetry values within specified tolerances. Operation of these sequences may be triggered on day, date, time, trouble conditions, operator activation, or other trigger conditions accessible via the remote control system.

CURRENT FCC REGULATIONS CONCERNING TRANSMITTER SYSTEMS

The December 1984 FCC Rules changes significantly altered the character of the sections pertaining to the Remote Control of transmitters. The intent of these changes was to "place responsibility on each licensee to assure compliance with the station authorization." As a result, the specific details of remote control operation have been left for the most part to the station licensee. This should allow maximum flexibility in meeting the requirements of remote control operation.

The key requirement of the new Rules is "Broadcast stations operated by remote control must provide at remote control points sufficient control and operating parameter monitoring capability to allow technical operation in compliance with the Rules applicable to that station and the terms of the station authorization." What is "sufficient" is left up to the licensee, and leaves room for individuality of station operation.

The failsafe requirements of the new Rules state that if a malfunction occurs which causes a loss of accurate meter readings, remote control operation may not continue beyond three hours after the malfunction is detected. Also, if the station is operating out of its authorization, and the problem cannot be solved by remote control, then operation must be terminated immediately. The telemetry failsafe function of remote control systems meet the first requirement above. If metering of particular channels vanishes or if the Control Terminal does not receive communications from the Remote Terminal then an alarm will occur to alert the operator that corrective action must be taken within three hours.

Requirements for television operation include off-air visual demodulators, and modulation and waveform monitors. Further information may be found in this chapter under "Elements of a Transmitter Remote Control System," and elsewhere in this handbook.

ATS failsafe requirements are somewhat different than those of remote control systems. An ATS failsafe is required to terminate transmission when any of the following conditions occur for a 3-minute period:

1. The automatic power-adjustment circuit fails.
2. The automatic modulation-adjustment circuit fails.
3. The mode-switching time clock fails (AM only).
4. The monitoring and alarm point cannot communicate with the ATS.
5. Any of the alarm systems functions fail, or
6. Sampling function are lost.

Be sure to consult the latest FCC Rules before making any changes or additions to your station operation. The sections applicable to transmitter control systems are:

AM ATS
73.140 Use of Automatic Transmission Systems (ATS)
73.142 Automatic Transmission Facilities
73.144 Fail-Safe Transmitter Control for Automatic Transmission Systems
73.146 Automatic Transmission System Monitoring and Alarm Points

FM ATS
73.340 Use of Automatic Transmission Systems (ATS)
73.342 Automatic Transmission Facilities
73.344 Fail-Safe Transmitter Control for Automatic Transmission Systems

73.346 Automatic Transmission System Monitoring and Alarm Points

Non-commercial Educational FM ATS
73.540 Use of Automatic Transmission Systems (ATS)
73.542 Automatic Transmission Facilities
73.544 Fail-Safe Transmitter Control for Automatic Transmission Systems
73.546 Automatic Transmission System Monitoring and Alarm Points

Remote Control
73.1400 Remote Control Authorizations
73.1410 Remote Control Operation

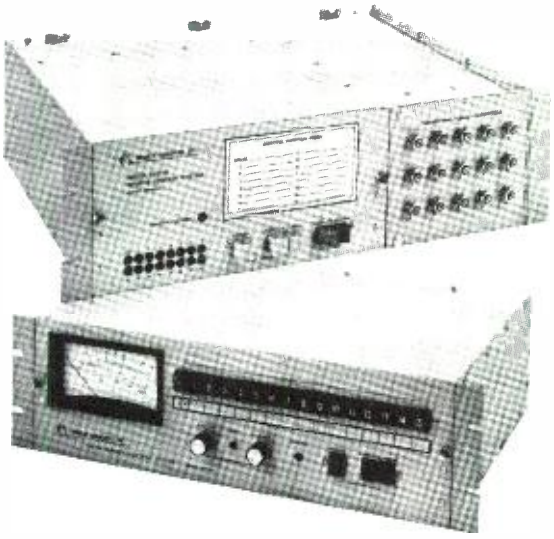


Fig. 1. Analog remote control system.

BASIC THEORY OF OPERATION

There are essentially two kinds of remote control systems, analog and digital. Early remote control systems were analog designs, i.e. their circuitry used a continuous range of voltage levels to operate. A typical analog remote control system is shown in Fig. 1. Its block diagram is shown in Fig. 2. Recent remote control systems are digital designs, i.e. their circuitry uses discrete voltage levels to operate. A binary (two-level) scheme is usually used. A typical digital remote control system is shown in Fig. 3; a typical digital block diagram is shown in Fig. 4. In analog systems, meters are used to take readings. Meters have inherent limitations in accuracy, generally limited to about 2%. Thus analog systems are also limited in their accuracy to about 2% which is the requirement under FCC rules. In digital systems, multi-digit displays are used to take readings. The accuracy of digital systems is theoretically limited only by the number of digits displayed, and the number of bits (binary pieces of information) used internally to convert the analog inputs to digital data. Accuracy of 0.5% or better is available with today's remote control systems. Calibration of analog systems typically requires two people, one at the transmitter tweaking the calibration potentiometer on the remote control system, and the other watching the meter from the studio, telling the first when to stop. In addition, daily calibration from the studio is often required to maintain specified accuracies. Calibration of digital systems, however, only requires one person. This is accomplished at the transmitter site by entering a series of keystrokes

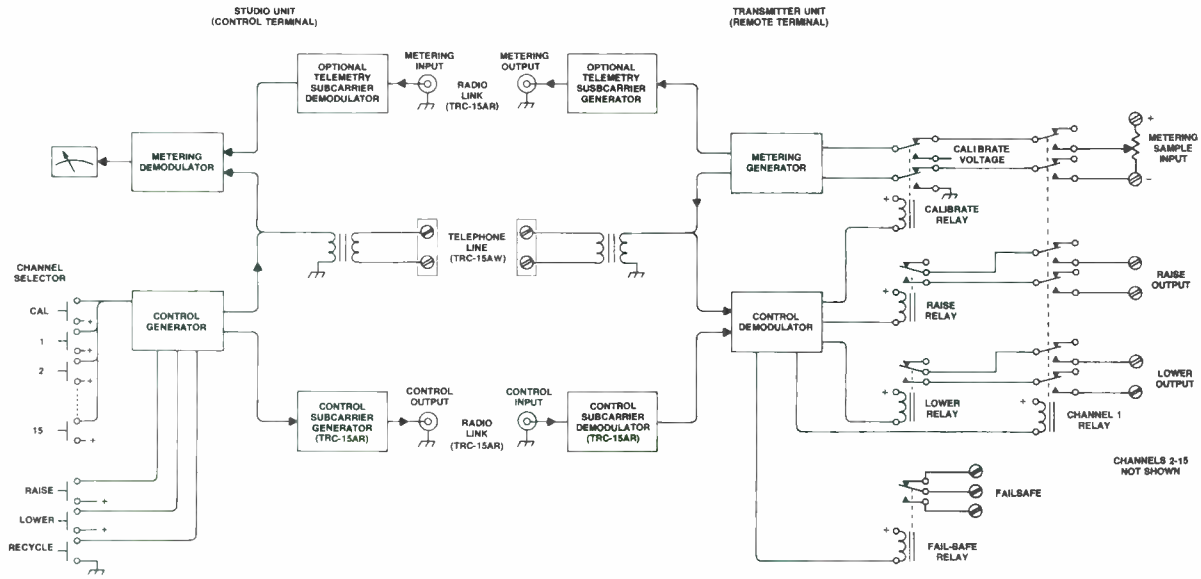


Fig. 2. Analog remote control block diagram.

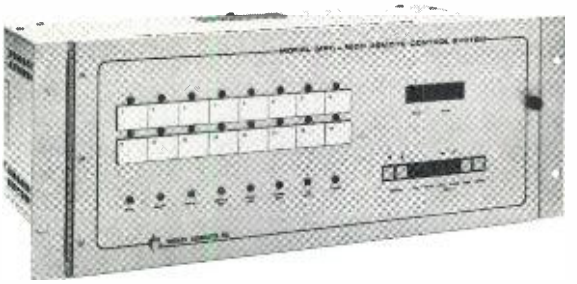


Fig. 3. Digital remote control system remote terminal.

on the front panel of the remote control system. Daily calibration is not required to maintain system accuracy. In addition, power-to-linear and other conversions are usually built in, eliminating the need for some external interface boxes. Communication between the studio and transmitter units of an analog system is usually accomplished with a series of tones; the duration or frequency of the tones determines the action to be taken. In digital systems, the tones take the form of digital words so that, in essence, the studio and transmitter units talk to each other in sentences. Much of the added flexibility of digital remote control systems has resulted from the use of microprocessors in their design.

Microprocessors can be found in almost any recent digital design of any complexity, and transmitter control systems are no exception. A microprocessor is a machine which executes instructions, usually stored in some form of ROM (Read Only Memory), which modify the contents of RAM (Random Access Memory), or which perform some I/O (Input/Output) function (see Fig. 4). By using microprocessors, designers can specify an arbitrary set of logic instructions (software) that will most readily accomplish the task at hand. In our case, that task is the (remote) control of transmitters. A microprocessor is usually the heart of each main component in a transmitter control system.

The part of the transmitter control system that interfaces directly to the transmitter can be called data acquisition and command. This is the I/O between the system and the transmitter. Data acquisition includes telemetry (analog) inputs, status (on/off) inputs, and binary or BCD (Binary Coded Decimal) inputs. Commands are the raise and lower outputs to the transmitter. Other outputs to the transmitter plant can include analog or digital (binary or BCD) outputs.

User setup (calibration) is mostly performed from the Remote Terminal front panel located at the transmitter plant. The setup parameters for each channel can include analog input mode (millivolt, linear, power, indirect, etc.) analog limits (one or more sets, upper and lower), status attributes (invert, latch), status alarms (rising edge, falling edge), and command output type (momentary, pulsed, latched). Setup parameters must be protected from power outages and several methods can be used. Battery backup is usually fairly inexpensive, but has a limited backup time (a few hours). Disk drives hold large amounts of data, but have moving parts that must occasionally be serviced. EEPROMS (Electrically Erasable Programmable Read Only Memories) have long retention times (about 10 years) and take up very little room, since they are integrated circuits.

Communication between the studio and transmitter can either be full-duplex (both ends talking at the same time) or half-duplex (one end talking at a time). Because of bandwidth limitations of phone lines, the rate of communication is usually limited to 300 baud for full-duplex and 1200 baud for half-duplex. The medium between the studio and the transmitter may be dedicated phone lines or subcarriers on an STL. The medium between the transmitter and the studio may be a dedicated phone line, a TSL, or a subcarrier or subaudible channel on the main carrier. Subaudible is not recommended for digital systems because only very limited bandwidth is available for the data.

All day-to-day operation is done at the studio from the Control Terminal. The operator may take telemetry and status readings, and make adjustments to the transmitter using the appropriate raise or lower command as required. Optionally, commands may be initiated via a direct command panel. Alarms generated by the system may be acknowledged by the operator and/or recorded by the automatic logger. In addition, the operator may overview the transmitter control system with a CRT display.

ELEMENTS OF A TRANSMITTER REMOTE CONTROL SYSTEM

A transmitter control system, whether it be for radio or television transmitter control, consists of several key elements. These key elements are the operator, who is normally located at a studio or master control room location; the Control Terminal sometimes called a (''studio unit''), located adjacent to the operator, the Remote Terminal (sometimes called a ''transmitter unit''), located adjacent to the equipment being controlled; and last, the equipment actually being controlled, which includes a broadcast transmitter and other equipment located at the transmitter plant, which is often called the ''remote site''.

The transmitter control system provides the necessary interfacing between these four key elements to allow the operator to properly monitor and control the transmitter plant,

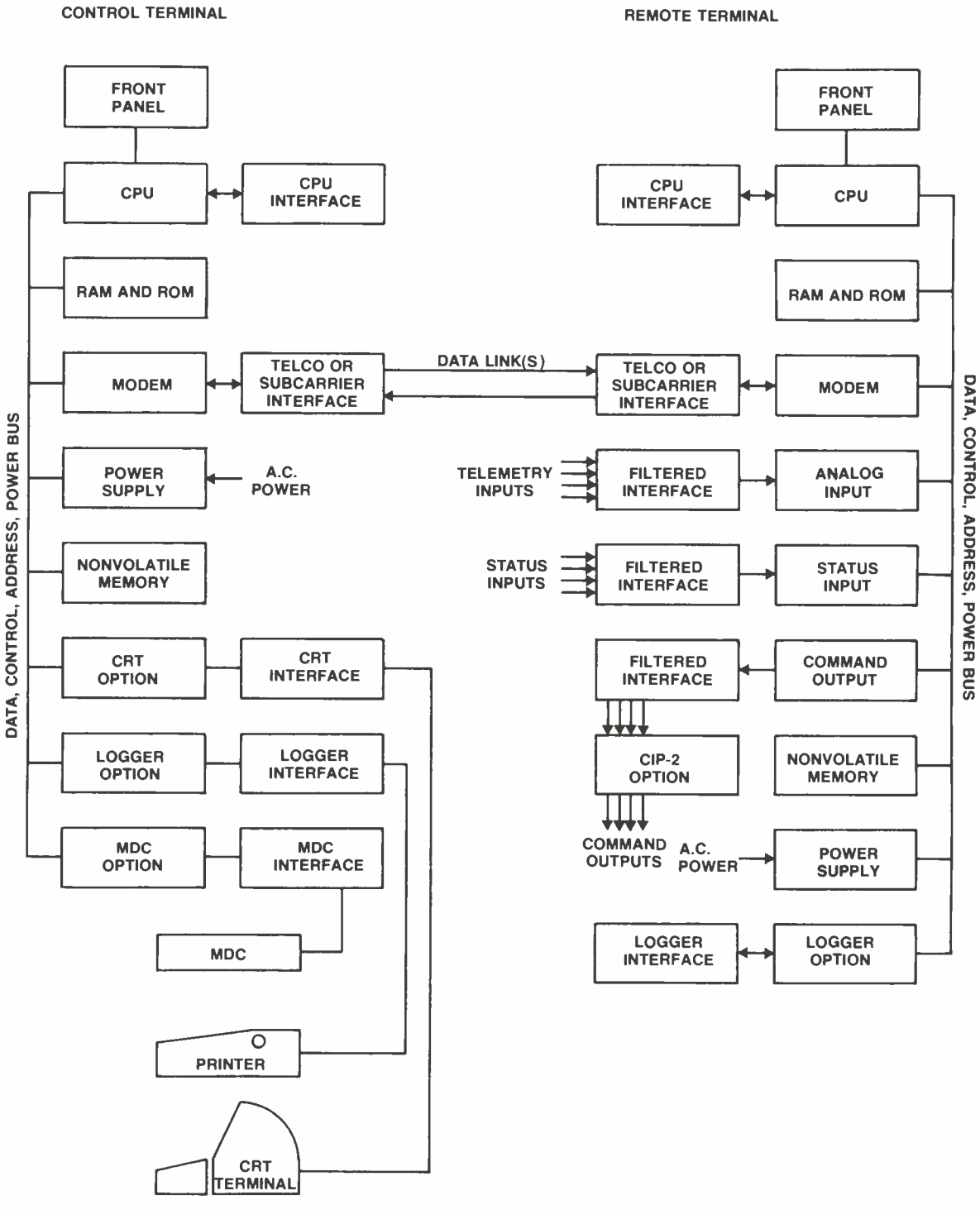


Fig. 4. Digital remote control block diagram.

whether it is on the other side of the building or miles away at a mountaintop transmitting site.

Control Terminal

The Control Terminal, located at the main control point, normally consists of a rack-mounted unit. Since most present-day remote control systems are microprocessor-based, the Control Terminals have become quite small, on the order of two to four rack units high. This minimizes the transmitter control system space requirements in the control room, where space is often at a premium. A typical Control Terminal, such as the one shown in Fig. 5, normally includes digital displays for telemetry and perhaps status monitoring as well as keyboards for calling up the individual telemetry and/or status channels and issuing commands to the transmitter plant. Modern transmitter control systems usually include the ability to program tolerance limits on telemetry channels so that the operator does not have to continually monitor those channels for compliance with the FCC Rules and Regulations.

Fig. 5. Remote control system control terminal.

Aural transmitter power output, for example, is often monitored automatically for tolerance limits. Similarily, status channels (on/off) may be monitored for changes in states that require alerting the operator. Smoke detectors, intrusion alarms, and transmitter overload indications are typically set up within the transmitter control system for operator alarms. The benefit of having the transmitter control system monitor both telemetry and status alarms is that the control room operator or disc jockey can concentrate on their other duties while being assured that the transmitter system is operating within the predetermined limits programmed into the remote control system, and that the transmitter plant buildings and equipment are inaccessible by unauthorized persons.

The typical interface between the operator and the Control Terminal is via the Control Terminal front panel, with its digital displays, LEDs, and keyboard. Accessory CRT terminals are often available for transmitter control systems to simplify the interface between the operator and the control terminal. Some CRT displays, such

Fig. 6. CRT display.

as the one shown in Fig. 6, include alphanumeric text capability. This text is normally programmed on site by the user, so that it can be changed if desired. On some systems, multiple CRT terminals may be installed at alternate control points within a studio complex to allow transmitter control to be shifted between control rooms during the broadcast day. The current FCC rules regarding control points for broadcast transmitters should be studied carefully before planning such a system, however.

An automatic logging option is available for many transmitter control systems. This option prints selected (or all) parameters on a printer at predetermined intervals. Most systems also will print the parameters if an out of tolerance telemetry condition or status alarm occurs. Some systems also allow the user to program heading text that will print at the top of each log page. A typical remote-control-system-generated log page is shown in Fig. 7.

Multiple direct command panels are available for some remote control systems; these panels allow the operator to access a given control function by pressing a single button. Similarly, remote status panels are also available for some advanced remote control systems. If access to multiple direct command panel buttons as well as the status panel indicator lamps is provided by the manufacturer, a relatively inexpensive "mimic" panel can be built by station personnel, customizing the installation to the station's transmitter plant configuration. Automatic control units, described in a previous section, are also available for some Control Terminals.

Some advanced transmitter control systems support more than one Control Terminal for those installations that have widely separated control points. Control of the transmitter may be

MRC-1600 Automatic Logging Option

MOSELEY ASSOCIATES, INC.
111 Castilian Drive
Goleta, CA 93117

The header, logged channels, and logging intervals are all user programmable.

TIME	Filament Voltage	Plate Voltage	Plate Current	Output Power	Refl. Power	Intake Temp.	Exhaust Temp.	Alarm System	Tower Lights
08:00	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
08:30	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
09:00	6.2	7.43	2.12	98.8	97.	27.5	56.9	On	On
09:30	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
10:00	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
10:30	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
11:00	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
11:23	ALARM - Status Channel 14: *Off								
11:24	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	*Off
11:30	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
12:00	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
12:30	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
13:00	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
13:30	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
14:00	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
14:30	6.2	7.43	2.12	98.7	97.	27.5	56.9	On	On
14:46	ALARM - Analog Channel 04: 105.1>								
14:47	6.6	7.93	2.12	105.3>	97.	27.5	56.9	On	On
15:00	6.6	7.93	2.12	105.3>	97.	27.5	56.9	On	On
15:30	6.6	7.93	2.12	105.3>	97.	27.5	56.9	On	On
16:00	6.6	7.93	2.12	105.3>	97.	27.5	56.9	On	On
16:30	6.6	7.92	2.12	105.2>	97.	27.5	56.9	On	On
17:00	6.6	7.92	2.12	105.2>	97.	27.5	56.9	On	On
17:30	6.6	7.92	2.12	105.2>	97.	27.5	56.9	On	On

Fig. 7. Automatic logger output.

passed back and forth between the Control Terminals. Again, current FCC Rules regarding control points for broadcast transmitters should be studied carefully before planning such a system.

Remote Terminal

The transmitter control system Remote Terminal, although tucked away in a rack at the transmitter site, forms the heart of the remote control system. It must be able to withstand high intensity RF fields, and "dirty" electrical power, yet still properly relay commands from the control point as well as convey telemetry and status signals from the transmitter plant to the studio. It is extremely important that the Remote Terminal be installed with adequate ventilation, which is a requirement for any rack-mounted equipment. In addition, the rack must be properly grounded to minimize RF interference (RFI). Lightning is sometimes a problem with transmitter control systems, especially as telephone lines are often used to interface to the Control Terminal. It is recommended that both telephone lines and the ac mains be installed underground for the last several hundred feet at the transmitter plant. In addition, lightning arrestor equipment should be used to protect both the ac mains and incoming telephone lines. Most Remote Terminals include some surge protection, but this protection is not intended to dissipate the enormous amounts of power generated by a direct lightning hit or even a near miss.

Newer radio and television transmitters include facilities for supplying telemetry samples, status closures, and command inputs to the transmitter. Accessory sampling and control kits, described later in this chapter, are available for assisting in interfacing older transmitters to remote control systems. The transmitter and/or remote control system manufacturer should be able to recommend interfacing techniques for transmitters that were not initially designed for remote control operation. Even some of the newer transmitters may require interface accessories to properly connect to the transmitter control system selected.

Telemetry (or analog or metering) samples into the Remote Terminal should normally be in the range of 1 to 4 Vdc full scale. Larger samples will normally have to be brought down by the use of voltage divider networks; smaller samples may be prone to inaccuracy due to hum and RFI on the samples, but if relatively clean, may be amplified by using a commercially available dc amplifier.

Metering inputs to a Remote Terminal may be either single ended (one side of input grounded) or floating (two sample lines, neither grounded, sometimes called differential). Some Remote Terminal analog telemetry inputs will tolerate a large amount of "float", (common-mode voltage) while others will only allow a few volts of potential above ground (or ground one side of the input). Samples with a large amount of common-mode voltage, such as cathode current samples, can be brought down near ground potential by the use of a dc isolation amplifier. In any event, it is not a good idea to apply samples floating more than about 50 volts above or below the ground to a Remote Terminal due to potential shock hazard while operating or servicing the equipment.

The transmitter control system manufacturer's input specifications should be studied carefully as to telemetry sample level, impedance, and configuration requirements. The Remote Terminal should be located directly adjacent to the transmitter(s) it is metering and controlling, and shielded cable may be required to eliminate RFI on the sample lines.

Most transmitter control systems allow telemetry inputs to be scaled for the proper readings given a representative sample of an actual parameter such as plate voltage. To illustrate, the actual plate voltage may be 7500 volts, the sample input to the Remote Terminal may be 2.5 volts, and the remote control system calibrated for a reading of 7500 by either the use of a potentiometer or a keyboard. Keyboard calibration simplifies metering calibration and verification at the transmitter site. In addition to linear calibration, many remote control systems offer power-to-linear conversion and product calibration (for indirect power). These types of calibration are accomplished in software and stored in the transmitter control system.

Some advanced transmitter control systems will accept direct digital telemetry inputs, usually in the form of binary or binary-coded decimal (BCD). This feature allows direct interface between, for example, a frequency meter and the transmitter control system. Once inputted, this telemetry may be processed like its analog counterparts as to tolerance limits, etc.

Status inputs to the Remote Terminal are normally required to be contact closures or voltages. Some remote control systems offer the ability to use either, and interfacing is possible on site between the two types of inputs using readily available components such as optical isolators.

Command outputs for transmitter control have traditionally been supplied as dry relay contacts, with the relays either contained in the Remote Terminal or on an accessory relay panel. Open collector transistor switch outputs are standard on some remote control systems, and the user may need to obtain either the manufacturer's accessory relay panel or build up relay interfacing on site for some control functions, especially for

older transmitters. Some remote control systems offer latching command outputs, but external latching relays may be required so that the latches are held during all conditions. Optically isolated command outputs are also available for some remote control systems to simplify transmitter interface for dc control.

Control failsafe contacts are normally provided on Remote Terminals. This usually consists of a closed (during normal operation) set of relay contacts that will open after a short predetermined interval if control has been lost from the Control Terminal. A second set of relay contacts is added (or integrated into the control failsafe function) to allow a telemetry failsafe shutdown.

Maintenance override ("go home") contacts are also usually provided at the Remote Terminal in addition to a front-panel indication to notify the maintenance personnel that they should leave the remote control system in "remote" mode before they leave the transmitter site. Maintenance override is essential to provide Remote/Local capability to protect personnel from inherent equipment hazards.

Control Terminal/Remote Terminal Communication

Several choices are available to the broadcast to provide communication between the Control Terminal and the Remote Terminal. The oldest method employs a telephone line or lines to carry control signals from the Control Terminal to the Remote Terminal as well as telemetry and status information from the Remote Terminal to the Control Terminal. Most transmitter control systimes called a voice-grade circuit). Some transmitter control systems require additional telephone line conditioning, so the user should check the transmitter control system requirements before purchasing the system to be sure that the required type of line is available between the studio and transmitter sites. Maximum allowable telephone line attenuation is also normally specified by the transmitter control manufacturer and should be checked with the telephone company. Both "two-wire" and "four-wire" telephone data circuits are available; both can be full-duplex. Almost all lines are a combination of types, as amplification via hybrids and unidirectional amplifiers is normally required at the telephone company central office to offset line losses.

Aural studio-to-transmitter links (STLs) are popular for relaying signals from the Control Terminal to the Remote Terminal. In this system, an aural subcarrier is generated either in or adjacent to the Control Terminal on a frequency capable of being carried by the aural STL without interfering with the program signal. A 26 kHz aural subcarrier is often used on a monophonic aural STL system, while 110 kHz, 152 kHz, or 185 kHz is often used on a composite aural STL system. The user should be sure that the frequency chosen will be properly carried by the STL system. Most aural STL systems accept a subcarrier of approximately 1.5 volts p-p (for 10% injection). It is then transmitted through the system and delivered at the same level by the STL receiver. The subcarrier signals are normally separated from the monophonic or composite baseband signal so that the control subcarrier is not sent on to the broadcast transmitter for general broadcast.

Television broadcasters have two options for carrying control information over their video STL systems. The first option is to employ the video STL manufacturer's standard audio subcarrier system, using a separate 15 kHz audio channel for the control information. The second (and more difficult) option is to inject a 26 kHz aural subcarrier into an existing audio subcarrier channel on the video STL. Many video STL systems do not offer subcarrier injection and recovery as part of their audio subcarrier scheme, so some ingenuity may be required to effect the required interface.

Low power UHF radio links, designed for continuous operation on the Group P channels in the 450 MHz range, may also be used to carry control signals. These low power radio links are intended for point-to-point communications, and may be thought of as one-way phone lines under the control of the broadcaster. Fig. 8 shows a typical UHF radio link for this application. These radio links are sometimes called Telemetry Return Links (TRLs) or Transmitter-to-Studio Links (TSLs).

Most of the choices described above are also applicable to relaying telemetry and status communications from the transmitter site back to the control point. All of them are available if one includes the possibility of program material originating at the transmitter site being relayed to the studio, such as in the case of television electronic news gathering (ENG) signals being received at the transmitter site and relayed to the studio.

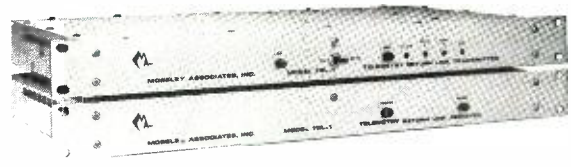


Fig. 8. Telemetry return link system.

In addition to those methods, the FM or television broadcaster may also insert a subcarrier on the broadcast transmitter aural carrier. FM broadcasters may use either 41 kHz, 67 kHz, or 92 kHz subcarriers for monophonic use; FM broadcasters transmitting in stereo may use either 67 kHz or 92 kHz. Television broadcasters normally use a 39 kHz subcarrier, although the transmission of stereo television requires that a secondary audio program channel (SAP) on 102.271 kHz be used for the telemetry signals.

Over-the-air subcarrier transmission of telemetry information is relatively inexpensive, but does have the drawback of not being available when the transmitter is off and does tie up subcarrier bandwidth that might be used for other services.

Some of the advanced transmitter control systems allow the use of two data transmission channels in either a simultaneous or alternate/main configuration to provide redundancy in case of failure of one data link. Dial-up telephone lines are not currently an alternative for broadcast transmitter remote control, as the control and telemetry capability must be continuous. Some systems do, however, allow the use of dial-up data links as an alternative during primary data link failure. (The dial-up link must be an "open" line to maintain continuous control and telemetry.)

A limited number of transmitter control systems allow the use of subaudible telemetry communications from the Remote Terminal to the Control Terminal. This subaudible information is either injected on an AM carrier or an FM subcarrier to avoid interference with the main signal. This is an inexpensive method of providing telemetry information. However, it does have the drawback of not being available when a transmitter is off the air, as well as employing a relatively low data transmission rate which translates into slow response time to changes at the transmitter. Figs. 9, 10, and 11 show some typical Control Terminal/Remote Terminal communication schemes.

Transmitter Facility Interfacing

As mentioned before, some interfacing is normally required between even the newest broadcast transmitters and the typical transmitter control systems. These interface requirements may include command outputs, telemetry inputs, and status inputs. Command Outputs provide for the actual functions to be accomplished at the

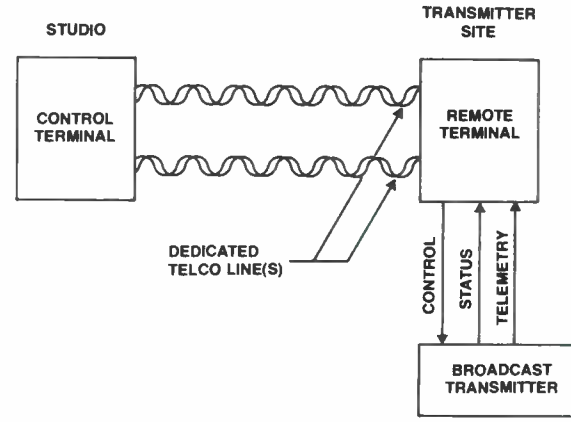


Fig. 9. Telco communications.

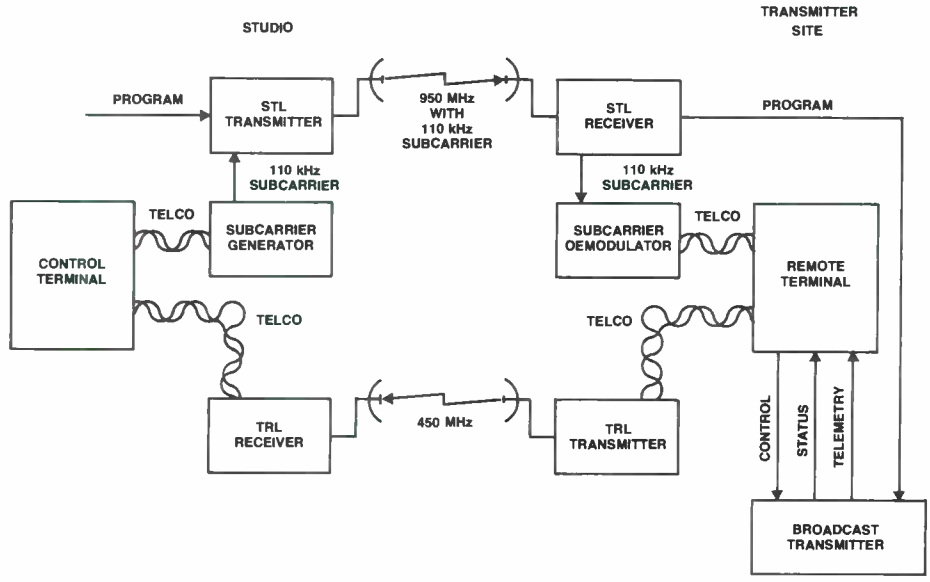


Fig. 10. Wireless communications.

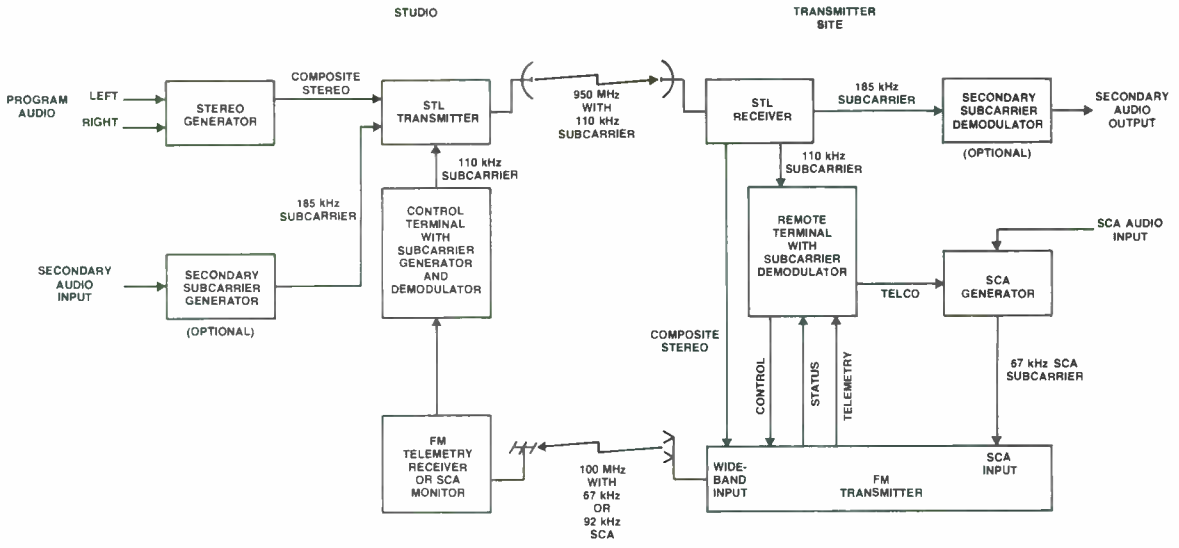


Fig. 11. Wireless communications via subcarrier.

transmitter plant such as filament on/off, plate voltage on/off, etc. Telemetry, or metering, is the sampling of the desired parameters, the result being a dc voltage of low value that is proportional to the sampled parameter. Status is the "go"/"no-go" input showing change of state.

Control/Command

Control from a transmitter control system is normally supplied as a momentary contact closure, either through a relay, through an optical isolator, or directly from a transistor switch. Individual transmitter control networks are normally the determining factors for the type of control interface, newer models requiring only a closure between a common terminal (usually ground) and various other terminals to remotely control the transmitter. In some cases, a common terminal and/or control terminations may be at such a voltage that relays are required to avoid shock hazard and/or excessive voltage within the transmitter control system. These relays also provide protection to the transmitter control system should an abnormal condition occur in the control network of the transmitter due to excessive voltage.

Some controls will be used to operate relays within the transmitter (filaments on/off, plate voltage on/off, etc.) while other closures in the transmitter system will be used to rotate devices such as potentiometers and variable capacitors. Most transmitter manufacturers provide, either as standard or as accessories, motor assemblies for controlling these variable devices. External reversible motors may also be used to translate transmitter control system commands to rotation.

Metering/Telemetry

Certain parameters must be monitored by the operator at the remote control point. These parameters are defined in the FCC Rules and Regulations relating to the particular type of service (AM, FM, or TV). These parameters typically include plate voltage, plate current, and output power. Most newer broadcast transmitters provide representative samples of these and other parameters for the remote control system. External interface units, described below, may be used for plate voltage, plate current and other parameters, such as tower light current, not provided as samples from the transmitter itself.

Plate Voltage

Plate voltage is normally sampled using a resistive voltage-divider network that reduces the plate voltage to a potential on the order of 1 to 5 volts dc. Fig. 12 shows a schematic of a commercially available plate voltage sampling unit.

This type of unit is available for use up to 20 kV,and can be extended to 30 kV by the use of an external resistor between the sample point and sampling unit input; this resistor would be in the same order of value and rating as those used within the plate voltage sampling unit.

Plate Current

Plate current can be sampled as a voltage across a low value resistor between the transmitter ground and the cathode. This current sample will, of course, include any grid and screen currents present. Universal plate circuit sampling kits are commercially available, providing the ability to monitor either plate current or plate voltage with

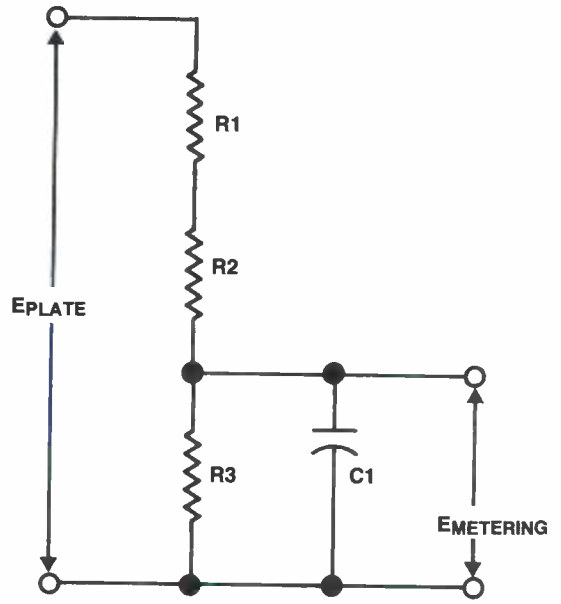


Fig. 12. Plate voltage sampling schematic.

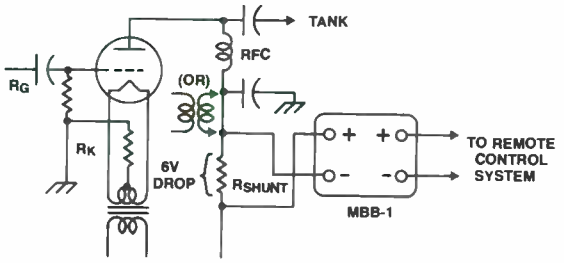


Fig. 13. Monitoring plate current.

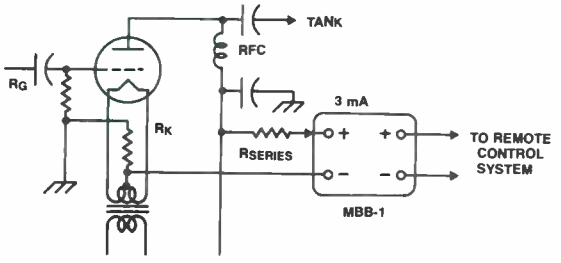


Fig. 14. Monitoring plate voltage.

up to a 10 kV potential. The voltage drop across these units is low, on the order of 4 to 6 volts. For current, external shunting is used across the input of these devices to keep the voltage drop quite low. Figs. 13 and 14 show typical installations to monitor plate current and plate voltage using this type of device.

Tower Lights

Tower light operation can be observed at the control point through the use of the transmitter control system. Both a flashing beacon as well as steady side lights may be monitored, with the preferred method being to monitor them separately. Tower light current sampling units are commercially available, consisting of a transformer winding and a rectifier circuit attached to a laminated core.

A current carrying conductor for the tower lighting being monitored is wrapped around the core up to several times to provide the proper sample output voltage.

AM Base Currents

Standard AM broadcast stations operating via remote control or ATS must provide a remote indication of antenna base current phase and amplitude. For those stations using directional arrays, all active towers plus the common point would have to be included. Commercially available AM tower monitoring units are available, and some include the ability to relay telemetry information to a remote control system via analog outputs. These telemetry outputs tend to be sequential on some units, however, so additional interfacing may be required in order to provide proper sample treatment for easy monitoring and/or automatic logging. The appropriate FCC Rules and Regulations should be consulted to determine the type of antenna sampling device to use for a given application.

RF Power Output

The output of broadcast transmitters may be sampled in a variety of ways. Most transmitters include a dc output for RF output sampling. External RF sampling devices are available from a number of manufacturers, and may be used to measure forward and reflected power. Inexpensive nondirectional output sampling units are also available. In some cases, it may be simpler to amplify the sample already present in the transmitter system if that will not adversely affect the reflectometer calibration. Power-to-linear conversion is normally done within the transmitter control system, so external devices for that application are no longer required. Care should be exercised so that the transmitter's forward and reflected power metering is not adversely modified by AM modulation.

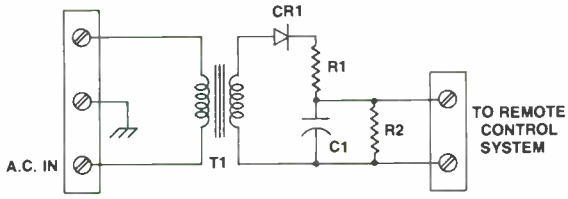


Fig. 15. Line voltage metering schematic.

Line Voltage

It is often desirable to monitor ac power mains voltage at the transmitter control point. Fig. 15 shows a typical line voltage sampling unit schematic, which may be used from 110 volts to 440 volts ac. Three-phase power may be monitored by using one of these units on each phase. Line current may be monitored by using a tower light sampling unit as described before.

Filament Voltage

A simple voltage divider and rectifier circuit may be used to adapt an incoming filament voltage for remote control monitoring. Fig. 16 shows a typical filament voltage sample schematic. Alternatively, an ac line voltage sampling unit may be used to sample the line voltage applied to the filament transformer.

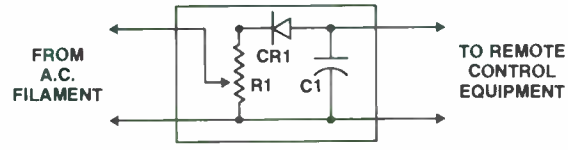


Fig. 16. Filament metering schematic.

Fig. 17. Temperature sensing kit.

Temperature

It is often desirable to be able to monitor critical temperature inside and outside the broadcast transmitter from the control point. This can be accomplished by the use of on/off thermostats, commonly available from heating supply stores, or by the use of temperature sensing units that convert temperatures above and below zero degrees to proportionate voltages positive and negative relative to zero volts. Some of these units allow the user to extend the temperature sensor away from the temperature sensing unit chassis. A typical air temperature sampling unit is shown in Fig. 17.

Status Inputs

Status inputs to a transmitter control system are typically either contact closures or dc voltages. In some cases, it is necessary to be able to convert the sample from one type to another for proper interface. Low voltage samples can be converted to contact closures (or their equivalent) by the use of readily available optical isolators with the appropriate resistance in series with the input. Higher voltages can often be converted to contact closures by the use of relays. In the case of conversion from contact closures to voltage input, the same type of interface units may be used, with external wetting voltage applied from a separate power supply. Various types of sensors are available commercially to provide on/off indications. These include smoke detectors, pressure switches, temperature switches, magnetic intrusion switches, photoelectric switches, sail switches for air movement, key switches, and motion detectors. In short, many types of parameters may be monitored for status input to the transmitter control system.

Uninterruptable Power Supply

Some installations have a requirement to know what is happening at the transmitter plant even during power failures. In this case, an Uninterruptable Power Supply (UPS) is probably required. The Remote Terminal and any communications equipment at the transmitter plant (STLs and TSLs) would be plugged into the UPS. The UPS would then supply ac power inverted from its own batteries to the transmitter control system when main ac power fails. UPSs are available from many manufacturers.

Television Monitoring Equipment

An off-air video demodulator is needed at the control point to permit continuous monitoring of the waveform and other characteristics of the transmitter visual signal. As an additional requirement, a separate video demodulator will be need-

ed at the transmitter site for use in making measurements and setup adjustments.

A video waveform monitor is required for continuous monitoring of the waveform and other characteristics of the video signal including the percentage of modulation. A vectorscope or other instrument designed to depict the instantaneous phase and amplitude relationships of color components must be provided if any portions of the transmissions are in color. This apparatus must be capable of providing full field displays, and displays of test signals inserted on selected lines in the vertical blanking interval. The waveform monitor at the remote control point must be calibrated against the waveform monitor maintained at the transmitter during each required inspection.

Although not required by the Rules, color monitors should be provided if color program material is transmitted. It is suggested that both a monochrome and a color video monitor be provided.

Vertical interval test signal (VITS) generation is no longer required by the FCC Rules and Regulations. The VITS generated signals, do however, allow monitoring of selected parameters any time during the broadcast day as well as providing a basis for automatic correction during picture transmission.

Modulation Monitors

Audio modulation monitors are no longer required by the FCC to be type accepted and located in each broadcast facility. Each licensee is, however, responsible for maintaining modulation within the limitations imposed by the FCC. For this reason, some sort of modulation monitoring must be employed, either on a continuous or intermittent basis, to be sure that overmodulation does not take place. A number of manufacturers produce modulation monitors for AM, monophonic FM, stereophonic FM, monophonic television, and television subcarrier modulation measurement. Stereophonic television modulation monitors are required for stereo television transmission as well as the secondary audio program channels (subcarriers).

3.8

Frequency and Aural Modulation Monitoring

Joseph C. Wu
President
TFT, Inc.
Santa Clara, California

GENERAL

Broadcast station monitors fall into two categories—**frequency monitors** and **modulation monitors.** These two functions are sometimes combined into one unit and are sometimes packaged as separate units.

Broadcast aural modulation monitors are also classified according to the type of modulation to be monitored:

- AM Monaural
- AM stereo
- FM monaural (and SCA as needed)
- FM stereo (and SCA as needed)
- TV monaural
- TV stereo (and multichannel sound)

Two of these monitoring functions are sometimes combined in one instrument.

The various types of monitors are discussed in the following paragraphs, together with the FCC rules that the monitored transmitter's emissions must comply with.

WHY MONITOR YOUR TRANSMITTER

There are three major reasons for using frequency and aural modulation monitors at the broadcast station:

Coverage.

Since coverage of the broadcast service area is a function of transmitter carrier power and modulation level, it is desirable to maintain the modulation level at the maximum legal limit.

Equipment Performance.

By means of the monitors, the station engineer can perform equipment performance measurements to ensure that the transmitter is operating within the technical specifications of the FCC Rules.

Compliance With Legal Requirements.

The monitors enable station employees to operate the transmitter in accordance with FCC Rules regarding aural modulation level and carrier frequency.

FCC RULES AFFECTING MONITORING

The FCC does not specify the type of aural modulation monitor or measuring equipment a broadcast station must use. It is up to the station engineer to decide what monitoring equipment is needed to ensure that the station transmitter emissions comply with FCC frequency and modulation requirements.

Frequency Monitoring

Parts 73.1540 and 73.1545 of the FCC Rules require that the carrier of center frequencies of AM, FM, and TV stations must be measured or determined as often as necessary to ensure that they are maintained within the following tolerances:

AM Stations - The carrier frequency for monophonic transmissions or the center frequency for stereophonic transmissions must be within ±20 Hz of the assigned frequency.

FM Stations - The center frequency must be within ±2000 Hz of the assigned frequency (±3000 Hz for transmitters having a power output of 10 watts or less).

TV Stations - The visual carrier frequency must be within ±1000 Hz of the assigned frequency. The aural carrier frequency must be 4.5 MHz ±1000 Hz above the actual visual carrier frequency.

Aural Modulation Monitoring

Although type-approved monitors are no longer required, Part 73.1570 of the FCC Rules states that modulation percentage is to be maintained at the highest level consistent with good transmission quality and broadcast service, not to exceed the following limits:

AM Stations - Modulation of the carrier must not exceed 100% on negative peaks of frequent recurrence, or 125% on positive peaks at any time. There are additional limitations for AM stereo and telemetry transmissions.

FM Stations - Total modulation must not exceed 100% on peaks of frequent recurrence referenced to 75 kHz deviation. However, stereo stations simultaneously providing subsidiary communication services on subcarriers may increase the total peak modulation 0.5% for each 1.0% of subcarrier injection modulation; but the total carrier modulation must not exceed 110% (82.5 KHz peak deviation).

TV Stations - In general, the total modulation of the aural carrier must not exceed 25 kHz deviation (monaural) on peaks of frequent recurrence. Stations transmitting multi-plexed subcarrier signals on the aural carrier must limit the modulation of the aural carrier by the arithmetic sum of the subcarrier(s) allowable deviation and the total modulation must not exceed 75 kHz deviation. Modulation requirements for stations transmitting aural subcarriers as part of encoded subscription programs are stated in the application for advance FCC approval.

ESSENTIAL FEATURES OF FREQUENCY MONITORS OR METERS

AM frequency monitors or meters must be capable of measuring and displaying carrier frequency error with a resolution sufficient to ensure compliance with the FCC carrier frequency requirements. Recommended resolution for AM monitoring is 1 Hz while FM and TV monitors should provide a resolution of 10 Hz or better. These tolerances call for an extremely accurate and stable internal frequency standard with an aging rate of 1 ppm per year or better which is traceable to the National Bureau of Standards (NBS).

If the transmitter is to be monitored at some distance from the transmitter site, a built-in or external preselector is required for receiving the signal off the air.

Fig. 1. A general purpose frequency counter may be used to measure carrier frequency as well as other frequencies within its range. Specified accuracy and resolution for the model shown here make it suitable for measuring carrier frequencies of AM, FM and VHF TV. (Courtesy of Leader Instruments Corp.)

The following features are also highly desirable in the frequency monitor:

- A means of presetting the frequency of broadcast transmitters off the air.
- An output (BCD or analog) for automatic logging of frequency error.
- An output to operate an alarm when present frequency limits are exceeded.
- Provision for calibrating the internal frequency standard against an NBS station or other highly accurate standard.

Fig. 2. This combined frequency and modulation monitor includes capabilities for monitoring various aspects of the FM stereo signal. (Courtesy of Belar Electronics Labs, Inc.)

ESSENTIAL FEATURES OF AN AURAL MODULATION MONITOR

General

As a minimum, all aural modulation monitors must have a peak-reading modulation meter to give a direct indication of modulation percentage. Meter accuracy should be ±4% or better. Other desirable features common to all modulation monitor are:

- Flashers, accurate to ±2% or better, to indicate when maximum positive and negative modulation peaks are occurring.
- Adjustable flashers to indicate when modulation peaks exceed preset levels.
- An internal calibrator to check the accuracy of the modulation meter and peak flashers, and a means for recalibrating the meter and flasher circuits.
- An output to operate an overmodulation alarm.
- An output to operate an external alarm when the modulation drops below a certain level (e.g. 10%) for a specified period of time.
- Outputs to operate a remote meter and remote peak flashers.

AM Monitors

AM monaural modulation monitors should possess the features described in the preceding paragraph. If a preselector is used with the monitor, its sensitivity should be approximately 100 μV for a 35 dB SNR, and 1 mV for a 50 dB SNR. Selectivity should be at least −40 dB at ±40 kHz, and image rejection should be at least 50 dB.

AM stereo monitors should have the following additional features:

- L + R and L − R channel decoding.
- L and R channel separation measurement capability.
- L and R channel signal-to-noise ratio measurement capability.
- L and R channel frequency response measurement capability.
- Pilot carrier injection level measurement capability.
- Channel crosstalk measurement capability.
- Signal output for distortion measurements.

FM Monitors

FM monitors must have a high signal-to-noise ratio, at least 70 dB. The discriminator must have a distortion figure of 0.1% or better and a frequency response of at least 25 Hz to 100 kHz.

If a preselector is used for off-the-air monitoring, its IF amplifier must have a bandwidth of at least ±275 kHz, and yet be narrow enough to reject alternate channels. A built-in multipath detector is highly desirable to minimize multipath interference. The FM monitor should be able to measure AM noise on the carrier as well as the FM signal.

FM stereo monitors must be able to measure the (L + R) channel level (30 Hz to 15 kHz), the (L − R) channel level (23 to 53 kHz), the 19 kHz injection level, and the 38 kHz subcarrier level. It must also be able to measure crosstalk (separation of left and right channels) up to 60 dB.

If an SCA signal is being transmitted, an SCA monitor must be used in addition to the FM modulation monitor. The SCA monitor must be able to measure modulation percentage, the SCA injection level on the composite signal, signal-to-noise ratio, and crosstalk. The SCA modulation measurement circuit must be adjustable for whatever deviation is defined as 100% modulation.

TV Monitors

Desirable features for TV monaural and stereo monitors are the same as for FM monitors. When

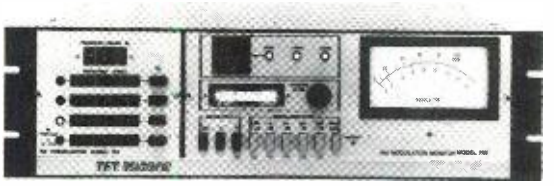


Fig. 3. For remote monitoring, a preselector is used to provide sufficient gain so that the signal will drive the modulation monitor. A multichannel preselector allows monitoring modulation characteristics of other stations in the market. (Courtesy of TFT, Inc.)

multichannel sound (MTS) is being transmitted, the operator should be able to monitor the main channel independently of the other channels, and vice-versa. The MTS monitor must receive and demodulate the composite baseband, and measure composite deviation as well as injection levels.

ON-SITE MONITORING TECHNIQUES

When monitoring is to be done at the transmitter site, the monitor is normally connected directly, or through an attenuator, to the RF sampling point of the transmission line feeding the antenna.

AM Monitoring

Most AM frequency monitors display carrier frequency error rather than frequency. Typically, a front-panel digital display indicates the carrier deviation from its assigned frequency in Hz, and a lighted "+" or "−" indicates whether the carrier is above or below its assigned frequency.

The percentage modulation of a monaural AM carrier is read directly on the monitor's front-panel meter or other indicating device. Monitors usually permit selection of either positive or negative modulation peaks by means of a front-panel switch. Peak flashers, used on some monitors, are intended to catch fast transients and peaks that the meter cannot respond to. There may be one flasher to indicate maximum allowable negative peaks (100%) and another to indicate maximum allowable positive peaks (125%). The monitor may also have an adjustable peak flasher. This can be present by means of digital switches in that it flashes when the modulation percentage exceeds the preset value.

For modulation monitoring of an AM stereo transmitter, an AM stereo monitor or a stereo monitor plus a compatible AM modulation monitor is required. The system used should enable the operator to read simultaneously the percentage modulation on both left and right channels, and to measure separation between channels and crosstalk between the main channel and subchannels.

FM Monitoring

A typical FM frequency monitor digitally displays carier frequency error in Hz, and indicates whether the carrier is above or below its assigned frequency. The RF input level must be adjusted so that sufficient signal is available for measurement but not so high that overloading occurs. When an FM stereo transmitter carrier frequency is being monitored, the stereo pilot carrier frequency can also be measured.

Monaural modulation percentage is normally displayed on a front-panel meter. Typically, either positive, negative, or combined modulation peaks can be selected for monitoring by a switch. Some monitors also provide peak flashers to indicate modulation peaks that exceed a preset percentage. The RF input must be adjusted to the correct level, as described in the instruction manual, before accurate readings can be taken.

For monitoring a stereo FM transmitter, an FM stereo modulation monitor or an FM modulation monitor with a compatible stereo monitor must be used. Left-channel, right-channel, and total modulation are read on front-panel meters. With the typical monitor, these meters can also be used to measure separation between the left and right channels as well as crosstalk between the main channel and subchannels, as described in the monitor's instruction manual.

TV Monitoring

A typical TV frequency monitor provides separate displays of the visual carrier, aural carrier, and intercarrier frequency errors. The RF input to the monitor should be adjusted to the correct level as described in the instruction manual before measurements are made.

Aural modulation percentage can be read on the monitor's front-panel meter. If the TV transmitter is also transmitting stereo and/or MTS, a monitor with a stereo decoder for left and right channels and a decoder for the SAP channel must be used.

OFF-SITE MONITORING TECHNIQUES

For remote, off-the-air transmitter monitoring, the monitor must contain a preselector (RF amplifier) or an external preselector must be used.

Input to the preselector is from a suitable antenna. Some preselectors are capable of measuring and indicating carrier frequency error. Such preselectors combined with a modulation monitor provide a complete transmitter monitoring capability.

Off-site monitoring techniques are generally the same as on-site techniques. RF input level to the preselector or monitor must be carefully adjusted, as described in the instruction manual, for accurate frequency and modulation measurements.

CALIBRATION AND MAINTENANCE OF MONITORS

Frequency Monitor Calibration

Frequency monitors should be calibrated periodically to ensure accurate measurement of transmitter carrier frequency error. The time between calibrations depends on the frequency of the monitor's internal standard, which in turn depends on the operating frequency of the transmitter. For a monitor having an internal crystal standard that has been correctly calibrated once and that has an aging rate of 1 ppm per year, the following calibration schedule is recommended:

Transmitter Frequency	Calibration Interval
AM band	Every 12 months
FM band	Every 12 months
Low VHF TV band (Chs 2 - 6)	Every 12 months
High VHF TV band (Chs 7 - 13)	Every 6 months
UHF TV band	Every 3 months

After the first few calibrations, the interval may be lengthened if the drift observed in the first few checks warrants it.

There are a number of ways the internal frequency standard can be calibrated:

a. A secondary standard such as an HP5245 Counter or an HP105A Quartz Oscillator can be used with an oscilloscope. The output of the secondary standard is used to synchronize the oscilloscope and the internal standard's output is applied to the vertical input of the oscilloscope. The frequency of the internal standard is then adjusted for the least movement of the oscilloscope display.

b. If the monitor's frequency display can be operated in a general-purpose counter mode, a frequency standard of higher accuracy than the monitor's internal standard (e.g., 3.58 MHz chromatic subcarrier transmitted on TV network originated programs) can be used with the counter to calibrate the internal standard. The external standard is connected to the counter input, and the internal standard (which furnishes the time base for the counter) is adjusted so that the counter displays the exact frequency of the external standard.

c. If a receiver capable of receiving one of the NBS stations (WWV, WWVB, etc.) is available, and if the monitor has an output from its internal standard that is nominally an exact subharmonic of the frequency of the NBS station being received, the monitor's internal standard can be calibrated by adjusting its frequency for zero beat with the NBS station frequency.

Aural Modulation Monitor Calibration

The monitor's aural modulation meter and peak flashers should be calibrated regularly. Most monitors have built-in calibrators, so that meter and flasher accuracy can be checked by simply pressing front-panel switches and observing the peak flashers and the meter reading. If the reading is in error, a simple adjustment corrects the error.

If an FM modulation monitor has no internal calibrator, the monitor must be calibrated against a laboratory standard or by means of a Bessel-null measurement using a spectrum analyzer and a precision audio frequency generator. If an AM modulation monitor has no internal calibrator, the monitor can be calibrated using an RF generator. The generator must be capable of very low distortion amplitude modulation, and the level of this modulation should be accurately observed by using a high quality oscilloscope that has high linearity.

Maintenance

A broadcast station monitor should be maintained in the same way as other precision laboratory instruments. It should be calibrated regularly as described in the preceding paragraphs.

Chapter 1: Television Signal Transmission Standards
Chapter 2: Microwave Engineering for the Broadcaster
Chapter 3: Satellite Earth Stations
Chapter 4: Fiber Optic Video Transmission Systems
Chapter 5: Aural Broadcast Studio Transmitter
and Intercity Relay Service

SECTION 4: PROGRAM TRANSMISSION FACILITIES

4.1

Television Signal Transmission Standards

INTRODUCTION

This chapter is intended to assist the broadcast engineer in evaluating the quality of television program transmissions. It consists primarily of the text of NTC Report No. 7, with additional material on audio signal measurements from EIA RS-250-B.

NTC Report No. 7 (1976) was prepared by the Network Transmission Committee of the Video Transmission Engineering Advisory Committee, a joint committee of television network broadcasters and the Bell System. It defines transmission parameters, test signals, measuring methods, and performance objectives. The performance objectives are applicable to an overall transmission system, including both local and inter-city relay facilities.

Since NTC-7 does not include audio channel standards, the audio section of the Electronic Industries Association Standards RS-250-B (1976) has been included.

EIA RS-250-B differs from NTC-7 primarily in that it includes performance objectives agreed upon by the television networks and AT&T for guaranteed performance for the coast to coast video networks. Since measuring methods and test signals are otherwise the same for the two standards, the performance objectives may be compared, as on the following chart. In general, RS-250-B is considered a more rigorous standard, reflecting industry-wide measures of performance, which may be used, for example, to test short, medium, satellite and long haul systems. NTC-7 is usually considered a standard for checking day-to-day operation of a network television interconnection system.

A third standard, said to be compatible with those EIA and NTC, is the AT&T Communications "Commercial Television Transmission Specification" (1984). As with RS-250-B, performance objectives are specified for short haul, medium haul, satellite, long haul, and end-to-end. AT&T also publishes similar standards for non-commercial television, premium grade audio and standard grade audio transmission.

A revised and updated version of EIA RS-250 has been in preparation and should be available some time in 1985.

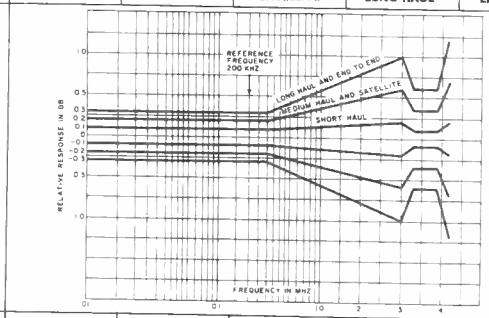
Further information on acquiring complete copies of all three standards follows at the end of this chapter.

Using This Chapter

The three-page chart presents a summary of the tests and performance objectives of RS-250-B and NTC-7. They are listed in the order consistent with RS-250-B, but there are references to the NTC-7 sections which follow. By referring to the chart and the complete test procedure, the reader may select the tests and performance objectives for a particular application.

For those familiar with NTC-7, the original order and numbering have been preserved.

To supplement NTC-7, the audio section of RS-250-B has been included. These tests, Section 6, appear between NTC-7 Section 5 and the two Appendices.

TEST NUMBER	VIDEO PERFORMANCE TEST	TELEVISION PERFORMANCE STANDARDS FOR RELAY FACILITIES						DISPLAYED VISUAL EFFECT
		NTC-7	EIA RS-250-B					
			SHORT HAUL	MEDIUM HAUL	SATELLITE	LONG HAUL	END-TO-END	
1 NTC 3.8	AMPLITUDE VS. FREQUENCY CHARACTERISTIC	WHITE FLAG AMPLITUDE ADJUSTED TO 100 IRE UNITS a) ALL FREQUENCY BURSTS AMPLITUDES SHALL BE: 50^{+3}_{-5} IRE UNITS b) COLOR BURST AMPLITUDE SHALL BE: 40 ±4 IRE UNITS						THE MOST COMMON AND MOST OBVIOUS LUMINANCE EFFECT RELATED TO LOW HIGH FREQUENCY RESPONSE IN THE VIDEO PASSBAND, IS POOR RESOLUTION OR SOFTNESS OBSERVED IN THE DISPLAYED PICTURE. IT SHOULD ALSO BE NOTED THAT NONLINEAR PHASE CHARACTERISTICS CAN APPEAR AS A CONSEQUENCE OF THE FREQUENCY ROLL RESPONSE OF THE VIDEO PASSBAND. IN THE EVENT THAT THE VIDEO PASSBAND IS PEAKED AT THE UPPER LIMIT, THIS WILL DISPLAY AN UNUSUAL CRISPNESS OR ENHANCEMENT IN THE DISPLAYED PICTURE. THE USE OF HIGH FREQUENCY PEAKING CIRCUITS IN VIDEO EQUIPMENT, AND TRANSMISSION CHANNELS IS REFERRED TO AS "IMAGE ENHANCEMENT."
2 NTC 3.6	CHROMINANCE TO LUMINANCE GAIN INEQUALITY	CHROMINANCE AMPLITUDE REFERENCED TO LINE BAR SHALL BE: 100 ±3 IRE UNITS (±6 %)	±1 IRE UNITS	±4 IRE UNITS	±4 IRE UNITS	±7 IRE UNITS	±7 IRE UNITS	THIS PROBLEM WILL AFFECT THE SATURATION LEVELS IN RECEIVED PICTURE WHICH WILL APPEAR AS OVER OR UNDER SATURATED COLORS. THIS DISTORTION IS SOMETIME REFERRED TO AS "SATURATION ERRORS."
3 NTC 3.7	CHROMINANCE TO LUMINANCE DELAY INEQUALITY	±75 nSEC	±20 nSEC	±33 nSEC	±26 nSEC	±54 nSEC	±60 nSEC	THIS DISTORTION IS MOST NOTICEABLE WITH RED LETTERING SMEARING INTO A NEUTRAL BACKGROUND. IN MORE SEVERE EXAMPLES OF THIS DISTORTION, THE EFFECT OF COLOR GHOSTING OR MISREGISTRATION IS DISPLAYED ON THE RECEIVED PICTURE.
4 NTC 3.3	FIELD TIME WAVEFORM DISTORTION	<4 IRE UNITS PEAK-TO-PEAK	3 IRE UNITS PEAK-TO-PEAK	3 IRE UNITS PEAK-TO-PEAK	3 IRE UNITS PEAK-TO-PEAK	3 IRE UNITS PEAK-TO-PEAK	3 IRE UNITS PEAK-TO-PEAK	OBVIOUS FIELD TIME ERRORS DISPLAY OBJECTIONAL VERTICAL SHADING FROM TOP TO BOTTOM IN THE RECEIVED PICTURE.
5 NTC 3.4	LINE TIME WAVEFORM DISTORTION	<4 IRE UNITS PEAK-TO-PEAK	0.5 IRE UNIT PEAK-TO-PEAK	1 IRE UNIT PEAK-TO-PEAK	1 IRE UNIT PEAK-TO-PEAK	1.5 IRE UNITS PEAK-TO-PEAK	2 IRE UNITS PEAK-TO-PEAK	APPEARS AS SMEARING OR STREAKING FROM LEFT TO RIGHT IN RECEIVED PICTURE. ALSO, UNEVEN SHADING MAY BE NOTICED FROM LEFT TO RIGHT. POOR CONTRAST NOTED.
6 NTC 3.5	SHORT TIME WAVEFORM DISTORTION	2T PULSE AMPLITUDE SHALL BE: 100 ±6 IRE UNITS LINE BAR EDGE OVERSHOOT SHALL NOT EXCEED 10 IRE UNITS (PEAK-TO-PEAK)	4 IRE UNITS PEAK-TO-PEAK	4 IRE UNITS PEAK-TO-PEAK	4 IRE UNITS PEAK-TO-PEAK	6.5 IRE UNITS PEAK-TO-PEAK	7 IRE UNITS PEAK-TO-PEAK	THIS TYPE OF DISTORTION AFFECTS HORIZONTAL RESOLUTION, SOMETIMES REFERRED TO AS DEFINITION. ALSO, CONTOURING OR RINGING CAN BE OBSERVED WHEN EXCESSIVE HIGH FREQUENCY RESPONSE OF THE VIDED PASSBAND IS PRESENT.
7 NTC 3.12	LONG TIME WAVEFORM DISTORTION (BOUNCE)	PEAK OVERSHOOT AT BLANKING SHALL NOT EXCEED 5 IRE UNITS. SETTLING TIME: LESS THAN 1 SEC	8 IRE UNITS PEAK 3 SEC SETTLING TIME	8 IRE UNITS PEAK 3 SEC SETTLING TIME	8 IRE UNITS PEAK 3 SEC SETTLING TIME	8 IRE UNITS PEAK 3 SEC SETTLING TIME	8 IRE UNITS PEAK 3 SEC SETTLING TIME	INTERMITTENT AND SLOW VARIATION IN PICTURE BRIGHTNESS. THESE DISTORTIONS ARE USUALLY VIEWED OVER LONG PERIODS OF TIME. FLICKER IS AN EXAMPLE OF A LONG TIME DISTORTION.
8 NTC 3.2	INSERTION GAIN VARIATION	SHALL NOT EXCEED ZERO ±3 IRE UNITS SHORT PERIOD (e.g. 5 SEC.) ±1 IRE UNIT MEDIUM PERIOD (e.g. 1 HR.) ±2 IRE UNITS	±0.15 DB HOURLY ±0.1 DB OVER ONE SEC	±0.3 DB HOURLY ±0.15 DB OVER ONE SEC	±0.2 DB HOURLY ±0.15 DB OVER ONE SEC	±0.45 DB HOURLY ±0.25 DB OVER ONE SEC	±0.5 DB HOURLY ±0.3 DB OVER ONE SEC	MAY BE NOTED BY OVER OR UNDER CONTRASTED PICTURES IN MONOCHROME TRANSMISSIONS. ALSO, OVER OR UNDER CONTRASTED AND SATURATED PICTURES IN COLOR TRANSMISSIONS.
9 NTC 3.9	LUMINANCE NON-LINEARITY	LARGEST DIFFERENTIATED PULSE REF AT 100 IRE. SMALLEST PULSE NO LESS THAN 90 IRE UNITS 10%, 50% OR 90% APL.	2%	4%	6%	8%	10%	NON-LINEAR TRANSFER CHARACTERISTICS IN A VIDEO CHANNEL WILL RESULT IN CONTRAST ERRORS RELATIVE TO THE TRANSMITTED PICTURE IN MONOCHROME SYSTEMS. MORE SERIOUS PROBLEMS OCCUR IN COLOR SYSTEMS, SUCH AS HUE AND SATURATION ERRORS RESULTING FROM NON-UNIFORMITIES IN THE LUMINANCE COMPONENT RELATIVE TO THE CHROMINANCE INFORMATION.

NTSC-M color television performance measurements for communication systems. (Page 1 of 3.)

TEST NUMBER	VIDEO PERFORMANCE TEST	TELEVISION PERFORMANCE STANDARDS FOR RELAY FACILITIES						DISPLAYED VISUAL EFFECT
		NTC-7	EIA RS-250-B					
			SHORT HAUL	MEDIUM HAUL	SATELLITE	LONG HAUL	END-TO-END	
10 NTC 3.13	DIFFERENTIAL GAIN	< 15% (± 15 IRE UNITS)	2%	5%	4%	8%	10%	THE VISUAL OBSERVATIONS NOTED AS A RESULT OF THIS DEGRADATION, ARE SATURATION ERRORS IN THE RECEIVED PICTURE INFORMATION.
11 NTC 3.14	DIFFERENTIAL PHASE	$<5^0$	$.5^0$	1.3^0	1.5^0	2.5^0	3.0^0	THE VISUAL OBSERVATIONS DISPLAYED ON THE RECEIVED PICTURE ARE CHANGES OR ERRORS IN HUE AS A FUNCTION OF LUMINANCE AMPLITUDE VARIATIONS
12 NTC 3.15	CHROMINANCE TO LUMINANCE INTERMODULATION	<3 IRE UNITS	1.0%	2.0%	2.0%	4.0%	4.0%	INCORRECT REPRODUCTION OF THE INCREASED SATURATED COLORED AREAS OF THE RECEIVED PICTURE.
13 NTC 3.10	CHROMINANCE NON-LINEAR GAIN	SMALLEST SUB-CARRIER AMPLITUDE 20 ±2 IRE UNITS LARGEST SUB CARRIER AMPLITUDE 80 ±8 IRE UNITS	1.0%	2.0%	2.0%	4.0%	5.0%	THE VISUAL EFFECT FOR THIS VIDEO IMPAIRMENT COULD ALSO BE THE INCORRECT REPRODUCTION OF INCREASED SATURATED AREAS. HOWEVER, THIS MAY NOT BE APPARENT BY JUST OBSERVING THE RECEIVED PICTURE WITHOUT COMPARING IT TO THE TRANSMITTED INFORMATION.
14 NTC 3.11	CHROMINANCE NON-LINEAR PHASE	$<5^0$	1^0	2^0	2^0	4^0	5^0	THE VISUAL OBSERVATION NOTED AT THE RECEIVER WOULD BE HUE SHIFTING IN HIGHLY SATURATED AREAS.
15 NTC 3.12	DYNAMIC GAIN OF THE PICTURE SIGNAL	DYNAMIC GAIN AT 10% OR 90% APL. REF 50% APL. ±3 IRE UNITS	2%	3%	4%	5%	6%	IF THE SYSTEM GAIN IS REDUCED AS A FUNCTION OF APL, THE DYNAMIC RANGE OF THE VIDEO SIGNAL WILL TYPICALLY BE COMPRESSED. THIS WILL CONTRIBUTE TO ALL NON-LINEAR DISTORTIONS WITH REDUCED CONTRAST RATIOS DISPLAYED ON THE RECEIVER PICTURE.
16 NTC 3.12	DYNAMIC GAIN OF THE SYNCHRONIZING SIGNAL	DYNAMIC GAIN AT 10% OR 90% APL. REF 50% APL. ±2 IRE UNITS	3%	4%	5%	6%	7%	NON-LINEAR TRANSFER CHARACTERISTIC OF THE VIDEO CHANNEL. THIS PROBLEM CONTRIBUTES TO ALL NON-LINEAR DISTORTIONS AS A FUNCTION OF APL. SEE ABOVE DISCUSSION. TYPICALLY A REDUCTION IN SYNCHRONIZING PULSE AMPLITUDE BELOW A DEFINED THRESHOLD WILL RESULT IN LOSS OF PICTURE LOCK-HORIZONTAL, VERTICAL, OR BOTH.
17	TRANSIENT SYNCHRONIZING SIGNAL NON-LINEARITY	———	1%	2%	3%	4%	5%	———
18 NTC 3.16	SIGNAL-TO-NOISE RATIO (10 KHZ – 5.0 MHZ)	≥53 DB (10 KHZ – 4.2 MHZ)	67 DB	60 DB	56 DB	54 DB	54 DB	SNOWEY PICTURE DISPLAYED ON MONOCHROME MONITORS. ON COLOR MONITORS THE EFFECT NOTED IS COLORED SNOW, ALSO REFERRED TO AS "CONFETTI".
19	SIGNAL-TO-LOW FREQUENCY NOISE RATIO (0 – 10 KHZ)	———	53 DB	48 DB	50 DB	44 DB	43 DB	TYPICAL SOURCES OF LOW FREQUENCY NOISE ARE POWER LINE OR POWER SUPPLY RELATED. OBSERVED VISUAL EFFECT FOR POWER LINE OR 60HZ PROBLEMS WOULD APPEAR AS ONE WIDE HORIZONTAL BAR ACROSS THE SCREEN. THE APPEARANCE OF TWO NARROWER BARS INDICATES 120HZ RIPPLE LEAKING IN FROM POWER SUPPLIES.

NTSC-M color television performance measurements for communication systems. (Page 2 of 3.)

TEST NUMBER	VIDEO PERFORMANCE TEST	TELEVISION PERFORMANCE STANDARDS FOR RELAY FACILITIES						DISPLAYED VISUAL EFFECT
		NTC-7	EIA RS-250B					
			SHORT HAUL	MEDIUM HAUL	SATELLITE	LONG HAUL	END-TO-END	
20 NTC 3.18	SIGNAL-TO-PERIODIC NOISE RATIO (300 HZ – 4.2 MHZ)	≥50 DB (< 1 KHZ) ≥50 DB (1 KHZ – 4.2 MHZ)	67 DB	62 DB	64 DB	58 DB	57 DB	OBSERVED VISUAL EFFECT OF EXTRANEOUS TONE IN THE DESIGNATED PASSBAND (300HZ-4.2 MHZ), DISPLAYED WITH THE RECEIVED PICTURE COULD BE FIVE OR MORE HORIZONTAL LINES NOTED ACROSS THE SCREEN OF VARYING INTENSITY. THIS WOULD TYPICALLY OCCUR BELOW LINE FREQUENCY 15734.264HZ AT OR MULTIPLES OF LINE FREQUENCY. THE DISPLAYED VIDEO COULD INCLUDE FROM ONE WIDE VERTICAL COLUMN TO SEVERAL LINES NOTED ACROSS THE RECEIVED PICTURE. HOWEVER, EXTRANEOUS SIGNALS ARE SELDOM AT LINE FREQUENCY. THEREFORE DIAGONAL LINES RACING WOULD BE VIEWED.
21 NTC 3.17	SIGNAL-TO-IMPULSE NOISE RATIO	≥ 23 DB (e.g. IMPULSE NOISE <7 IRE PEAK-TO-PEAK, FREQUENCY OF OCCURENCE ≤ 1 PER MINUTE).	NOT SET	NOT SET	NOT SET	NOT SET	NOT SET	THE VISUAL EFFECT NOTED FOR IMPULSE NOISE DISPLAYED ON A MONOCHROME SYSTEM WOULD BE BLACK AND WHITE DOTS RACING ACROSS THE SCREEN IN A HAPHAZARD ARRANGEMENT. IN COLOR SYSTEMS: BLACK AND WHITE, AND COLOR SPECKLES WOULD BE VIEWED.
22 NTC 3.19	SIGNAL-TO CROSSTALK NOISE RATIO	≥ 60 DB	———	———	———	———	———	THIS DISTORTION COULD TYPICALLY PRODUCE MANY DIFFERENT TYPES OF ERRATIC PATTERNS DISPLAYED ON THE RECEIVED PICTURE. THE OBSERVATIONS NOTED WOULD BE INDICATIVE OF OTHER VIDEO SOURCES OR EXTRANEOUS TONES IN DISPLAYED PICTURE.
23	CONTINUITY OF VIDEO SERVICE		99.99% OBJECTIVE	99.99% OBJECTIVE	99.99% OBJECTIVE	99.99% OBJECTIVE	99.99% OBJECTIVE	———
24	K-FACTOR	———	———	———	———	———	———	K-FACTORS SPECIFICALLY RELATE TO THE MONOCHROME OR LUMINANCE COMPONENT IN VIDEO SYSTEMS. THE PARTICULAR DISPLAYED VISUAL EFFECT WOULD BE OBTAINED UNDER TEST NUMBER 5, (LINE TIME DISTORTION) AND TEST NUMBER 6, (SHORT TIME DISTORTION). ASYMMETRY IN THE 2T SINE SQUARE PULSE DENOTE GROUP ENVELOPE DELAY IN THE 1-3 MHZ REGION.
25	COLOR BURST AMPLITUDE	40 IRE UNITS ±4 IRE UNITS	40 IRE UNITS ±0.5 IRE BASED ON GAIN/ FREQUENCY SPECIFICATION	40 IRE UNITS ±2.0 IRE BASED ON GAIN/ FREQUENCY SPECIFICATION	40 IRE UNITS ±2.0 IRE BASED ON GAIN/ FREQUENCY SPECIFICATION	40 IRE UNITS ±3.0 IRE BASED ON GAIN/ FREQUENCY SPECIFICATION	40 IRE UNITS ±3.0 IRE BASED ON GAIN/ FREQUENCY SPECIFICATION	LOW AMPLITUDE OF THE COLOR BURST WILL RESULT IN LOSS OF COLOR SNYCHRONIZATION. LOSS OF COLOR SYNCHRONIZATION WILL FIRST BE NOTICED WITH A RED, BLUE, AND GREEN "RAINBOW" EFFECT ACROSS THE ENTIRE VIDEO DISPLAY. THIS IS SOMETIMES REFERRED TO AS THE (BARBER POLE EFFECT). FURTHER REDUCTION OF THE REFERENCE BURST WILL TURN A COLOR TRANSMISSION INTO A MONOCHROME DISPLAY.
26 NTC 5.1	RELATIVE BURST GAIN ERROR	40 IRE UNITS ±1 IRE UNIT	———	———	———	———	———	HIGH OR LOW COLOR SATURATION OBSERVED IN THE RECEIVED PICTURE AS A CONSEQUENCE OF A MISADJUSTED PROCESSING AMPLIFIER INSERTED IN THE SIGNAL CHANNEL. NOTE, THE EXISTENCE OR NONEXISTENCE OF A PROCESSING AMPLIFIER IN THE SIGNAL CHANNEL, MAY NOT BE APPARENT BY VISUAL OBSERVATION ALONE.
27 NTC 5.2	RELATIVE BURST PHASE ERROR	ZERO $\pm 1^0$	———	———	———	———	———	A CHANGE OR VARIATION IN HUE OBSERVED IN THE RECEIVED PICTURE, AS A CONSEQUENCE OF A MISADJUSTED VIDEO PROCESSING AMPLIFIER, INSERTED IN THE SIGNAL CHANNEL. NOTE, THE EXISTENCE OR NONEXISTENCE OF A PROCESSING AMPLIFIER IN THE SIGNAL CHANNEL, MAY NOT BE APPARENT BY VISUAL OBSERVATION ALONE.

Credit: Michael J. Shumila
Member, Technical Staff
RCA Laboratories
David Sarnoff Research Center
Princeton, NJ

NTSC-M color television performance measurements for communication systems. (Page 3 of 3.)

Section 3*: Parameters, Measuring Techniques and Performance Objectives

GENERAL AND WAVEFORM TECHNOLOGY

This section describes the transmission parameters, measuring techniques and performance objectives that are applicable to all video transmission facilities leased from the Bell System.

It should be noted that except where full-field test signals are essential to the measurement of a particular transmission parameter, e.g., field-time waveform distortion, the measuring technique and its associated performance objective specified for each transmission parameter apply equally to both vertical interval test signals (VITS) and full-field test signals. Furthermore the performance objectives apply irrespective of the average picture level (APL) within the APL range 10% to 90%. This is an important point to remember when making VITS measurements, particularly during program transmission periods where control cannot be exercised over the APL value of picture signal. Many of the transmission parameters can be markedly affected by APL variations. Acordingly, the operator should allow sufficient time when making VITS measurements to ensure a good portion of the APL range is explored by the picture signal before recording the test signal measurement. In every case the highest distortion measurement observed during this period should be recorded and then compared with the performance objective to determine whether or not the facility is within the stated objective.

Waveform measurement techniques described in this report are based on the IRE scale units of measurement (see Fig. 1) except where specifically noted otherwise. The waveform technology used throughout the report is in accordance with the definitions shown in Fig. 2 wherein the standard composite color video signal is defined.

The two principal test signals that are required to conduct the various measurements described in this report are:

A. The composite test signal shown in Fig. 3, which consists of a line bar, a 2T pulse, a chrominance pulse, and a 5-riser staircase signal.

B. The combination test signal shown in Fig. 4, which consists of a white flag, a multiburst and a 3-level chrominance signal.

When conducting in-service VITS measurements the composite test signal shall be inserted on line 17, field 1, and the combination test signal shall be inserted on line 17, field 2.

NOTE: The performance objectives specified in this report pertaining to television transmission facilities, apply only when the recommended test signals are originated directly at the designated broadcaster/TELCO interface. No broadcaster maintained and operated equipment shall be used between the test signal generator output and the interface point.

*Section and test numbers are original NTC-7 numbers.

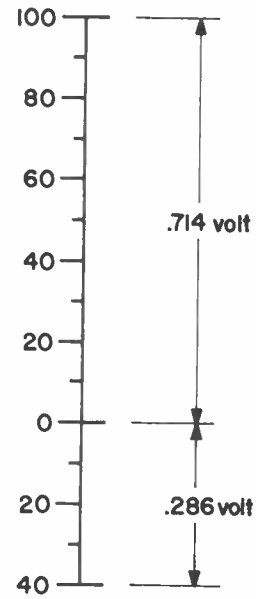
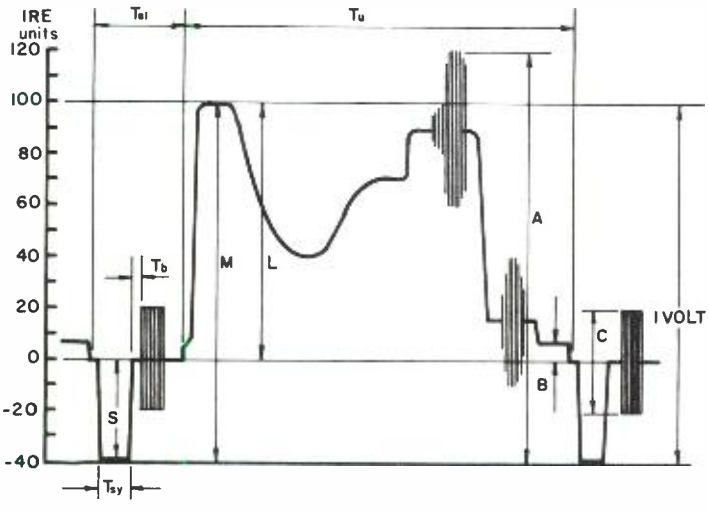


Fig. 1. The IRE scale units.
(For a 1V P-P composite signal)



WAVEFORM TERMINOLOGY

A: The peak-to-peak amplitude of the composite color video signal
B: The difference between black level and blanking level (set-up)
C: The peak-to-peak amplitude of the color burst
L: Luminance signal—nominal value
M: Monochrome video signal peak-to-peak amplitude (M = L + S)
S: Synchronizing signal—amplitude
T_b: Duration of breezeway
T_{si}: Duration of line blanking period
T_{sy}: Duration of line synchronizing pulse
T_u: Duration of active line period

Fig. 2. The standard composite color video signal.

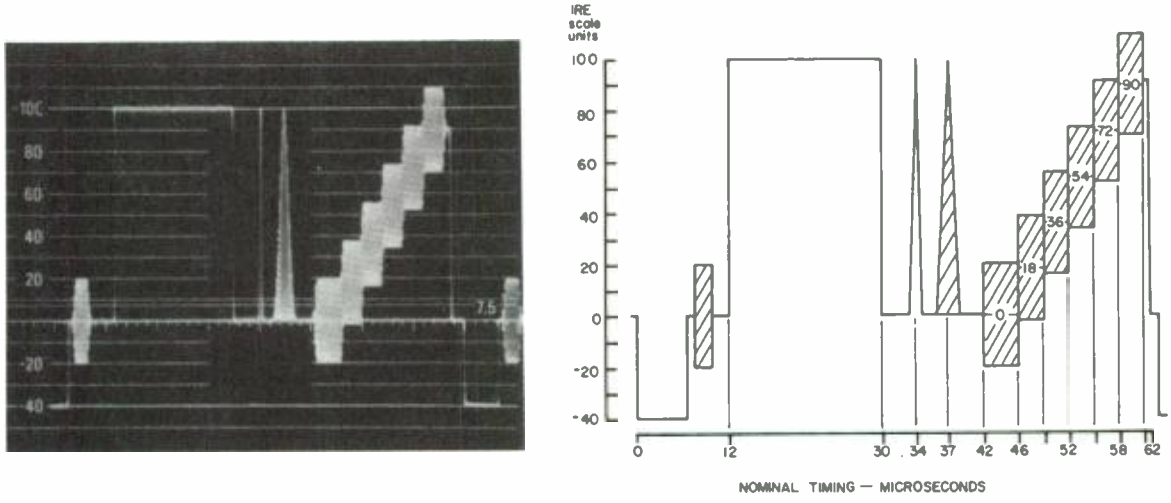


Fig. 3. The composite test signal.

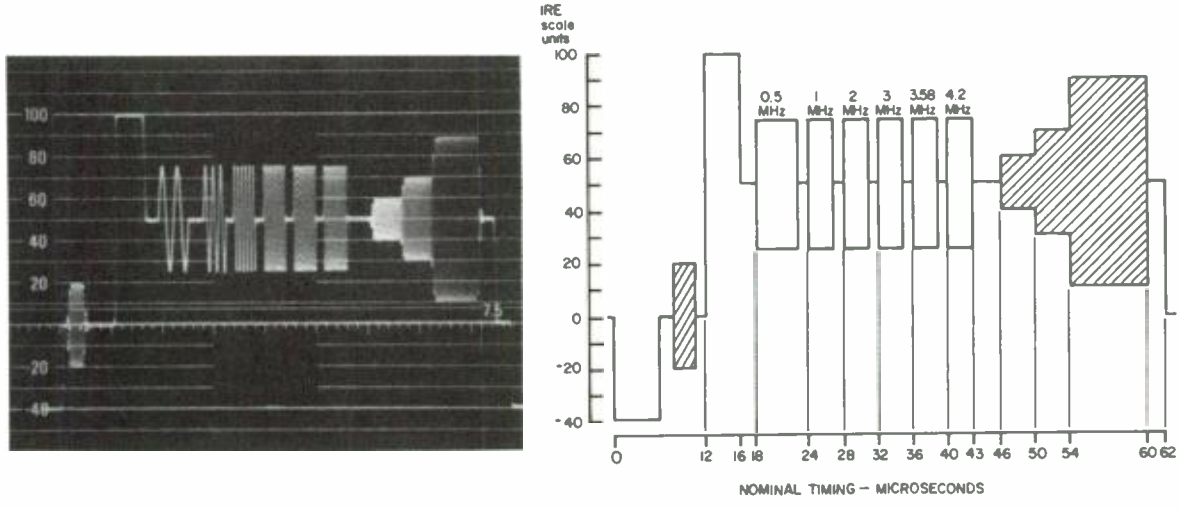


Fig. 4. The combination test signal.

3.2 INSERTION GAIN

Definition:

Insertion gain is defined as the difference, in IRE units, between the peak-to-peak amplitude of a specified test signal at the receiving end of a television facility and the nominal amplitude of the test signal at the sending end.

Measurement:

The line bar portion of the composite test signal shown in Fig. 5 is used when measuring insertion gain. The test signal's amplitude must be accurately adjusted at the sending end prior to the commencement of the test. Similarly, the waveform monitor at the receiving end should be properly calibrated.

Following the above, the peak-to-peak amplitude of the test signal should be measured, in IRE units, at the receiving end using the points approximating to b_1 and b_2 as shown in Fig. 5. The difference between the measured amplitude of the test signal and its nominal amplitude of 100 IRE units is the insertion gain of the television facility. If the measured amplitude is less than 100 IRE units then the insertion gain should be recorded with a negative sign. Such an example is shown in Fig. 6.

Performance Objectives:

a. The insertion gain shall not exceed zero ± 3 IRE units.
b. Variations in insertion gain shall not exceed
   i. Short period (e.g., 5 seconds): ± 1 IRE unit.
   ii. Medium period (e.g., 1 hour): ± 2 IRE units.

These variations in gain are permissible only within the range specified in objective a.

NOTE 1: The performance objectives shown above apply equally to full-field and in-service VITS measurements.

NOTE 2: Insertion gain may also vary as a function of APL. This is termed dynamic gain, and is covered in section 3.12.

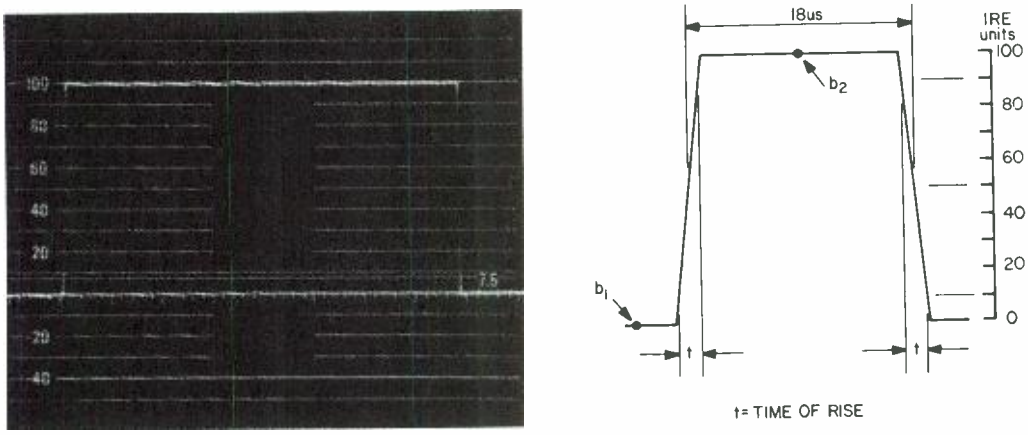
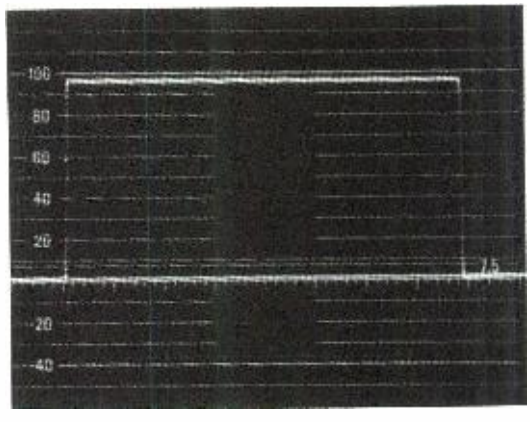


Fig. 5. The line bar test signal.

Generator Output Specifications

Peak amplitude	:	100 ± 0.5 IRE units *(reference white amplitude)*
Line-time waveform distortion	:	less than 0.3 IRE units
Time of rise and time of fall of bar edges (10%-90%)	:	t = 125 ± 5 nanoseconds with integrated sine-squared shape



Insertion gain is -3 IRE units.

Fig. 6. An example of negative insertion gain.

3.3 FIELD-TIME WAVEFORM DISTORTION

Definition:

When a television test signal having a period of one television field, and of reference white amplitude is applied to the sending end of a television facility, the field-time waveform distortion is defined as the change in shape of the top of the test signal at the receiving end. The beginning and end of the test signal, equivalent to a few scanning lines, are excluded from the measurement.

Measurement:

The field bar test signal shown in Fig. 7 is used when measuring field-time waveform distortion. The test signal's amplitude must be accurately adjusted at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the magnitude of the distortion is obtained by measuring, in IRE units, the peak-to-peak change in amplitude of the bar top with the amplitude of the bar center adjusted to 100 IRE units. In order to avoid leading and trailing overshoots, the first and last 250 microseconds (approximately four television lines) are ignored in this measurement. An example of field-time waveform distortion is shown in Fig. 8.

Performance Objective:

The peak-to-peak excursions of the bar top shall not exceed 4 IRE units.

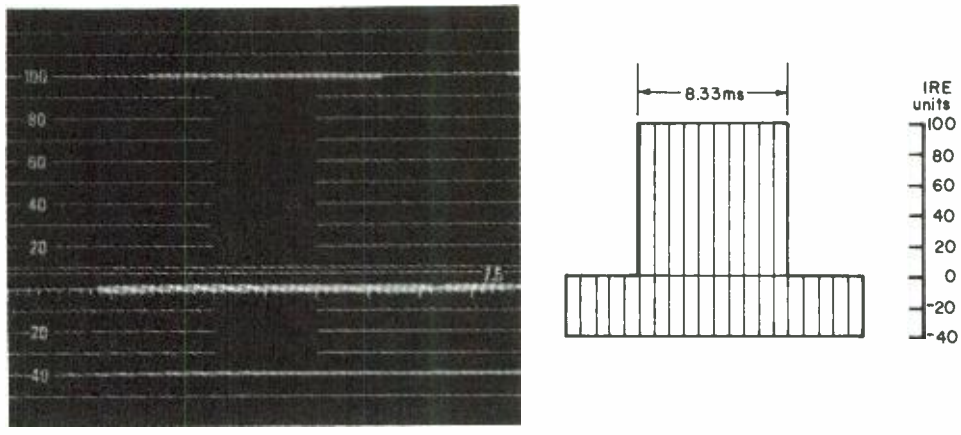
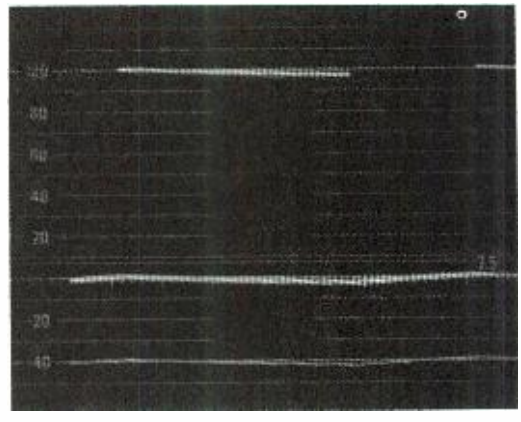


Fig. 7. The field bar test signal.

Generator Output Specifications

Peak amplitude of luminance signal	:	100 ± 0.5 IRE units
Peak amplitude of synchronizing signal	:	40 ± 0.5 IRE units
Field-time waveform distortion	:	less than 0.3 IRE units
Horizontal component	:	100 IRE unit flat field of 52.45 microsecond nominal duration

NOTE: This signal should be generated with field and line synchronizing pulses.



Field-Time Distortion is 3 IRE units. (+1, −2)

Fig. 8. An example of field-time distortion.

3.4 LINE-TIME WAVEFORM DISTORTION

Definition:

When a television test signal having a period of one television line and of reference white amplitude is applied to the sending end of a television facility, the line-time waveform distortion is defined as the change in shape of the top of the test signal at the receiving end. The beginning and end of the test signal, equivalent to a few picture elements, are excluded from the measurement.

Measurement:

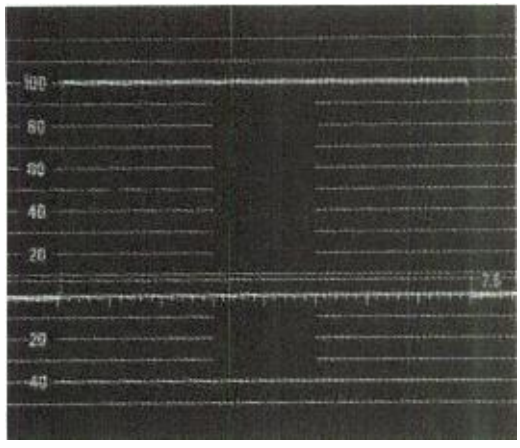
The line bar test portion of the composite test signal shown in Fig. 9 is used when measuring line-time waveform distortion. The test signal's amplitude must be accurately adjusted at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the magnitude of the distortion is obtained by measuring, in IRE units, the peak-to-peak change in amplitude of the bar top with the amplitude of the bar center adjusted to 100 IRE units. The first and last one microsecond are ignored in this measurement. An example of line-time waveform distortion is shown in Fig. 10.

Performance Objective:

The peak-to-peak excursions of the bar top shall not exceed 4 IRE units.

NOTE: The performance objective shown above applies equally to both full-field and in-service VITS measurements.



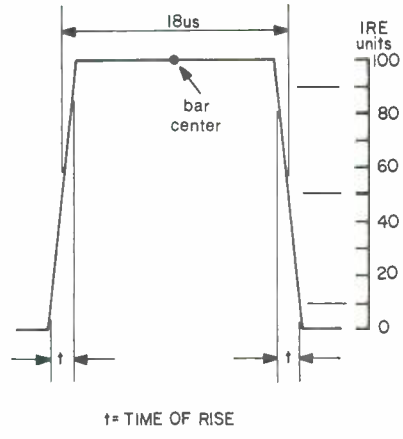
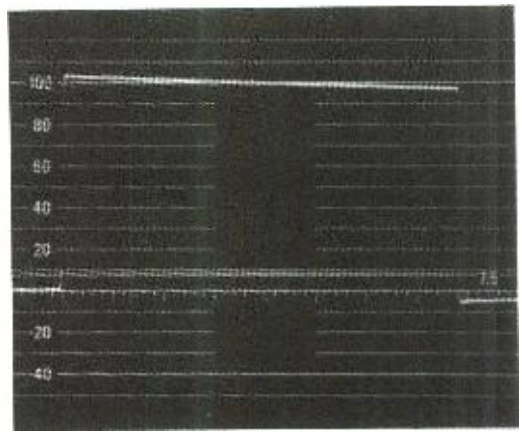


Fig. 9. Line bar test signal.

Generator Output Specifications

Peak amplitude	:	100 ± 0.5 IRE units
Line-time waveform distortion	:	less than 0.3 IRE units
Time of rise and time of fall of bar edges (10%-90%)	:	t = 125 ± 5 nanoseconds with integrated sine-squared shape



Line-Time Distortion is 4 IRE units. (+2, −2)

Fig. 10. An example of line-time distortion.

3.5 SHORT-TIME WAVEFORM DISTORTION

Definition:

If a short pulse or rapid step function of reference white amplitude and defined shape is applied to the sending end of a television facility, the short-time waveform distortion is defined as the departure of the output pulse or step from its original shape. The choice of the half amplitude duration of the pulse or the rise-time of the step is determined by the nominal cutoff frequency of the television facility.

Measurement:

The line bar portion of the composite test signal shown in Fig. 9 and the 2T pulse test signal shown in Fig. 11 are used when measuring short-time waveform distortion. The test signal's amplitude must be accurately adjusted at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the amplitude of the 2T pulse test signal is measured, in IRE units, having previously adjusted the amplitude of the line bar test signal to exactly 100 IRE units.

The peak-to-peak variations within the 1 microsecond intervals on either side (preceding and following) the T-step transitions (rise and fall) are then measured with the amplitude of the line bar test signal adjusted to 100 IRE units as measured between blanking and a point approximately 2 microseconds from the bar edge. (A graticule method of measuring short-time waveform distortion is currently under study by IEEE.) Examples of short-time waveform distortion are shown in Figs. 12 and 13.

Performance Objective:

a. The 2T pulse amplitude shall be 100 ± 6 IRE units.
b. The peak-to-peak amplitude variations preceding or following the T-step transitions to the line bar test signal shall not exceed 10 IRE units.

NOTE: The performance objectives shown above apply equally to both full-field and in-service VITS measurements.

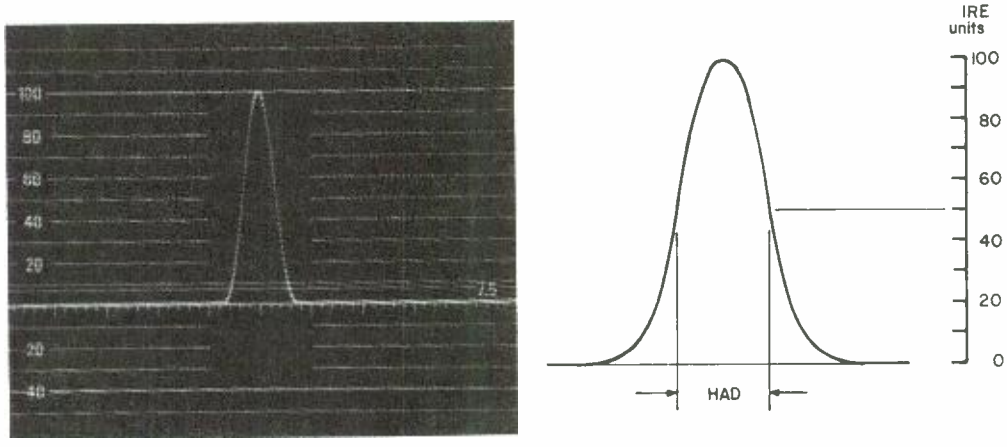


Fig. 11. The 2T pulse test signal.

Generator Output Specifications

Peak amplitude	:	100 ± 0.5 IRE units
Half amplitude duration (HAD)	:	250 ± 10 nanoseconds

2T Amplitude is 92 IRE units.

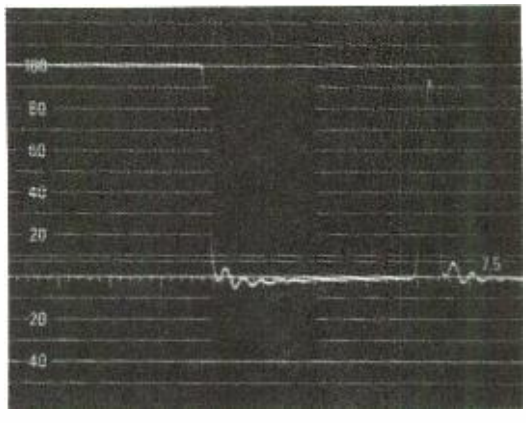


Fig. 12. An example of short-time distortion as it affects the 2T pulse amplitude.

Amplitude variations following the T-step transition are 10 IRE units peak-to-peak.

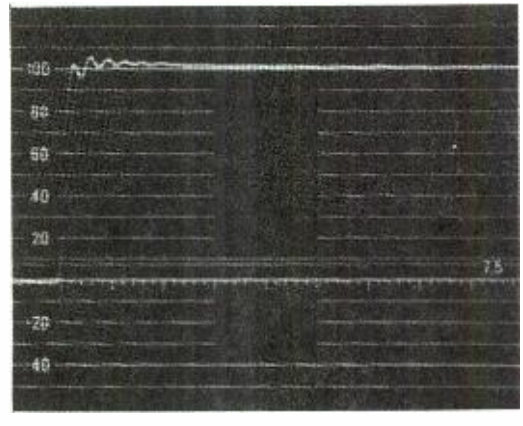


Fig. 13. An example of short-time distortion as it affects the edge response of the line bar.

3.6 CHROMINANCE-LUMINANCE GAIN INEQUALITY

Definition:

When a test signal having defined luminance and chrominance components is applied to the sending end of a television facility, the chrominance-luminance gain inequality is defined as the change in amplitude at the receiving end of the color component of the test signal relative to the luminance component.

Measurement:

The chrominance pulse portion of the composite test signal shown in Fig. 14 is used when measuring chrominance-luminance gain inequality.* The test signal's amplitude must be accurately adjusted at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the amplitude of the Chrominance Pulse Test Signal is measured in IRE units, having previously adjusted the amplitude of the line bar test signal to exactly 100 IRE units. This method is accurate to within 2% with up to 300 nanoseconds of chrominance-to-luminance delay present. The convention of Fig. 17B shows how the chrominance pulse will look with different types of gain and delay distortion. If harmonic distortion is present on the chroma pulse, as evidenced by multiple irregularities of the baseline, this method is invalid and an accurate measurement cannot be made. Methods to make measurements in the presence of harmonic distortion are presently under study.

An example of low chrominance amplitude is shown in Fig. 15.

Performance Objective:

The amplitude of the chrominance pulse shall be 100 ± 3 IRE units.

NOTE: The performance objective shown above applies equally to both full-field and in-service VITS measurements.

*This parameter is also called Realtive Chroma Level (RCL), and is expressed as a percentage of P-P chrominance referenced to the line bar amplitude, as shown in Fig. 15. Hence, the performance objective expressed as RCL would be ± 6%.

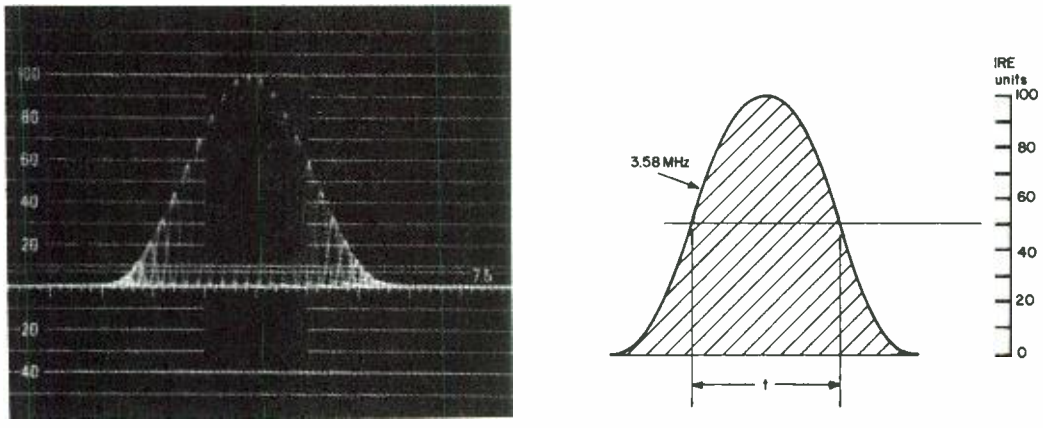
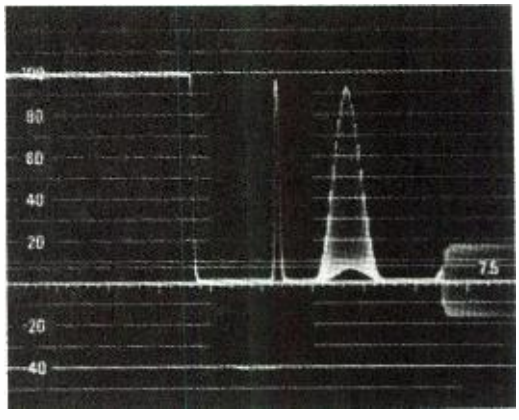


Fig. 14. The chrominance pulse test signal.

Generator Output Specifications

Peak amplitude	:	100 ± 0.5 IRE units
Half amplitude duration	:	t = 1562.5 ± 50 nanoseconds
Inherent chrominance luminance		
a) gain inequality (RCL)	:	less than ± 0.5 IRE (± 1%)
b) delay inequality (RCT)	:	less than 5 nanoseconds, delayed or advanced
Subcarrier harmonic distortion	:	less than 1%
Irregularities in the pulse base line	:	less than ± 0.5 IRE units



Chrominance Pulse Amplitude is 94 IRE units (RCL = −12%) no delay inequality is present.

Fig. 15. An example of chrominance-luminance gain inequality.

3.7 CHROMINANCE-LUMINANCE DELAY INEQUALITY

Definition:

When a test signal having defined luminance and chrominance components is applied to the sending end of a television facility, the chrominance-luminance delay inequality is defined as the change in relative timing, at the receiving end, of the chrominance component of the test signal relative to the luminance component.

Measurement:

The chrominance pulse portion of the composite test signal shown in Fig. 14 is used when measuring chrominance-luminance delay inequality.* The test signal's amplitude must be acurately adjusted at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the amplitude of the chrominance pulse test signal should be adjusted to exactly 100 IRE units. The nomogram shown in Fig. 17A should be used to compute the magnitude of the chrominance-luminance delay inequality. If the chrominance component of the test signal starts with a positive going lobe then the chrominance-luminance delay inequality should be recorded as delayed chroma. The delay inequality can also be computed by the formula: CLDI (RCT) in ns = $20\sqrt{Y_1 \cdot Y_2}$. If harmonic distortion is present, as evidenced by multiple irregularities of the baseline, this method is invalid and an accurate measurement cannot be made. Methods to determine chrominance-luminance delay inequality in the presence of harmonic distortion are currently under study.

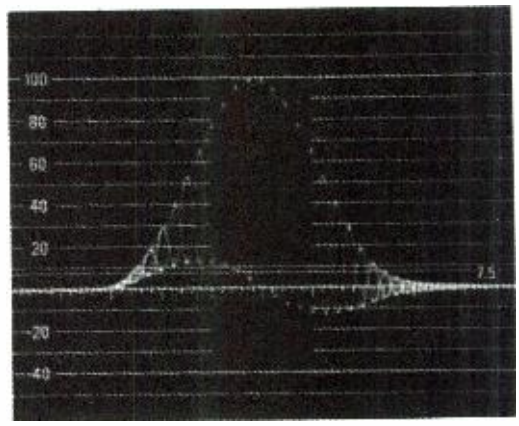
An example of chrominance-luminance delay inequality is shown in Fig. 16 below.

Performance Objective:

The chrominance-luminance delay inequality shall be no greater than 75 nanoseconds, advanced or delayed chroma.

NOTE: The performance objective shown above applies equally to both full-field and in-service VITS measurements.

*This parameter is also called **Relative Chroma Time**.



CLDI(RCT) is 240 Nanoseconds Delayed Chroma with no gain inequality present.

Fig. 16. An example of chrominance-luminance delay inequality.

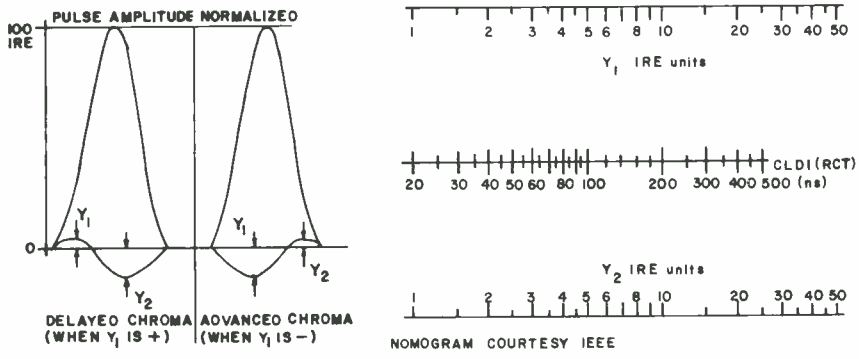


Fig. 17A. Chrominance-luminance delay nomogram with measurement convention.

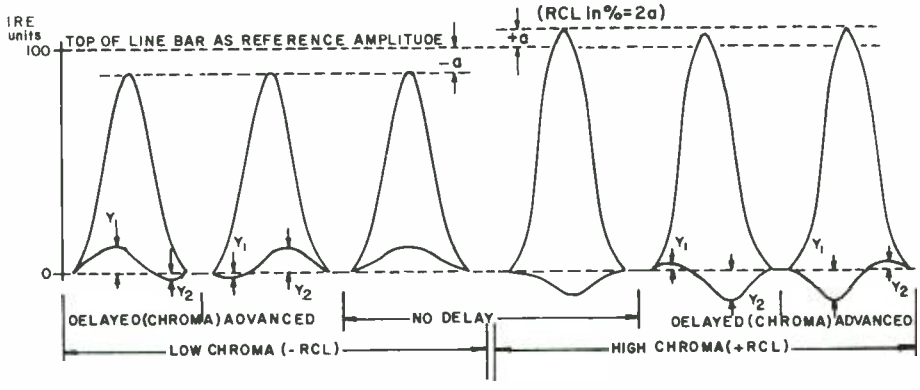


Fig. 17B. Chrominance-luminance gain measurement convention.

3.8 GAIN/FREQUENCY DISTORTION

Definition:

The gain/frequency distortion of a television facility is defined as the variation in gain over the frequency band extending from the television field repetition frequency to the nominal cutoff frequency of the facility, relative to the gain at a suitable reference frequency.

Measurement:

The multiburst portion of the combination test signal shown in Fig. 18 is used when measuring gain/frequency distortion in the range from 500 kHz to 4.2 MHz. The test signal's amplitude must be accurately adjusted at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the amplitude of the white flag should be adjusted to exactly 100 IRE units and then the peak-to-peak amplitude of each burst frequency should be measured and recorded. An example of gain/frequency distortion is shown in Fig. 19.

Performance Objective:

With the white flag amplitude adjusted to 100 IRE units:

a. All frequency burst amplitudes shall be 50 +3, −5 IRE units.
b. Color burst amplitude shall be 40 ± 4 IRE units.

NOTE: The performance objective shown above applies equally to both full-field and in-service VITS measurements.

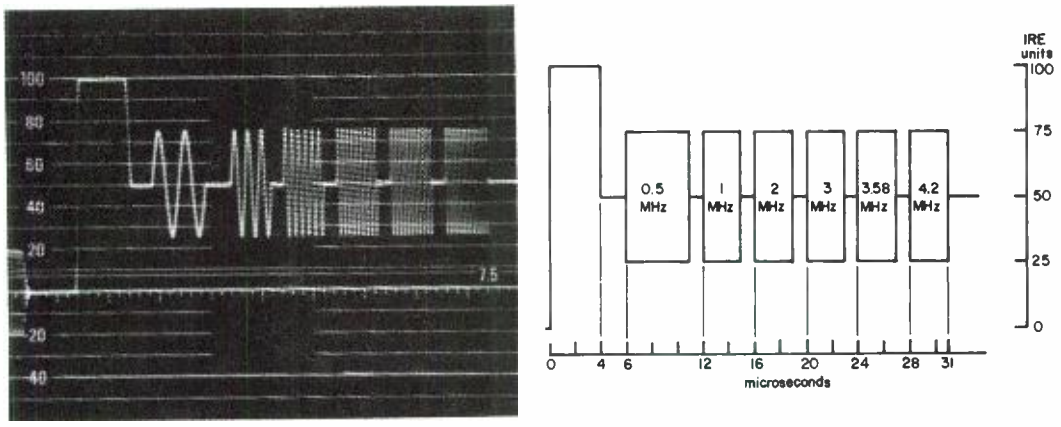


Fig. 18. The multiburst test signal.

Generator Output Specifications

A) **White Flag**

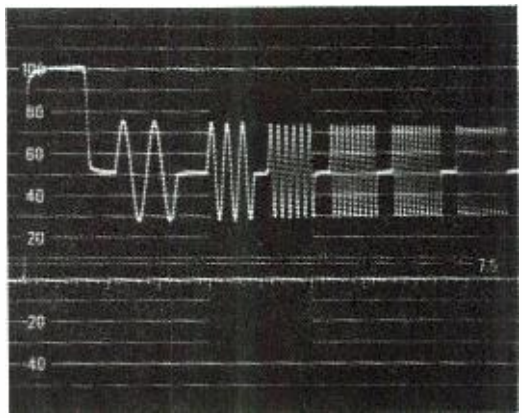
Peak amplitude	:	100 ± 1 IRE unit.
Time of rise and time of fall of flag edges	:	derived from the shaping network of the 2T sine-squared pulse.
Overshoot	:	less than ± 1 IRE unit.
Tilt	:	less than ± 1 IRE unit.

B) **Multiburst Frequencies**

All half-amplitude points of all burst frequencies	:	50 ± 1 IRE unit.

(The starting point of each burst frequency shall be at zero phase of each sinewave.)

Peak-to-peak amplitude of all bursts 50 ± 0.5 IRE units.



In this example, high frequency roll-off is shown. The burst amplitudes vary from 50 IRE units in the 500 kHz burst to 42 IRE units in the 4.2 MHz burst.

Fig. 19. An example of gain/frequency distortion.

3.9 LUMINANCE NON-LINEAR DISTORTION

Definition:

For a particular value of average picture level (APL), the non-linear distortion of the luminance signal is defined as the departure from proportionality between the amplitude of a small unit step function at the sending end of a television facility and the corresponding amplitude at the receiving end, as the level of the step is shifted from blanking level to white level.

Measurement:

The modulated 5-riser staircase portion of the composite test signal shown in Fig. 20 is used when measuring luminance non-linear distortion. The test signals amplitude at each step level must be accurately adjusted at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the test signal is passed through a differentiating and shaping network of the type shown in Fig. 21 with the output of the network connected to the waveform monitor being used for the measurement. The function of the network is that of transforming the test signal into a train of 5 pulses of equal amplitude under zero distortion conditions. The gain of the waveform monitor should be increased to the point where the largest pulse amplitude is 100 IRE units and then the amplitude of the smallest pulse can be measured and recorded. This is the Luminance non-Linear Distortion at 50% APL. The above measurement procedure should be repeated using the same test signal transmitted on every fifth television line with intermediate lines set at blanking level for a 10% APL value and then at peak white for a 90% APL value.*

An example of Luminance non-Linear Distortion is shown in Fig. 22.

Performance Objective:

With the largest pulse amplitude adjusted to 100 IRE units, the difference between it and the smallest pulse amplitude shall not be greater than 10 IRE units at 10%, 50%, or 90% APL.

NOTE: The performance objectives above also apply to in-service VITS measurements.

*For in-service VITS measurements the procedures outlined in Section 3 introduction should be followed.

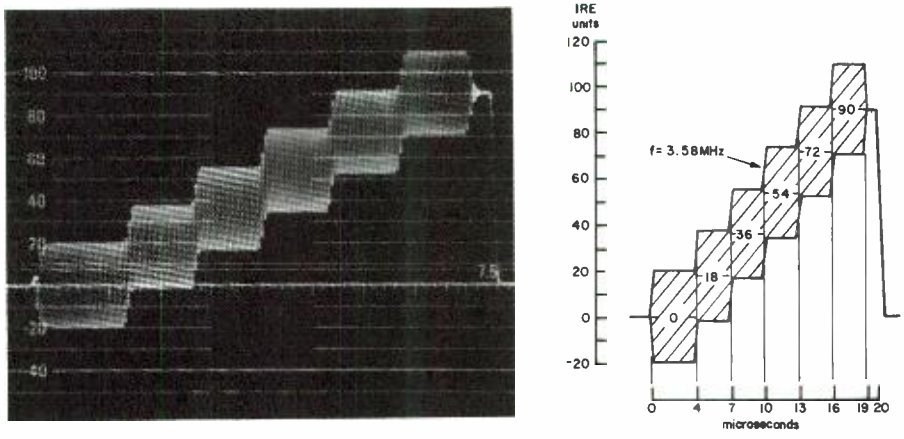


Fig. 20. The modulated 5-riser staircase test signal (see section 3.13 for chrominance specifications).

Generator Output Specifications

Peak amplitude of each riser	:	shall be such that the luminance non-linear distortion shall be greater than 99.5 IRE units.
Rise time of each riser	:	250 ± 10 nanoseconds
Step duration	:	3.0 ± 0.1 usecs; final step 4.0 ± 0.1 microseconds (4.0 ± 0.1 microseconds at blanking level).
Tilt on any step	:	less than 0.3 IRE units
Overshoot on any step	:	less than 0.3 IRE units

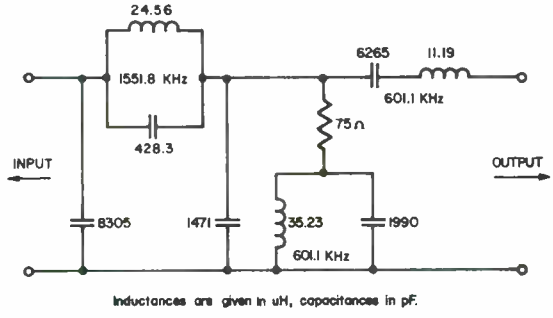


Fig. 21. Differentiating and shaping network for luminance non-linearity measurement.

Luminance Non-Linear Distortion is 4 IRE units.

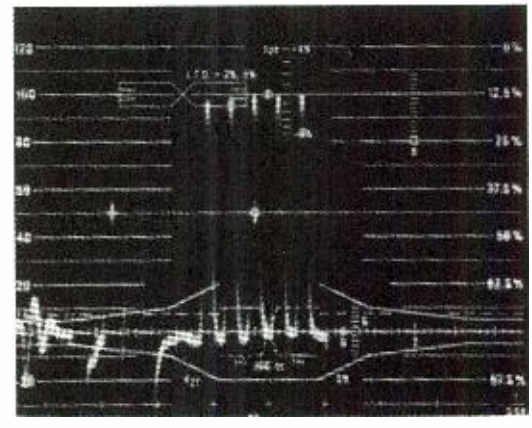


Fig. 22. An example of luminance non-linear distortion.

3.10 CHROMINANCE NON-LINEAR GAIN DISTORTION

Definition:

For fixed values of luminance level and average picture level, the non-linear gain distortion of the chrominance signal is defined as the departure from proportionality between the amplitude of the chrominance subcarrier at the sending end of a television facility and the corresponding amplitude at the receiving end as the amplitude of the subcarrier is varied from a specified minimum value to a specified maximum value.

Measurement:

The 3-level chrominance portion of the combination test signal shown in Fig. 23 is used when measuring chrominance non-linear gain distortion. The test signal's amplitude at each chrominance level must be accurately adjusted at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the test signal is passed through a high-pass filter network* and the output of the network is connected to the waveform monitor being used for the measurement. The gain of the waveform monitor is adjusted to the point where the *middle* subcarrier amplitude is exactly 40 IRE units and then the amplitude of the largest and smallest subcarrier levels are measured and recorded. An example of chrominance non-linear gain distortion is shown in Fig. 24.

Performance Objective:

With the middle subcarrier amplitude adjusted to 40 IRE units the amplitude of the other two subcarrier levels shall be:

a. The smallest subcarrier amplitude shall be 20 ± 2 IRE units.
b. The largest subcarrier amplitude shall be 80 ± 8 IRE units.

NOTE: The performance objective shown above applies equally to both full-field and in-service VITS measurements.

*The chroma filter network incorporated into most television waveform monitors is suitable for this test.

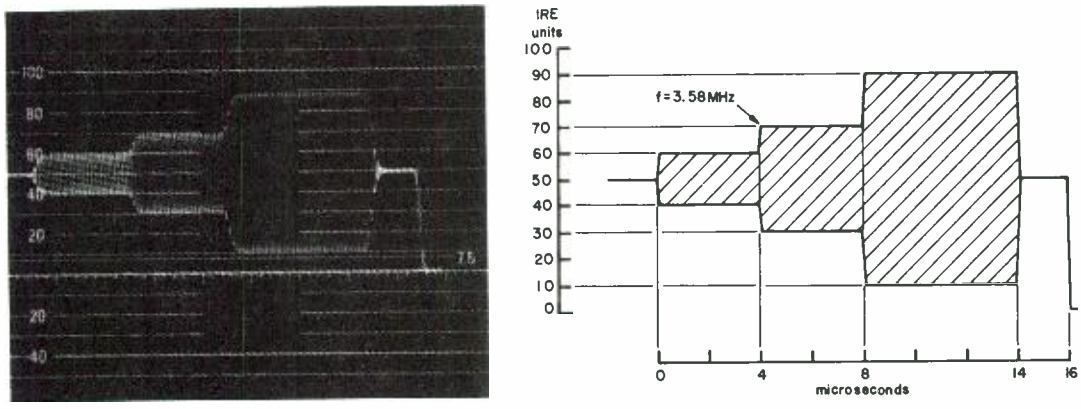
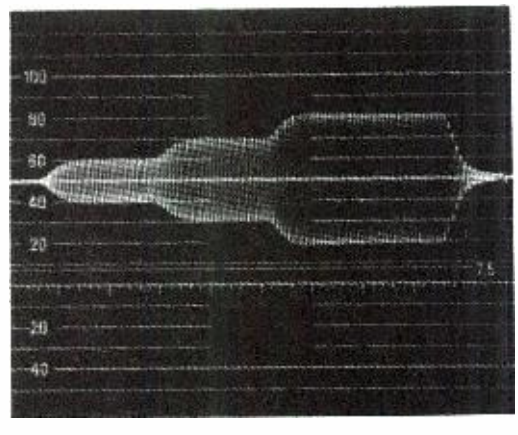


Fig. 23. The 3-level chrominance test signal.

Generator Output Specifications

Peak-to-peak amplitudes of the 3-levels	:	20,40 and 80 IRE units ± 0.5 IRE units
Sub-carrier frequency phase	:	90° ± 1° relative to reference burst; 0° ± 0.2° any one relative to the other two.
Rise and fall of chrominance envelopes	:	400 ± 25 nanoseconds
Duration of entire signal	:	14 ± 0.5 microseconds



The chrominance non-linear gain distortion is evidenced by the largest burst being equal to 64 IRE units.

Fig. 24. An example of chrominance non-linear gain distortion.

3.11 CHROMINANCE NON-LINEAR PHASE DISTORTION

Definition:

For fixed values of luminance signal level and average picture level, the non-linear phase distortion of the chrominance signal is defined as the variation in phase of the chrominance subcarrier at the receiving end of a television facility as the amplitude of the subcarrier is varied from a specified minimum value to a specified maximum value.

Measurement:

The 3-level chrominance portion of the combination test signal shown in Fig. 23 is used when measuring chrominance non-linear phase distortion. The test signal's amplitude and *phase* at each chrominance level must be accurately adusted at the sending end prior to the commencement of the test. Similarly the waveform monitor and phase comparator (e.g., vectorscope) at the receiving end should be properly calibrated.

Following the above, the test signal should be fed through a high pass filter network to the phase comparator (or directly to the vectorscope). Under zero distortion conditions the phase at each level of the 3-level chrominance test signal should be $-90°$ relative to the phase of the color burst (see Fig. 25).

The phase of the three levels of the test signal should be measured relative to the phase of the color burst and recorded.

The peak-to-peak variation of the phase of the 3-level chrominance test signal is the difference between the largest and smallest readings obtained.

It should be noted that processing amplifiers can change the phase of the test signal chrominance information relative to the phase of the color burst. Care should be taken to ensure a processing amplifier is not in the circuit during tests of this kind on television facilities.

An example of chrominance non-linear phase distortion is shown in Fig. 26.

Performance Objective:

The peak-to-peak phase variation of the 3-level chrominance test signal shall not exceed $5°$.

NOTE: The performance objective shown above applies equally to both full-field and in-service VITS measurements.

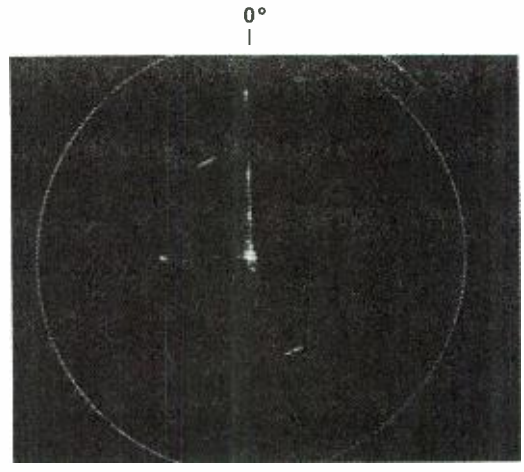


Fig. 25. Chrominance non-linear phase distortion display showing zero distortion.

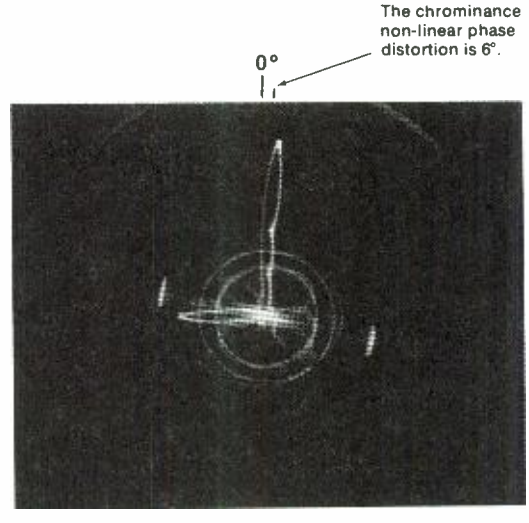


Fig. 26. An example of chrominance non-linear phase distortion.

3.12 DYNAMIC GAIN DISTORTIONS

Definitions:

If, at the sending end of a television facility, the average picture level (APL) of a video signal is stepped from a low value to a high value, or vice versa, the operating point within the transfer characteristic of the system may be affected and introduce various distortions on the receiving end. This section covers two such distortions known, respectively, as long-time waveform distortion and dynamic gain.

Long-Time Waveform Distortion (Bounce)*

Measurement:

The flat-field 'bounce' test signal, as shown in Fig. 27, is used when measuring long-time waveform distortion. The test signal is switched between 10 and 90 IRE units, at an appropriate rate, while the following measurements are made on a properly calibrated dc-coupled oscilloscope or waveform monitor, with any internal clamp in the instrument disabled.

With the waveform monitor on the field rate, observe any instantaneous peak excursion of the blanking level when the switch from 10 to 90 IRE, or vice versa, is made and record in IRE units. Also, observe the time necessary for blanking to settle to within 1 IRE unit of its final position. This may be as long as several seconds and the blanking level may undergo several peak-to-peak changes before stabilizing.

If an oscilloscope is used, a sweep time of 1 sec./cm will generally enable the entire transient to be observed. The Tektronix 1480 MOD. 6 or 7 is presently the only waveform monitor with a slow sweep feature.

A photograph of this slow sweep is the best method of observing these distortions.

An example of long-time waveform distortion is shown in Fig. 28.

Performance Objectives:

Peak overshoot at blanking shall be no greater than 5 IRE units and the time for blanking to settle to within 1 IRE unit of its final level shall be less than 1 sec.

NOTE: This distortion only occurs when the APL change is accompanied by a change in dc component.

*For in-service measurement of long-time waveform distortion the procedure outlined in Section 3 introduction should be followed.

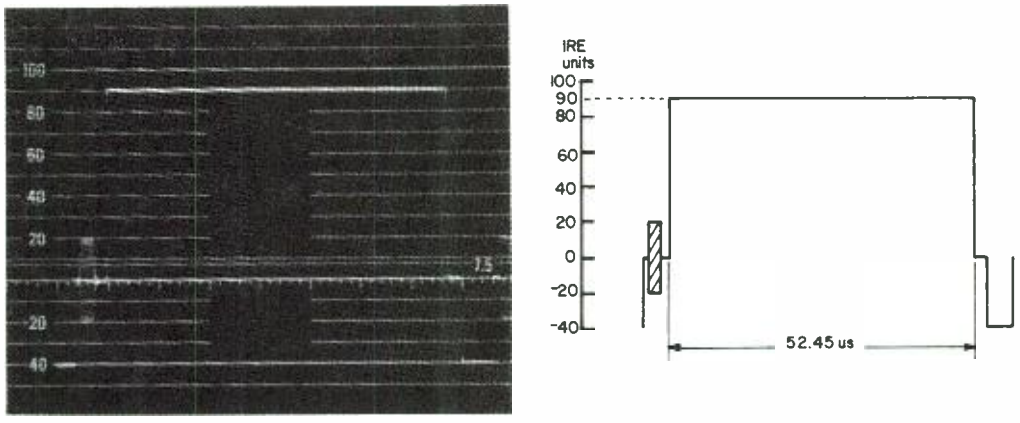


Fig. 27. The flat-field bounce test signal (90% APL value shown).

Generator Output Specifications

Time of rise and fall of bar edge	:	derived from the shaping network of the sine-squared pulse.
Bar Duration	:	nominally 52.45 microseconds
Bar Amplitude	:	(High) 90 ± 1 IRE unit (Low) 10 ± .5 IRE units
Tilt	:	Less than 1 IRE unit (10-90 IRE units)
Time of Transition (10-90 or 90-10)	:	Less than 10 microseconds
Rate of Transition	:	≃ 5 sec.

Peak overshoot is 50mV (7 IRE), settling time .75 sec.
sweep = 1 sec./CM gain = .2V/CM (DC—Coupled)

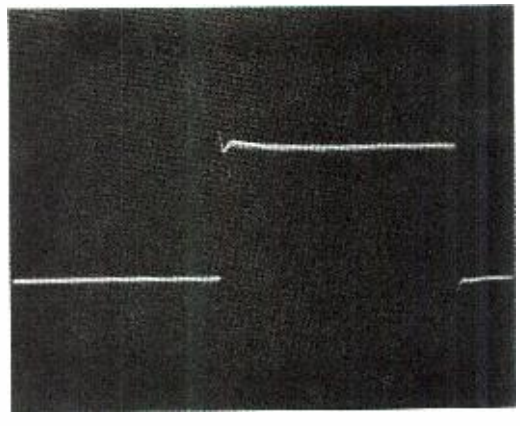


Fig. 28. An example of long-time waveform distortion.

Dynamic Gain*

Measurement:

Switch the flat-field test signal out of the 'bounce' mode and select 50% APL (Fig. 29A). Next, switch the waveform monitor to display the composite test signal on line 17, field one (Fig. 3). If necessary, normalize the gain of the waveform monitor for 100 IRE units at bar center. This is the reference amplitude for the following measurements.

Next, switch the test signal to 10% APL and observe and record, in IRE units, any change in amplitude of the line bar and/or synchronizing pulses. Finally, select 90% APL and record again any change in amplitude of the line bar and/or synchronizing pulses from the reference amplitude at 50% APL.

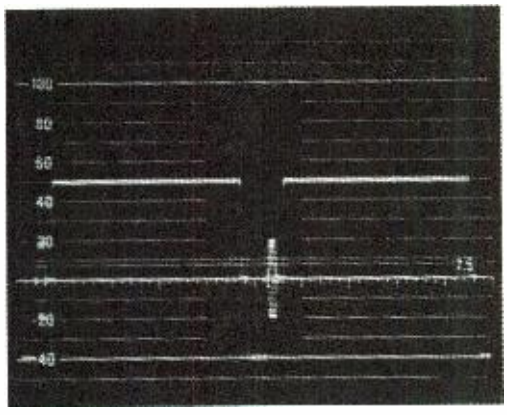
Examples of dynamic gain distortion are shown in Fig. 29B and C.

Performance Objectives:

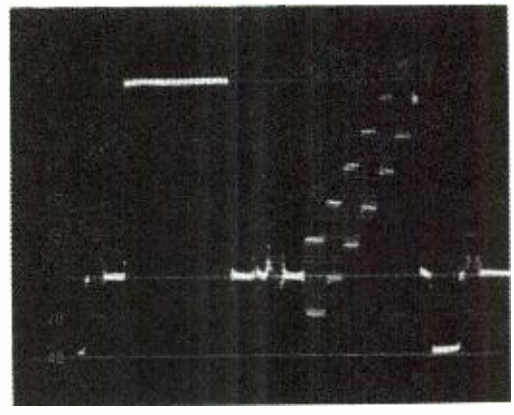
At 10% or 90% APL, dynamic gain-picture shall not exceed ± 3 IRE units and dynamic gain-sync shall not exceed ± 2 IRE units referenced to the amplitude at 50% APL.

NOTE: This distortion may occur with or without a change in dc component accompanying the APL change.

*For in-service measurements of dynamic gain the procedure outlined in Section 3 introduction should be followed.

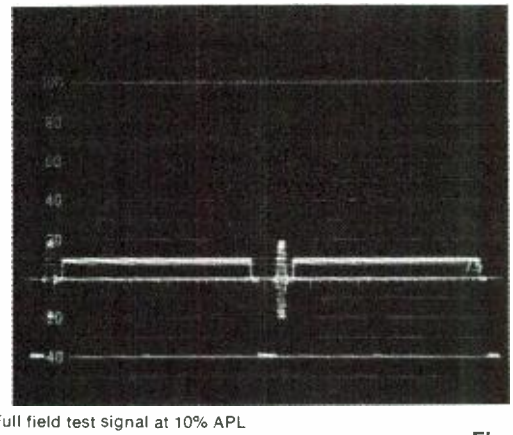


Full field test signal at 50% APL

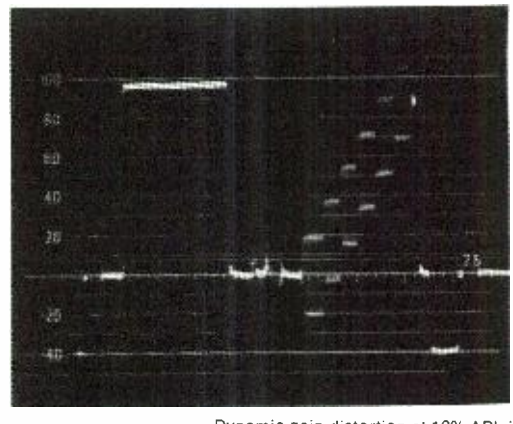


Line 17 field one, reference amplitude
Picture 100 IRE units
Sync 38 IRE units

Fig. 29A.

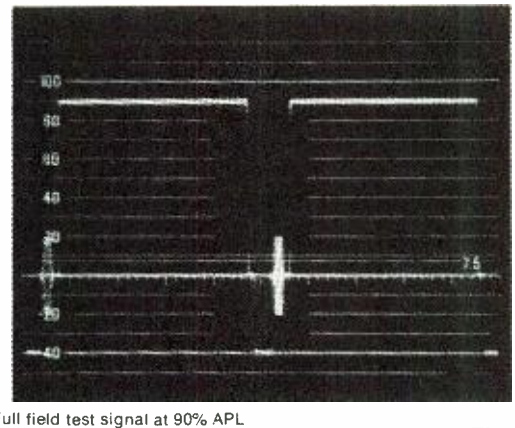


Full field test signal at 10% APL

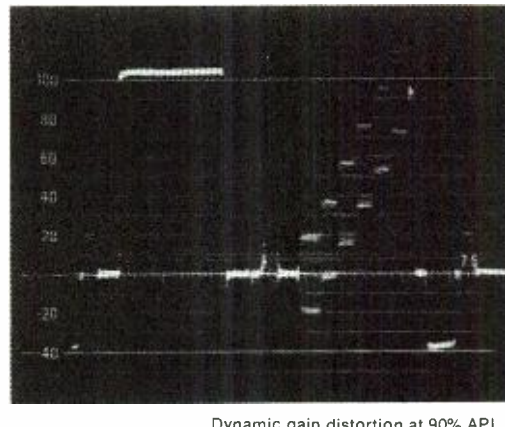


Dynamic gain distortion at 10% APL is
Picture: −3 IRE units
Sync: +2 IRE units

Fig. 29B.



Full field test signal at 90% APL



Dynamic gain distortion at 90% APL is
Picture: +3 IRE units
Sync: 0 IRE units

Fig. 29C.

3.13 DIFFERENTIAL GAIN

Definition:

If a small constant amplitude of chrominance subcarrier, superimposed on a luminance signal, is applied to the sending end of a television facility, the differential gain is defined as the change in amplitude of the subcarier at the receiving end as the luminance varies from blanking level to white level, the average picture level being maintained at a particular value.

Measurement:

The modulated 5-riser staircase portion of the composite test signal shown in Fig. 30 is used when measuring differential gain. The test signal's amplitude at each step level must be accurately adjusted at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the test signal should be fed through a high-pass filter network* and the output of the network connected to the waveform monitor being used for the measurement. The gain of the waveform monitor is then adjusted until the highest subcarrier peak-to-peak amplitude is exactly 100 IRE units. The peak-to-peak amplitude of the lowest subcarrier is then measured. The difference between the highest subcarrier amplitude and the lowest subcarrier amplitude is the differential gain distortion at 50% APL. The above measurement procedure should be repeated using the same test signal transmitted on every fifth television line with intermedite lines set at blanking level for a 10% APL value and then at peak white level for a 90% APL value. The maximum differential gain distortion measured should be recorded.**

An example of differential gain distortion is shown in Fig. 31.

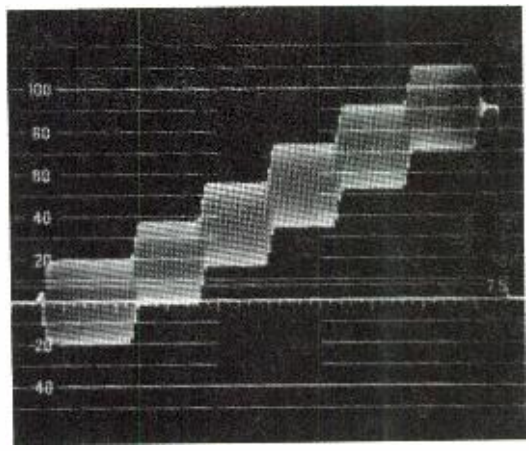
Performance Objective:

At 10%, 50%, and 90% APL, the differential gain shall not exceed 15 percent (15 IRE units).

NOTE: The performance objective shown above also applies to the in-service VITS measurement.

*The chroma filter network incorporated into most television waveform monitors is suitable for this test.

**For in-service VITS measurement of differential gain the procedure outlined in Section 3 introduction should be followed.



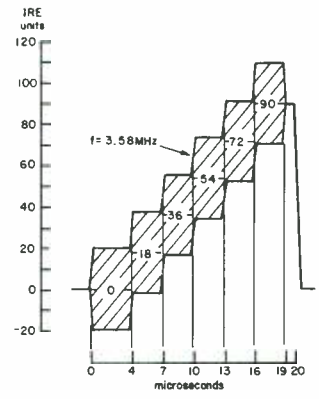
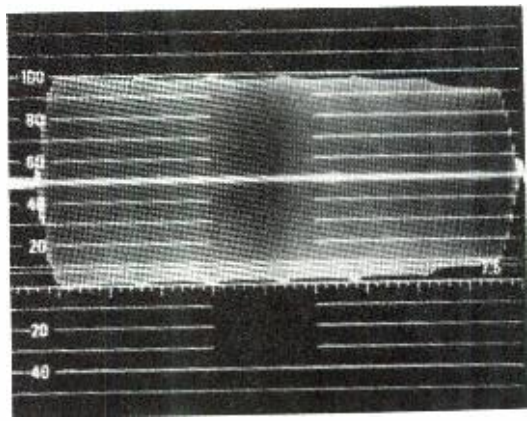


Fig. 30. The modulated 5-riser staircase test signal.

Generator Output Specifications

(In addition to the luminance specifications shown with Figure 20 in Section 3.9)

Chrominance amplitude	:	40 ± 0.5 IRE units
Inherent differential gain	:	less than 0.5 percent
and differential phase	:	less than 0.2°
Rise and fall times of the modulation envelope	:	400 ± 25 nanoseconds
Phase of chrominance signal relative to reference burst phase	:	0° ± 1.0° over the range 10% to 90% APL



Differential gain is 16 percent.

Fig. 31. An example of differential gain distortion.

3.14 DIFFERENTIAL PHASE

Definition:

If a constant amplitude of chrominance subcarrier without phase modulation, superimposed on a luminance signal, is applied to the sending end of a television facility, the differential phase is defined as the change in the phase of the subcarrier at the receiving end as the luminance varies from blanking level to white level, the average picture level being maintained at a particular value.

Measurement:

The modulated 5-riser staircase portion of the composite test signal shown in Fig. 30 is used when measuring differential phase. The test signal's amplitude and its subcarrier phase at each step level must be accurately adjusted at the sending end prior to the commencement of the test. Similarly the waveform monitor and phase comparator (e.g., vectorscope) at the receiving end should be properly calibrated. A vectorscope display of differential phase with zero distortion is shown in Fig. 32.

Following the above, the test signal should be fed through a high-pass filter network to the phase comparator (or directly to the vectorscope). The differential phase distortion is the measured peak-to-peak change in subcarrier phase at 50% APL. The above measurement procedure should be repeated using the same test signal transmitted on every fifth television line with intermediate lines set at blanking level for a 10% APL value and then at peak white level for a 90% APL value. The maximum differential phase distortion should be recorded.*

An example of differential phase distortion is shown in Fig. 33.

Performance Objective:

At 10%, 50% and 90% APL the differential phase shall not exceed 5 degrees.

NOTE: The performance objective shown above also applies to the in-service VITS measurement.

*For in-service VITS measurement of differential phase the procedure outlined in Section 3 introduction should be followed.

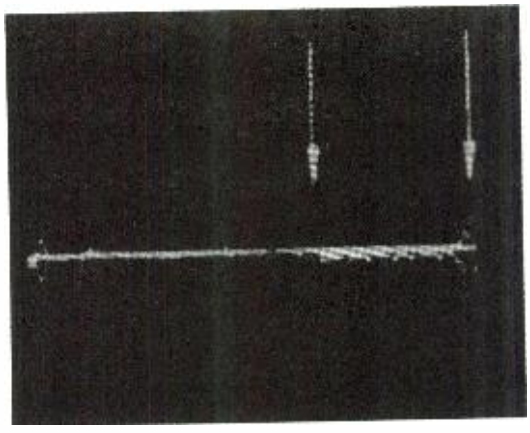


Fig. 32. Vectorscope display of differential phase showing zero distortion (between arrows).

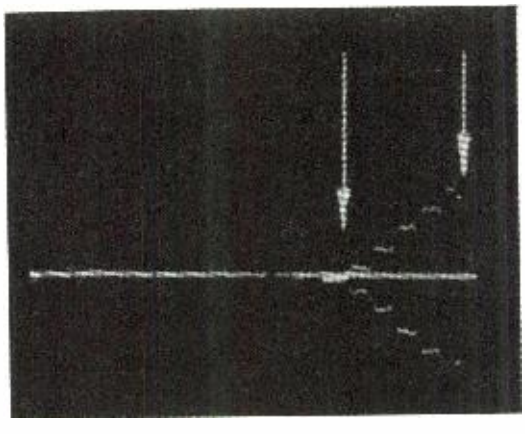


Fig. 33. Vectorscope display showing differential phase distortion (between arrows).

3.15 CHROMINANCE-TO-LUMINANCE INTERMODULATION

Definition:

If a luminance signal of constant amplitude is applied to the sending end of a television facility, the intermodulation is defined as the variation of the amplitude of the luminance signal at the receiving end resulting from the superimposition on the luminance signal of a chrominance signal of specified amplitude.

Measurement:

The 3-level chrominance portion of the combination test signal shown in Fig. 34 is used when measuring chrominance-to-luminance distortion. The test signal's amplitude at each chrominance level must be accurately adjusted at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated. A waveform monitor display of chrominance-to-luminance intermodulation with zero distortion is shown in Fig. 35.

Following the above, the test signal is passed through a low-pass filter network* the output of which is connected to the waveform monitor being used for the measurement. The chrominance-to-luminance intermodulation is the maximum amplitude departure in IRE units of the filtered luminance pedestal from the amplitude of that portion of the luminance pedestal which did not contain the superimposed subcarrier, with the pedestal adjusted to exactly 50 IRE units.

An example of chrominance-to-luminance intermodulation is shown in Fig. 36.

Performance Objective:

Chrominance-to-luminance intermodulation shall displace the luminance component no more than 3 IRE units from the 50 IRE unit reference level.

NOTE: The performance objective shown above applies equally to both full-field and in-service VITS measurements.

*The low-pass filter network incorporated into most television waveform monitors is suitable for this test.

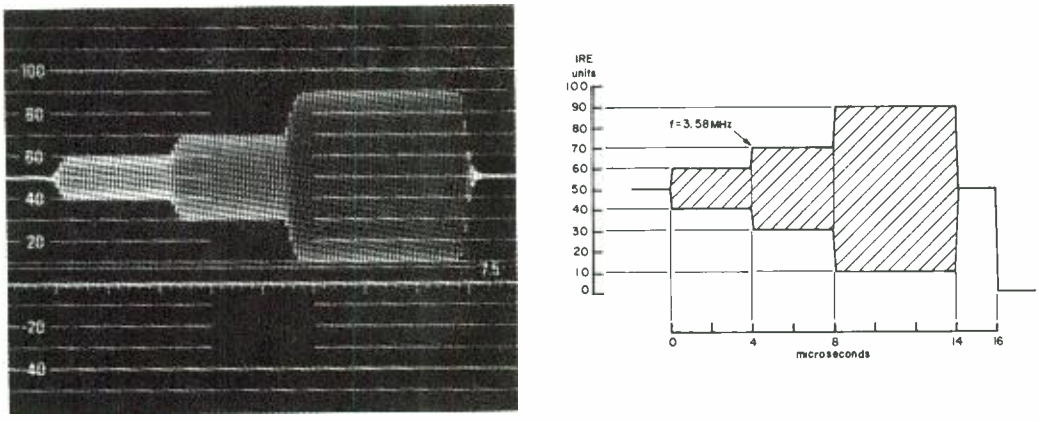


Fig. 34. The 3-level chrominance signal.

Generator Output Specifications

Peak-to-peak amplitudes of the 3-levels	:	20,40 and 80 IRE units ± 0.5 IRE units
Sub-carrier frequency phase	:	90° ± 1° relative to reference burst; 0° ± 0.2° any one relative to the other two.
Rise and fall of chrominance envelopes	:	400 ± 25 nanoseconds
Duration of entire signal	:	14 ± 0.5 microseconds

The chrominance-to-luminance intermodulation is + 3 IRE units.

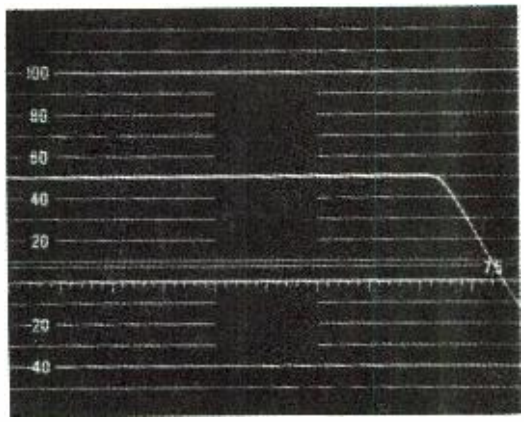


Fig. 35. Waveform monitor display showing zero chrominance-luminance intermodulation.

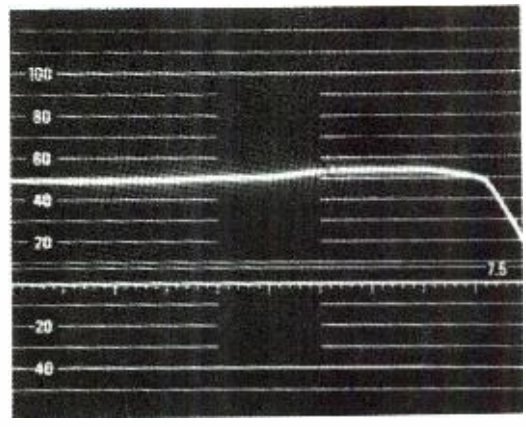


Fig. 36. Waveform monitor display showing chrominance-luminance intermodulation distortion.

3.16 RANDOM NOISE—WEIGHTED

Definition:

The signal-to-weighted noise ratio of a television facility is defined as the ratio, expressed in decibels, of the nominal amplitude of the *luminance* signal (100 IRE units) to the RMS amplitude of the noise measured at the receiving end after band-limiting and weighting with a specified network. The measurement should be made with an instrument having, in terms of power, a time constant or integrating time of 0.4 seconds.

Measurements:

In general, the random noise-weighted measurement should be made with an RMS reading instrument with the video signal removed from the television facility and the input to the facility terminated in its characteristic impedance. However, the measurement can also be made either with a flat-field test signal as shown in Fig. 37 or using a specified line in the vertical blanking interval which is kept free of picture information, provided the measuring instrument accurately integrates the measured noise over the full-field period. In all of the above measurements the band-limiting and weighting networks shown in Fig. 38 shall be inserted at the receiving end of the television facility prior to the noise measuring instrument.

The signal-to-weighted noise ratio in decibles can be computed using the following formula:

$$\text{Signal-to-weighted noise (dB)} = 20 \log_{10} \frac{\text{P-P signal amplitude}}{\text{RMS weighted noise}}$$

An example of random noise is shown in Fig. 39.

Performance Objective:

The signal-to-random noise ratio shall be greater than or equal to 53 dB.

NOTE: Appendix II describes a technique for approximating weighted video random noie.

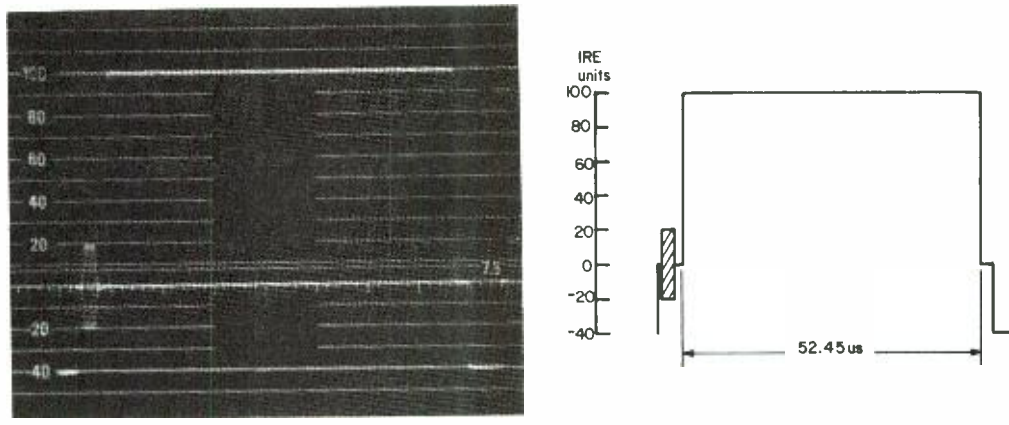


Fig. 37. The 100% flat-field test signal.

Generator Output Specifications

Time of rise and fall	:	derived from the shaping network of the sine-squared pulse.
Amplitude	:	100 ± 1 IRE unit.
Tilt	:	less than 1 IRE unit.
Time of bar duration	:	nominally 52.45 microseconds.

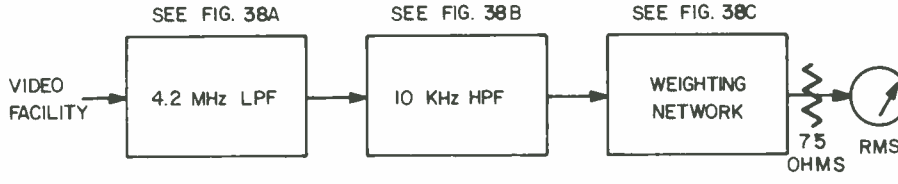


Fig. 38 Band limiting and weighting network for measurement of random noise—weighted.

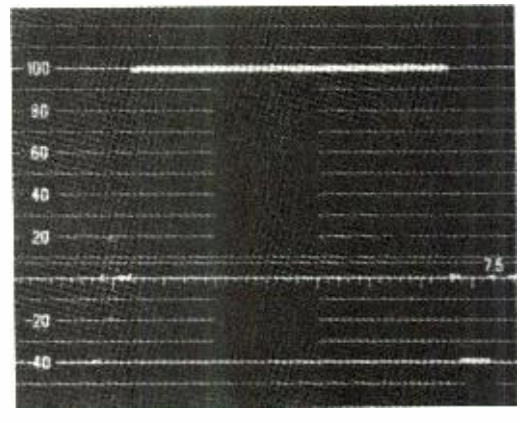
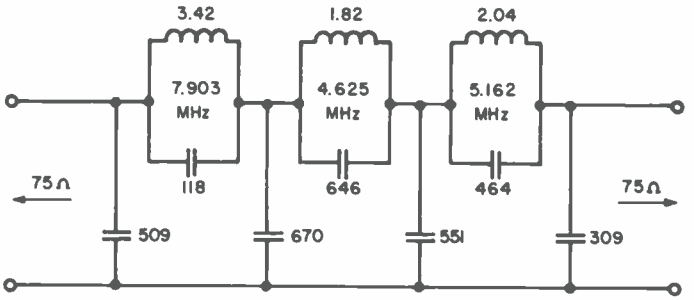
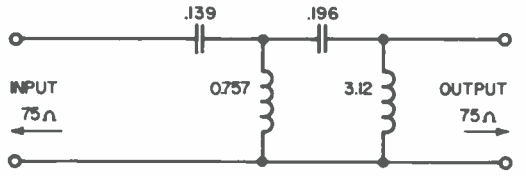


Fig. 39. An example of random noise.



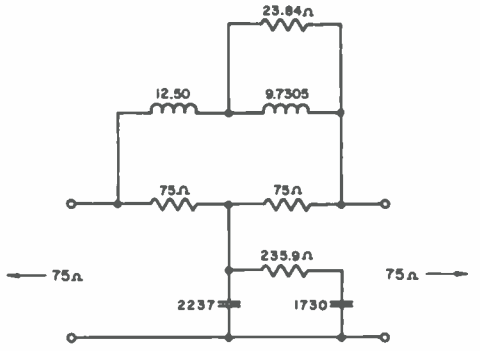
Inductances are given in uH, and capacitances in pF. Q measured at 5 MHz is between 80 and 125 for all inductors.

Fig. 38A. Low-pass filter for use in noise measurements (f_c = 4.2 MHz).



Inductances are given in MH, capacitances in pF. Q measured at 10 kHz should be 100 or more.

Fig. 38B. High-pass Filter (f_c = 10 kHz).



Capacitances are given in pF, inductances in uH.
Capacitor and resistor tolerance ±1%.

$$\text{Insertion loss (dB)} = 10 \log_{10} \frac{[1+(f/f_1)^2][1+(f/f_2)^2]}{[1+(f/f_3)^2]},$$

where f_1 = 0.270MHz, f_2= 1.37MHz, and f_3= 0.390 MHz.

Fig. 38C. Random noise weighting network.

3.17 IMPULSIVE NOISE

Definition:

The signal-to-impulsive noise ratio of a television facility is defined as the ratio, expressed in decibels, of the nominal amplitude of the *luminance* signal (100 IRE units) to the peak-to-peak amplitude of the noise.

Measurement:

The flat-field test signal shown in Fig. 37 is used when measuring impulsive noise. The test signal's amplitude must be accurately adjusted to 100 IRE units at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the test signal's amplitude should be adjusted to be exactly 100 IRE units at the receiving end and the waveform display then examined closely to determine if impulsive noise interference (occasional random spikes or transients) is present. The peak-to-peak amplitude of the interference is then measured, in IRE units, and recorded. To compute the signal-to-impulsive noise ratio in decibels, the following formula can be used:

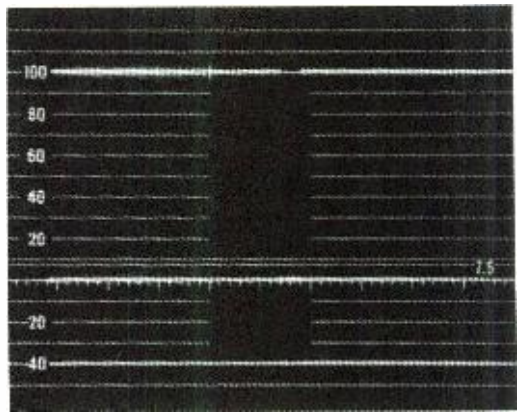
$$\text{Signal-to-impulsive noise (dB)} = 20 \log_{10} \frac{100 \text{ IRE units}}{\text{peak-to-peak amplitude of impulsive noise}}$$

Alternatively, the actual peak-to-peak amplitude of the impulsive noise, in IRE units, can be used directly to determine if the television facility meets the performance objective stated below.

An example of impulsive noise interference is shown in Fig. 40.

Performance Objective:

The impulsive noise shall be no greater than 7 IRE units peak-to-peak which equals a signal-to-impulsive noise ratio of no greater than 23 dB. The frequency of occurrence of noise impulses shall not exceed one per minute.



Impulsive noise is 12 IRE units peak-to-peak.

Fig. 40. An example of impulsive noise interference.

3.18 PERIODIC NOISE

Definition:

The signal-to-periodic noise ratio is defined as the ratio in decibels of the nominal amplitude of the *luminance* signal (100 IRE units) to the peak-to-peak amplitude of the noise. Different performance objectives are sometimes specified for periodic noise (single frequency) between 1 kHz and the upper limit of the video frequency band and for power supply hum, including low-order harmonics.

Measurement:

The flat-field test signal shown in Fig. 37 is used when measuring periodic noise. The test signal's amplitude must be accurately adjusted to 100 IRE units at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the test signal's amplitude should be adjusted to be exactly 100 IRE units at the receiving end and the waveform display then examined to determine if periodic noise interference is present. The peak-to-peak amplitude, in IRE units, of periodic noise which is low-frequency in nature (power-supply hum, etc.) should be measured and recorded separately from the periodic noise in the nominal frequency range 1 kHz to 4.2. MHz.* Examples of periodic noise interference are shown in Figs. 41 and 42. To compute the signal-to-periodic noise ratio in decibels the following formula can be used:

$$\text{Signal-to-periodic noise (dB)} = 20 \log_{10} \frac{100 \text{ IRE units}}{\text{peak-to-peak amplitude of periodic noise}}$$

Performance Objective:

The signal-to-periodic noise ratio,

a. below 1 kHz (including power-supply hum and lower order harmonics) shall be greater than or equal to 50 dB.

b. between 1 kHz and 4.2 MHz** shall be greater than or equal to 50 dB.

NOTE: In specific instances where an exact measurement must be made, a spectrum analyzer or a frequency-selective voltmeter should be used. As these devices are normally RMS reading instruments, 9 dB should be substracted from the performance objective (to convert from peak-to-peak noise to RMS noise).

*It may be necessary to use the high-gain setting on the waveform monitor when making this measurement. If so, care should be taken to ensure that it is properly calibrated.

**The low-pass filter network shown in Figure 38A should be used when measuring periodic noise interference in the range 1 kHz to 4.2 MHz.

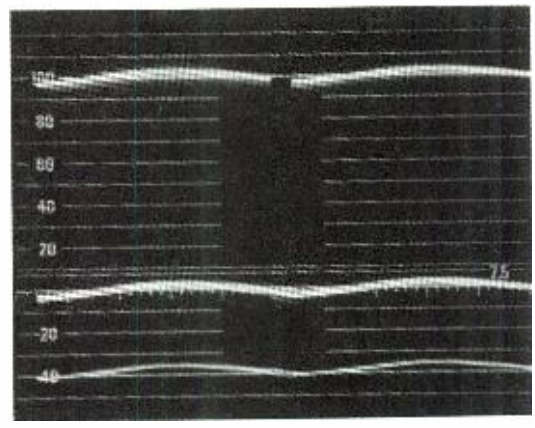


Fig. 41. Example of below 1 kHz (i.e., 60 Hz.) periodic noise—field rate display.

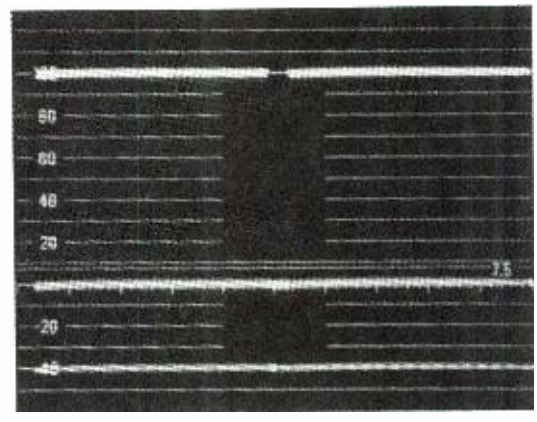


Fig. 42. An example of above 1 kHz (i.e., 5 kHz) periodic noise—field rate display.

3.19 CROSSTALK NOISE

Definition:

The signal-to-crosstalk ratio is defined as the ratio, in decibels, of the nominal amplitude of the *luminance* signal (100 IRE units) to the peak-to-peak amplitude of the interfering waveform.

Measurement:

The flat-field test signal shown in Fig. 37 is used when measuring crosstalk. The test signal's amplitude must be accurately adjusted to 100 IRE units at the sending end prior to the commencement of the test. Similarly the waveform monitor at the receiving end should be properly calibrated.

Following the above, the test signal's amplitude should be adjusted to be exactly 100 IRE units at the receiving end. The waveform display and a suitable broadcast-quality picture monitor can then be examined to determine if crosstalk interference is present. The peak-to-peak amplitude of the interfering waveform is then measured, in IRE units, and recorded.*

To compute the signal-to-crosstalk ratio in decibles the following formula can be used:

$$\text{Signal-to-crosstalk (dB)} = 20 \log_{10} \frac{100 \text{ IRE units}}{\text{peak-to-peak amplitude of crosstalk}}$$

Performance Objective:

The signal-to-crosstalk ratio shall be greater than or equal to 60 dB.**

*It may be necessary to use the high gain setting on the waveform monitor when making this measurement. If so, care should be taken to ensure that it is properly calibrated.

**The low-pass filter network shown in Figure 38A should be used when measuring crosstalk noise interference.

Section 4: Interconnection Requirements

INTRODUCTION

This section defines the accepted standard interconnection requirements that both the Bell System and the major television networks must comply with at their common interface points. Deviations from these requirements are permitted only if mutually agreed upon prior to the provision and acceptance of the service.

IMPEDANCE

At the points of interconnection between the customer and the telephone company, the input and output impedance (Z_o), of each link shall be specified as unbalanced to ground.

Performance Objective:

Nominally 75 ohms resistive, unbalanced to ground.

SIGNAL AMPLITUDE

The nominal video signal amplitude shall be 1.0 volt peak-to-peak (140 IRE units).

SIGNAL POLARITY

The polarity of the signal shall be "positive," i.e., such that black-to-white transitions are positive going.

NON-USEFUL DC COMPONENT

The non-useful dc component present across the interface point with or without the load impedance connected shall be zero ±50mv. (Non-useful dc component is that which is produced by the transmission equipment and is not related to picture content.)

RETURN LOSS

Definition:

The return loss , relative to Z_o, of an impedance Z, in the frequency domain is

$$20 \log_{10} \left| \frac{Z_o + Z(f)}{Z_o - Z(f)} \right| \text{ dB}$$

and in the time domain

$$20 \log_{10} \left| \frac{A_1}{A_2} \right| \text{ dB}$$

Where A_1 is the peak-to-peak amplitude of the incident signal and A_2 is the peak-to-peak amplitude of the reflected picture signal. Numerically, the result is the same as that obtained by the frequency domain method if the return loss is independent of frequency.

Performance Objective:

Greater than 30 dB from 0 to 4.2 MHz at the point of interconnection.

Section 5: Processing Errors

INTRODUCTION

This section describes two types of signal processing errors that can arise when a video signal is fed through a processing amplifier that has been incorrectly adjusted. It should be noted that while it is not the practice of the Bell System to use processing amplifiers in the provision of television facilities and therefore processing errors will not arise on these facilities, these errors can and do significantly affect the technical quality of color television transmission. Accordingly, it was felt that the two most commonly encountered processing errors should be included in this document.

5.1 RELATIVE BURST GAIN ERROR

Definition:

Relative burst gain error is defined as the change in gain (amplitude) of the color burst signal relative to the gain (amplitude) of the chrominance subcarrier, in the active line time, caused by processing the video signal.

Measurement:

The 5-riser modulated staircase signal shown in Fig. 30 is used when measuring relative burst gain error. The test signal's amplitude must be accurately adjusted prior to the commencement of the test. Similarly, the waveform monitor to be used for the measurement should be properly calibrated.

Following the above, the test signal is fed to the processing amplifier input and the output of the processing amplifier is fed to the waveform monitor via a high-pass filter network.* The gain of the waveform monitor is then adjusted until the blanking level burst of the 5-riser staircase signal is exactly 40 IRE units. The amplitude of color burst is then measured and recorded.

Performance Objective:

The amplitude of the color burst shall be 40 ± 1 IRE units with respect to the amplitude of the blanking level burst of the 5-riser modulated staircase.

5.2 RELATIVE BURST PHASE ERROR

Definition:

Relative burst phase error is defined as the change in phase of the color burst signal relative to the phase of the chrominance subcarrier, in the active line time, caused by processing the video signal.

Measurement:

The 5-riser modulated staircase signal shown in Fig. 30 is used when measuring relative burst phase error. The test signal's amplitude and phase must be accurately adjusted prior to the commencement of the test. Similarly, the phase comparator (e.g., vectorscope) to be used for the measurement should be properly calibrated.

Following the above, the test signal is fed to the processing amplifier input and the output of the processing amplifier is fed to the phase comparator. The phase of the color burst signal is then measured relative to the phase of the blanking level chrominance burst of the 5-riser staircase signal and recorded.

Peformance Objective:

The relative phase of the color burst signal shall be zero ± 1° with respect to the phase of the blanking level burst of the 5-riser modulated staircase.

*The high pass filter network incorporated into most television waveform monitors is sufficient for this purpose.

Section 6: Performance Characteristics of the Audio Signal Channel

The following is from EIA RS-250-B*, for single channel audio. NTC-7 does not cover audio transmission.

6.1 AMPLITUDE VS. FREQUENCY RESPONSE

Definition:

The audio amplitude versus frequency characteristic of a television relay system is an expression of amplitude variation as a function of audio frequency of a sine-wave voltage when applied to the system audio input and measured at the system audio output. The amplitude variation is expressed in decibels.

Standard:

The audio amplitude versus frequency characteristic shall be within the applicable limits specified in Figure 43. This standard applies equally to short haul, medium haul, satellite, long haul, and end-to-end performance on the assumption that audio will be demodulated from its subcarrier only once in any system or interconnection.

Method of Measurement:

The measuring equipment shall terminate the output of the audio channel under test in a standard load impedance. The grounded or balanced-to-ground connection normally used shall be maintained. Standard test tone of 1000 Hz shall be applied to the input of the system and rated modulation shall be established. The output level control shall be set to deliver standard output. If no preemphasis and no deemphasis are used, the response shall be measured under the above conditions while maintaining constant input to the system and measuring output variations. If preemphasis and deemphasis are used, after adjusting the circuit as described above, the input to the system shall be decreased approximately 20 dB, and maintained at this level during the complete frequency response measurement. The output level control shall not be reset. This requirement is necessary to prevent overload of the audio system at the higher audio frequencies due to the "boost" provided by the preemphasis network.

*Reprinted with permission of the Electronics Industries Association, Washington, D.C.

6.2 HARMONIC DISTORTION

Definition:

Audio frequency harmonic distortion is the production of harmonic frequencies at the output of the system caused by nonlinearities, when a non-distorted sinusoidal voltage is applied to the input of the system.

Standard:

The harmonic distortion of the audio frequency signal, including all harmonics up to 30 kHz, shall not exceed the values given in the following table.

Frequency Range	Limit Distortion in %
50-15,000 Hz	1.0

This standard applies equally to short haul, medium haul, satellite, long haul and end-to-end performance on the assumption that audio will be demodulated from its subcarrier only once in any system or interconnection.

Method of Measurement:

The audio channel shall be operated at standard input and output test tone level and the measuring equipment shall terminate the circuit in a standard load impedance. A test tone of 1000 Hz, having less than 0.1% RMS harmonic distortion, shall be applied to the audio input of the system and rated maximum modulation established. If no preemphasis and no deemphasis are employed, distortion shall be measured at this level, with readings taken on as many frequencies as necessary to ensure compliance. If preemphasis and deemphasis are employed, the input level to the system shall be adjusted at each measurement to operate the system at rated maximum modulation. This will require dropping the input voltage level with increasing frequency as many dB as the preemphasis curve rises. The input and output level controls shall not be readjusted during this procedure.

6.3 SIGNAL-TO-NOISE RATIO

Definiton:

The audio signal-to-noise ratio of the system is the ratio of RMS standard test tone voltage

to the RMS noise voltage at the system output terminals. Noise is any extraneous output voltage in the frequency band from 50 Hz to 15 kHz.

Standard:

The signal-to-noise ratio for the systems listed shall be at least:

Short Haul	66 dB
Medium Haul	65 dB
Satellite	58 dB
Long Haul	57 dB
End-to-End	56 dB

Method of Measurement:

The system shall be operated at standard input and output test tone levels, and the measuring equipment shall terminate the system in a standard load impedance. A test tone of 1000 Hz shall be applied to the audio input of the system and rated maximum modulation established. The system output shall be measured with an RMS indicator. The test tone shall then be removed, the system input terminated with a standard impedance, and the noise output of the system measured with the RMS indicator.

NOTE

Should the system utilize circuits that are common to the audio and video signals, the audio signal-to-noise measurements shall be made in the presence of a standard composite picture under standard input and output conditions. The staircase signal of Figure 9, shall be used for this purpose at 50% APL.

6.4 INSERTION GAIN

Definition:

The audio signal insertion gain of a relay system is the ratio in dB of the output signal level with respect to the input signal level.

Standard:

The preferred standard of insertion gain is 0 dB ±0.5 dB. In order to accommodate the input level and output level*, equipment may have input and output level adjustment capability to allow insertion gains of up to ±18 dB.

Method of Measurement:

The audio signal input and output levels shall be measured as described below* and the difference expressed in dB. Generally accepted audio measuring equipment, shall be used.

6.5 CONTINUITY OF AUDIO SERVICE

Definition:

The performance tolerances designed into a television relay system as detailed in this standard are not only system objectives describing the initial performance of such a system but also describe the performance of that system with time to the extent indicated in the standards that follow.

Standards:

a) The objective for continuity of audio service is 99.99% of the annual operating time.

b) The continuity of audio service will be deemed as interrupted if one or more of the following conditions exist:

(1) There is a total loss of the desired audio signal.

---

*INPUT SIGNAL LEVEL

Definition: The audio signal level is the test tone level which produces rated maximum modulation of the audio signal channel at test tone frequency. It is expressed in dBm.

NOTE

Nominal program transmission level should be at least 10 dB and preferably as much as 18 dB below test tone level.

Standard: The audio test tone input level for rated maximum modulation shall be in the range from 0 dB to + 18 dBm. The frequency of the test tone signal shall be 1000 Hz.

Method of Measurement: The audio input level shall be measured directly across the audio input terminals of the relay system. Generally accepted audio measuring equipment shall be used.

OUTPUT SIGNAL LEVEL

Definition: The audio output signal level is the test tone level which results from rated maximum modulation of the audio signal channel at the test tone frequency. It is expressed in dBm.

NOTE

Nominal program transmission level should be at least 10 dB and preferably as much as 18 dB below test tone level.

Standard: The audio test tone output level for rated maximum modulation shall be in the range from 0 dBm to + 18 dBm. The frequency of the test tone shall be 1000 Hz.

Method of Measurement: The audio output level shall be measured directly across the audio output terminals of the relay system. Generally accepted audio measuring equipment shall be used.

(2) The signal-to-noise ratio is less than 25 dB.

(3) The performance standards are exceeded to the extent that the audio signal is not usable.

Method of Measurement:

Parameters of paragraph b. provide guidelines for the calculation of system statistical performance. Methods of measurement for real systems cannot be readily established at this time.

6.6 AUDIO-VIDEO TIME DIFFERENTIAL

Definition:

Audio-video time differential is the departure from equality in the transmission time of associated audio and video signals. It is usually exhibited as a delay of the audio signal with respect to the video signal.

Standard:

The time differential between the audio signal with respect to its associated video signal shall not exceed 25 ms lead or 40 ms lag for all systems.

REF: CMTT Report 412-1 (Geneva 1974)

Method of Measurement:

The system shall be operated at standard input and output levels of both audio and video signals and terminated in standard load impedances. The measurement shall be made with a storage oscilloscope with a dual trace amplifier. Provisions shall be made at the system input to simultaneously initiate or interrupt the audio and video signals. The time differential is read on the oscilloscope display at the system output.

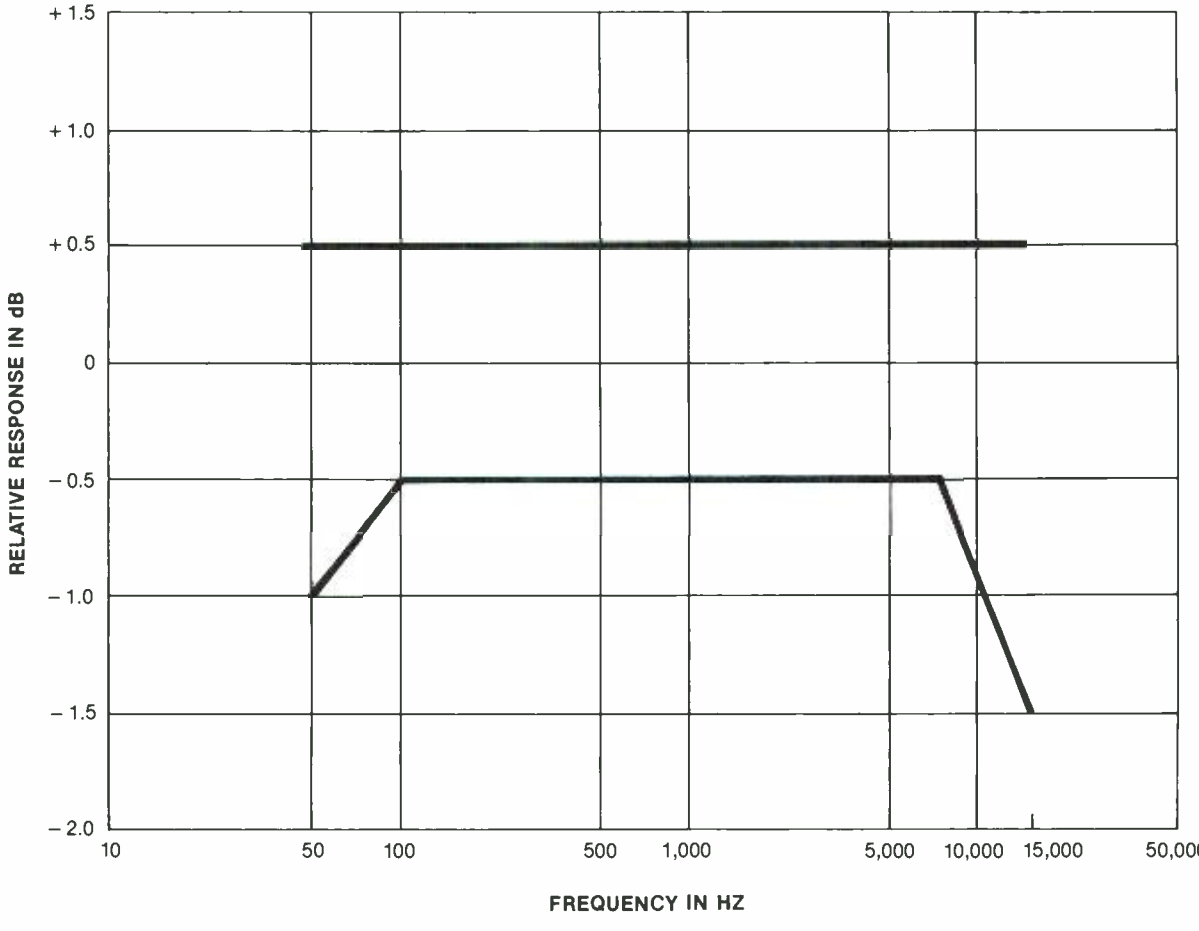


Fig. 43. Audio amplitude vs. frequency response.

Appendix I. Example of a Weekly VITS Log

WEEKLY VITS LOG

WEEK BEGINNING SUNDAY _____

STATION _____ LOCATION _____

PARAMETER	SIGNAL	LIMIT	SUN	MON	TUES	WED	THUR	FRI	SAT
INSERTION GAIN (See Sec. 3.2)	BAR	±3 IRE							
LINE TIME DISTORTION (See Sec. 3.4)	BAR	4 IRE PK-PK							
SHORT TIME DISTORTION (See Sec. 3.5)	2T	±6 IRE P/B							
	BAR EDGE	10 IRE PK-PK							
CHROMA-LUMINANCE GAIN INEQUALITY (See Sec. 3.6)	CHROMA PULSE	100 ±3 IRE							
CHROMA-LUMINANCE DELAY INEQUALITY (See Sec. 3.7)	CHROMA PULSE	(CHROMA) 75 nSec ADV or DLY							
GAIN-FREQUENCY (See Sec. 3.8)	MULTI-BURST	45-53 IRE (0.5, 1.0, 2.0, 3.0, 3.58, 4.2)							
DIFFERENTIAL GAIN (See Sec. 3.13)	STAIR-CASE	15 %							
DIFFERENTIAL PHASE (See Sec. 3.14)	STAIR-CASE	5°							
CHROMA NON-LINEAR GAIN DISTORTION (See Sec. 3.10)	3 LEVEL CHROMA	40 REF: 20±2 IRE 80±8 IRE							
CHROMA NON-LINEAR PHASE DISTORTION (See Sec. 3.11)	3 LEVEL CHROMA	5°							
CHROMA-LUMINANCE INTERMODULATION (See Sec. 3.15)	3 LEVEL CHROMA	3 IRE							
RANDOM NOISE (See Appendix II)	"GRASS" ESTI-MATE	53 dB							

NOTES: OBSERVATIONS TO BE MADE AHEAD OF ANY STATION EQUIPMENT.

THESE NETWORK TRANSMISSION OBSERVATIONS SHOULD BE SUPPLEMENTED, AS APPROPRIATE, BY OBSERVATIONS OR MEASUREMENTS OF THE OTHER PARAMETERS COVERED IN NTC REPORT NO. 7.

SECTION NO. UNDER PARAMETER REFERS TO APPROPRIATE SECTION OF NTC REPORT NO. 7.

Appendix II.

TECHNIQUE FOR APPROXIMATING WEIGHTED VIDEO RANDOM NOISE

When an RMS reading noise meter is not available, an alternate method of determining video S/N should be used. The one suggested here is accurate to within 2 dB if care is taken in setting scope brightness and operator estimation of the peak-to-peak noise is done in a consistent manner.

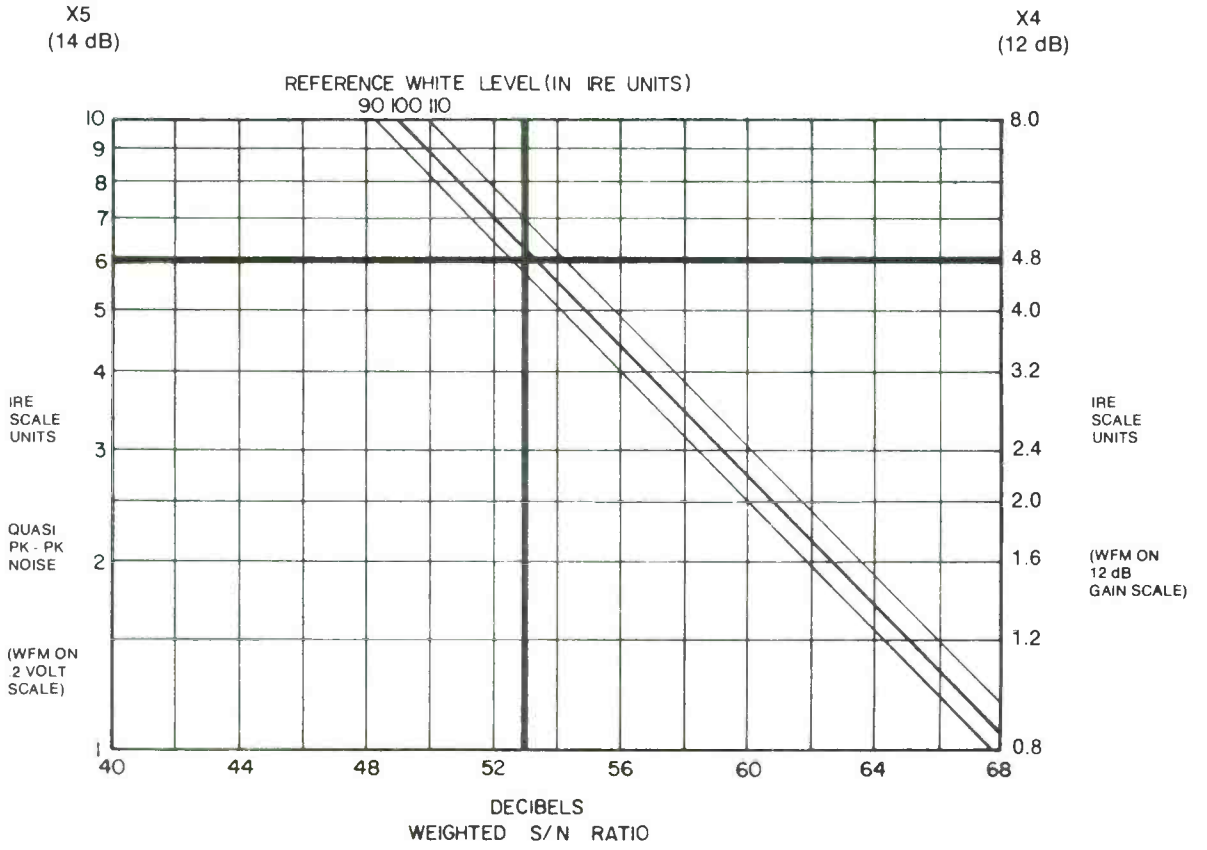
This procedure uses the low-pass filter and video weighting networks shown in Fig. 38A and 38C, respectively, of Sect. 3.16. Place these two networks in tandem between the video facility and the waveform monitor. After noting the amplitude of the line bar (for VITS) or the 100% flat field (for a full-field test) place the waveform monitor vertical gain to the 0.2 volt range* and estimate the quasi peak-to-peak** amplitude of the grass at blanking level. Transfer this reading to the S/N nomograph and determine the weighted video S/N ratio.

The objective is 53 dB or greater as shown by the heavy line.

*14 dB gain.

**Quasi peak-to-peak is the average level ignoring large occasional spikes of noise.

NOTE: The network of Fig. 38B, 10 kHz high-pass filter, is not needed as the line selector acts as a digital filter and cuts off frequencies below 15 kHz.



STANDARDS AND SOURCES

ANSI/EIA Standard RS-250-B "Electrical Performance Standards for Television Relay Facilities" September 1976.

For further information, contact:

Electronic Industries Association
Engineering Department
2001 Eye Street, NW
Washington, DC 20006

NTC Report No. 7 "Video Facility Testing Technical Performance Objectives"

For further information, contact:

Public Broadcasting Service
Engineering Services
475 L'Enfant Plaza, SW
Washington, DC 20024

The following four Technical References are from AT&T Communications.

"Commercial Television Transmission Specification" January 1984, 326-031, PUB 62600.

"Noncommercial Television Transmission Specification" January 1984, 326-032, PUB 62601.

"Premium-grade Program Audio Transmission Specification" January 1984, 326-033, PUB 62602.

"Standard-grade Program Audio Transmission Specification" January 1984, 326-034, PUB 62603.

For further information, contact:

Engineering Director
Network Capabilities Planning
AT&T Communications
295 North Maple Avenue
Basking Ridge, NJ 07920

4.2

Microwave Engineering for the Broadcaster

J. C. Carroll
E. M. Hickin
D. J. McCarthy
M/A-COM MAC, Inc.
Burlington, Massachusetts

INTRODUCTION

Microwave transmission has become increasingly important in the broadcast engineer's operation. The Studio-to-Transmitter Link (STL) has been the backbone of the industry for decades. Equipment design today allows for essentially transparent, full color video transmission, as well as subcarriers capable of full FM audio bandwidth and multiple voice and remote control functions.

The more recent development of Electronic News and Field Production— as well as Satellite Earth Stations (TVRO's) which require local back-haul, Satellite Studios and Regional News Networks—has demanded a continuous awareness on the part of the broadcast engineer.

In most cases, microwave equipment suppliers are prepared to support broadcast engineers in their design needs. Path profiling, surveying and predicting path performance, are services available from consultants and suppliers.

The following discussions are presented to aid broadcast engineers in their own understanding of this techonology.

*The authors gratefully acknowledge the assistance of Mrs. Rosemary MacKay in the preparation of this section.

PATH PERFORMANCE

Free Space Path Loss

Free space path loss for any electromagnetic wave arises from the spreading of the wavefront radiating from the source, like ripples on a pond after a stone has been thrown in. The loss increases by 6 dB (4:1 in power) every time the range doubles once outside the near field of the antenna. Since a 2:1 increase in range gives

$$4{:}1(2^2{:}1) \qquad [1]$$

reduction in power, this relationship is sometimes referred to as the inverse square law.

Free-space loss (i.e. the loss which is independent of ground or atmospheric effects) is given by:

$$L_{fs}(dB) = 36.6 + 20 \log F\,(MHz) + 20 \log D\ \text{(miles)}$$
$$\text{or } 96.6 + 20 \log F\,(GHz) + 20 \log D\ \text{(miles)}$$

This loss is expressed between isotropic antennas (a theoretical antenna which radiates equally in all directions). The gain (G) of a microwave antenna is then expressed in dBi (gain relative to isotropic). Below about 1000 MHz it is usual to express gain as dBd (gain relative to a dipole): OdBd = 2.2 dBi. Strictly the "gain" is the amount by which the directional properties of the

antenna reduce the coupling loss (20 log F in the above formula). Thus the ratio of received power to transmitted power between two antennas of gain G, D miles apart will be:

$$+G_1 - 36.6 - 20 \log F - 20 \log D + G_2 = L_p$$

This number will be negative; the numerical value is referred to as "path loss".

If the antennas are 6-foot diameter parabolic type and D is 30 miles then:

At 2 $GHz + 28.6 - 132.2 + 28.6 = -75.0$ dB path loss
7 $GHz + 39.8 - 143.0 + 39.8 = -63.4$ dB path loss
13 $GHz + 45.1 - 148.4 + 45.1 = -58.2$ dB path loss

If the antennas are 4-foot diameter parabolic type and D is 10 miles then:

At 13 $GHz + 41.7 - 138.9 + 41.7 = -55.5$ dB path loss
18 $Ghz + 44.4 - 141.7 + 44.4 = -52.9$ dB path loss
23 $GHz + 46.5 - 143.8 + 46.5 = -50.8$ dB path loss

Fig. 1 shows path loss for free space and between pairs of antennas of various sizes for 2, 6.8, 13, and 23 GHz.

Other Sources of Path Loss

As shown in Fig. 1 below, the free space loss is easily calculated, and antenna manufacturers issue slide rules from which the loss and antenna gains can be read.

However, atmospheric and other changes will cause the loss to vary from time to time and the effects must be considered when planning a system.

Multipath (i.e. signals arriving at the receiving antenna by reflections from water, hills, buildings or atmospheric discontinuities as well as by the direct path) can add to or cancel the signal causing an increase up to 6 dB or a decrease of more than 50 dB.

Atmospheric bending of the wavefront due to abnormal changes of temperature and/or humidity with height can cause loss of signal due to diversion from the desired direction. This effect is discussed below under "K factor".

Rainfall, and to a lesser extent snowfall, can attenuate the signal, an effect which increases markedly with increasing frequency.

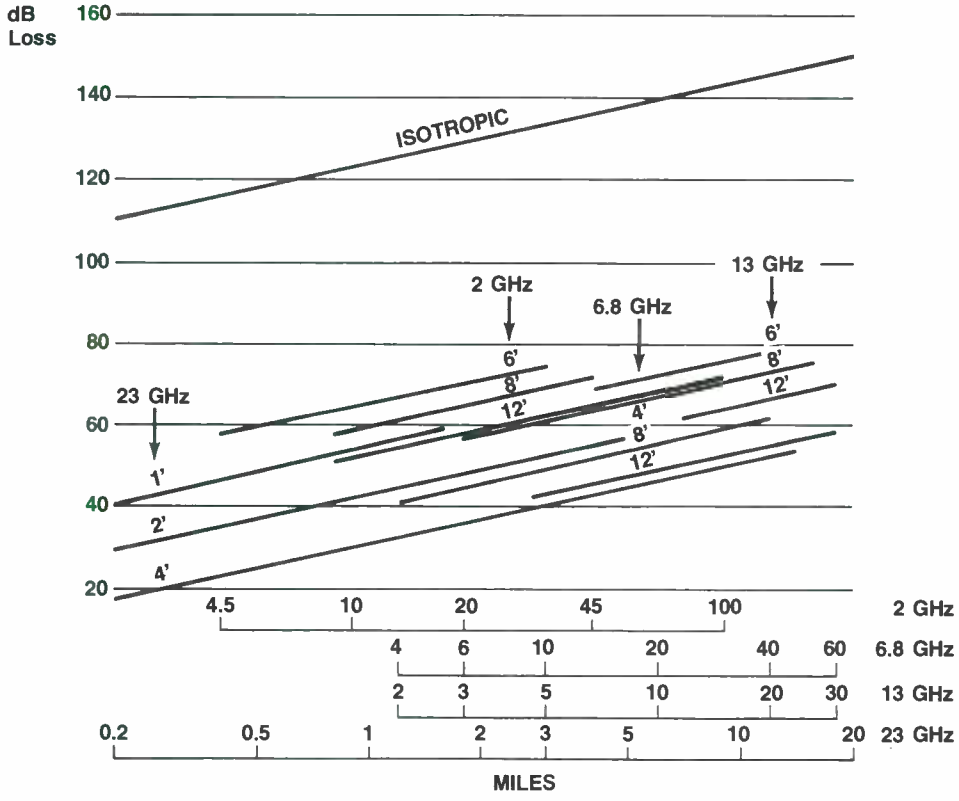


Fig. 1. Path loss versus distance between antennas of various sizes at 2, 6.8, 13 and 23 GHz.

To offset these effects a system is designed to have a more than adequate signal level at the receiver under free space loss conditions (which is the norm for at least 90% of the time). The excess of signal over the minimum required is called the fade margin. Typical fade margins are in the range 26 to 46 dB and ideally will be larger for higher frequencies, longer paths and over-water or similar difficult paths.

The choice of fade margins may involve compromises for example when existing towers of masts limit the size of the antenna. It should also be influenced by the environment, more being desirable in humid, flat country and less in dry mountainous areas.

Outages

Outage time (time out of service due to propagation), or availability, equals 100x (1-outage) when the latter is expressed as a fraction of time, can be calculated from an accepted formula. This assumes the path has adequate clearance for the area, and is based on frequency, path length and two factors related to terrain roughness (the rougher the better as this breaks up the atmosphere) and humidity (the lower the better as moisture can cause discontinuities).

The formula, derived by Barnett and Vigants from the average of many Bell paths, is

$$a \times b \times 2.5 \times 10\text{-}^{6} \times f \times D^{3} \times 10^{-0.1F} \qquad [2]$$

a = 4: for very smooth terrain, including over water
1: for average terrain with some roughness
0.25: for mountainous, very rough or very dry areas

b = 0.5: Gulf Coast or similar low, humid areas
0.25: normal, interior, temperate or northern
0.125: mountainous or very dry

f = frequency in *GHz*
D = path length in miles
F = fade margin to minimum acceptable point in *dB*

However, rainfall is not covered by this formula and can be more or less important depending on the area.

Figs. 2 and 3 show outage time in hours per year for 30 mile paths at 2 GHz and 20 mile paths at 13 GHz, in both Wyoming and Alabama (extremes of rainfall).

The vertical scale is fade margin, i.e. the amount by which the "free-space" receiver input signal exceeds the threshold or minimum acceptable input level.

A third figure (Fig. 4) shows (for the Wyoming case) how the performance varies with path length for various fade margins.

K Factor

The pressure and hence the density of the atmosphere surrounding the earth varies with height, getting less as the height increases and the weight of air above decreases.

As a result, the dielectric constant also decreases with height and thus has a prismatic effect causing microwaves (and light waves) to bend towards the earth. Under normal conditions the bending is less than the curvature of the earth, but nonetheless the microwaves will go further than simple geometry would suggest. A convenient radius way in which to allow for this is to increase the effective radius of the earth until the microwaves appear to be travelling in straight lines.

The ratio of the effective to the true earth radius is called K and is approximately 4/3 or 1.33 for over 90% of the time in most parts of the world. However, there are times when K can be anything from infinity to as low as 0.45. K = infinity (flat earth) is a condition where mirages will be seen and radar echoes received from hundreds of miles away. It is an embarrassment as interference between systems is increased; fortunately, it is relatively rare.

K values between 1 and 0.5 can occur for a few percent of a year and it is necessary to design a link to take this into account if a reliable system is to be achieved. Within the USA a map showing contours of minimum K factor is available (Fig. 5) and should be consulted before settling on the necessary antenna heights.

Clearance Requirements

Fig. 6 shows the way in which the microwave signal is attenuated when the path is close to an obstruction. Clearance is stated as a ratio of the first Fresnel zone, a function of frequency.

First Fresnel zone (feet) is given by:

$$FZC = 2280 \sqrt{\frac{d.(D-d.)}{FD}} \qquad [3]$$

Where:
F = frequency (MHz)
D = path length (miles)
$d.$ = distance of obstruction from either end of path (miles)

From Fig. 6 it will be seen that the attenuation with a clearance 0.6 FZC is equal to the free space attenuation. However, as noted in the figure above, K factor variation will mean that more clearance must be built in to allow for values less than 4/3, and a typical design parameter is to plan for 0.3 FZC for the lowest K value expected on the path (taken from Fig. 5). While such a

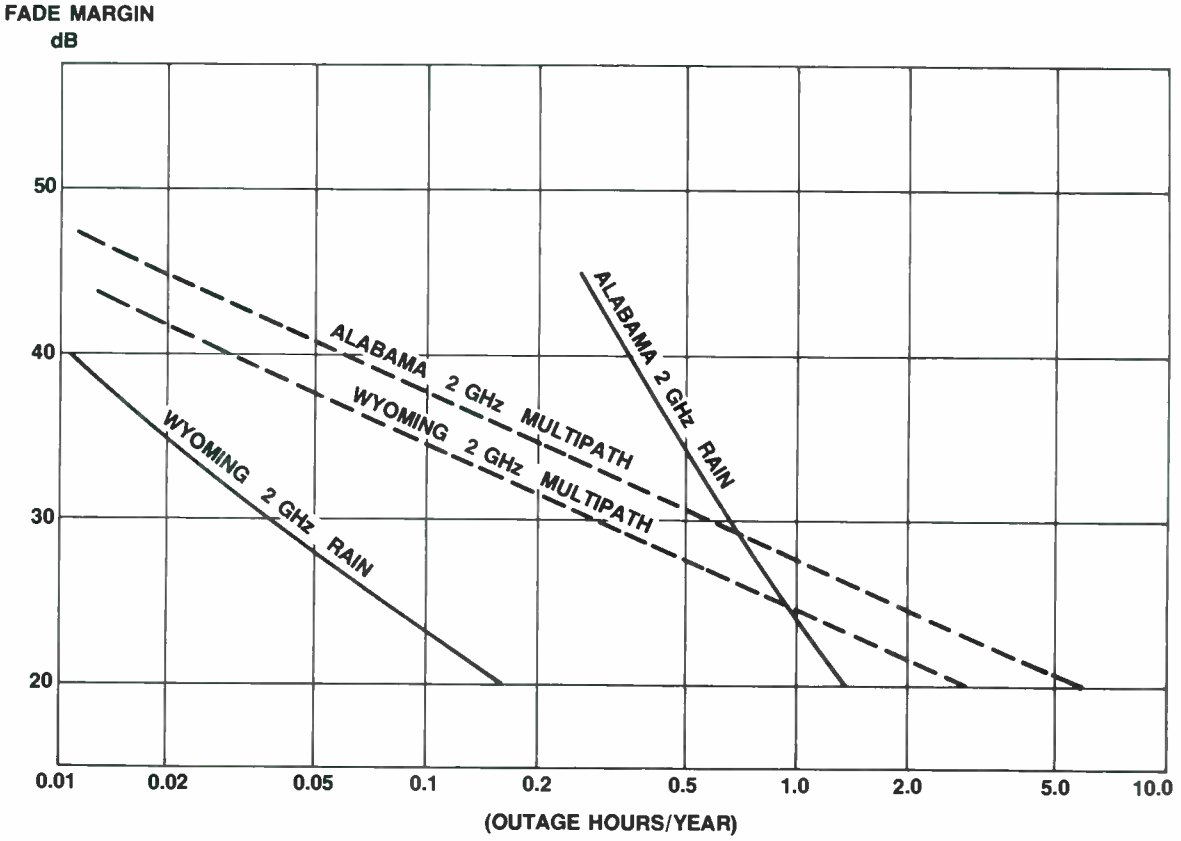


Fig. 2. Outage time in hours for differing fade margins on 2GHz, 30 mile path in Wyoming and Alabama.

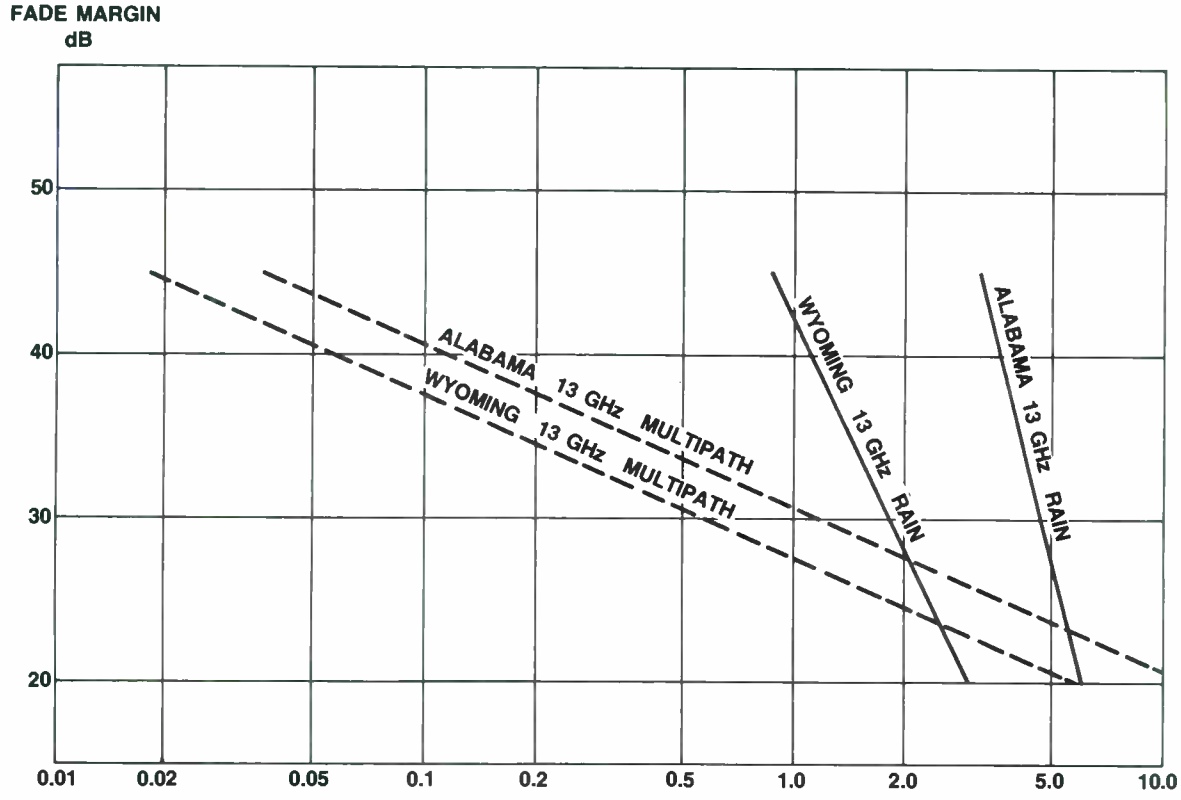


Fig. 3. Outage time in hours for differing fade margins on 13GHz, 20 mile path in Wyoming and Alabama.

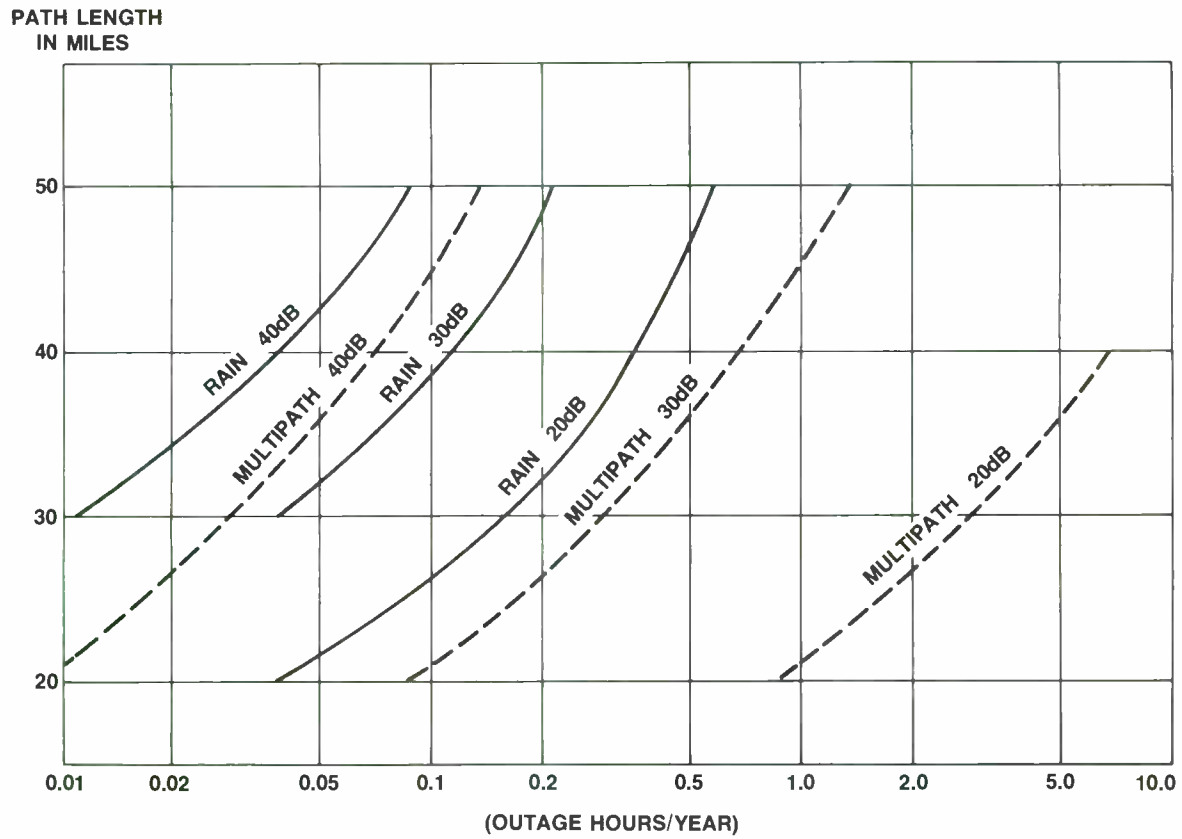


Fig. 4. Outage time in hours as a function of path length and fade margin for 2 GHz path in Wyoming.

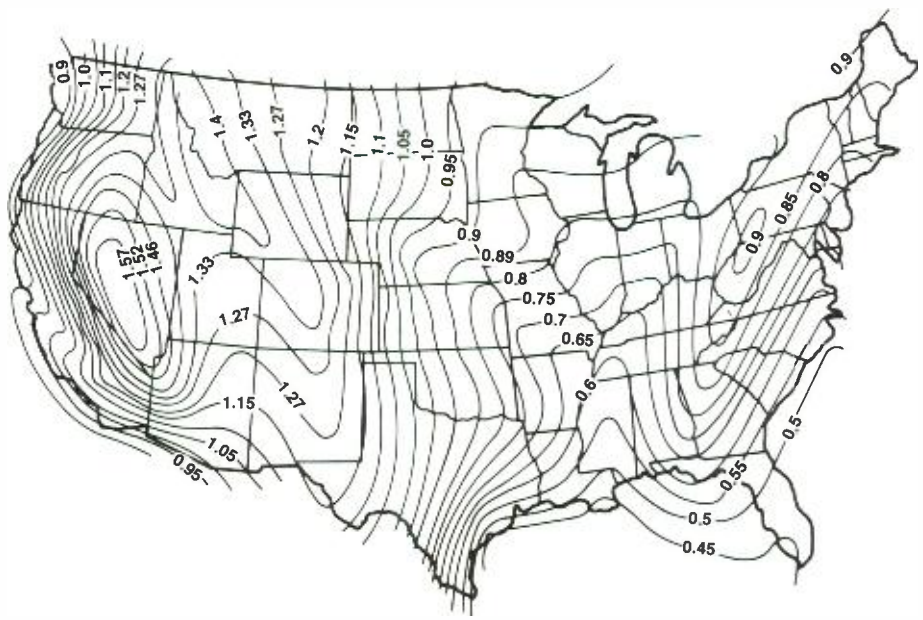


Fig. 5. Estimated minimum K-factor for the Continental United States.

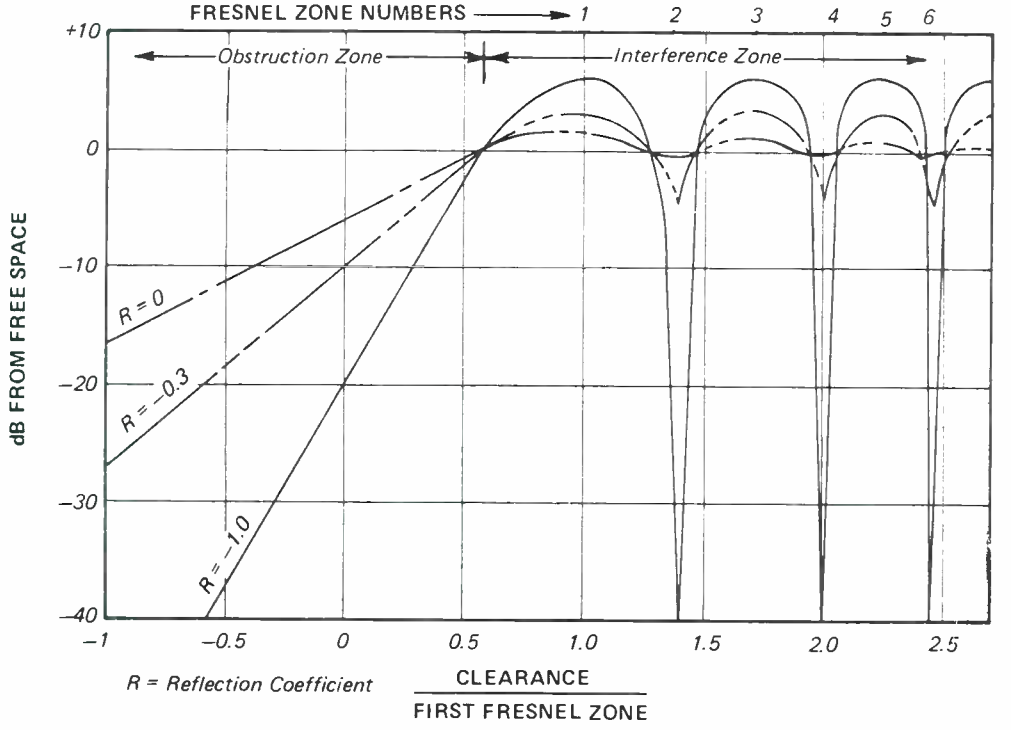


Fig. 6. Behavior of attenuation vs. path clearance for various types of obstruction.

clearance will introduce 2 to 8 dB of loss, this is well within the fade margin of a well-designed link.

Path Profiles

Sites for microwave link terminals are likely to be studios, earth stations or TV transmitters, all of which are pre-determined. Choice of sites for repeaters, if they are necessary, may be constrained by availability and access.

To see if any combination of sites is viable, and to determine the antenna heights at each end of the chosen path, will require the plotting of a profile.

The profile, a plot of ground height against distance, can be drawn on simple squared or special K factor paper (usually K = 4/3). Squared paper has the advantage that any convenient scales can be used for x and y axes; 4/3 paper has the advantage that potential obstructions are more obvious and the effect of path length on necessary clearance stands out. Whichever paper is used, the next step after plotting the profile is to add an allowance to high points for trees on buildings. Then the effect of low values of K must be added to any potential obstruction point, using the following formulae:

a) If using squared paper:

To each obstruction point add

1) $0.6\ FZC + d(D - d.)/2 + T$
2) $0.3\ FZC + d(D - \text{d.})3K/2 + T$

Where:

T is height of trees or buildings in feet.

or

b) if using 4/3 paper:

1) $0.6\ FZC + T$
2) $0.3\ FZC + d(D - d)\ 3K/4 + T$

Then a straight line clearing the upper values at each point will pass through the terminals at the minimum antenna height for adequate clearance. If most obstructions are near one end of the path, it may be more economic to raise the antenna at that end and save more height at the other end.

Figs. 7 and 8 show an example of the same profile plotted on rectangular and 4/3 paper and the final selection of antenna height; the worst-condition K factor assumed was 2/3 (− 2 on each profile at the main obstruction point at 8 miles).

ANTENNA AND WAVEGUIDE CONSIDERATIONS

Antenna Systems

Several different types of antenna are used in a TV microwave system. Omnidirectional vertical and directional horizontal stacked arrays are used for portable and vehicular applications. Parabolic

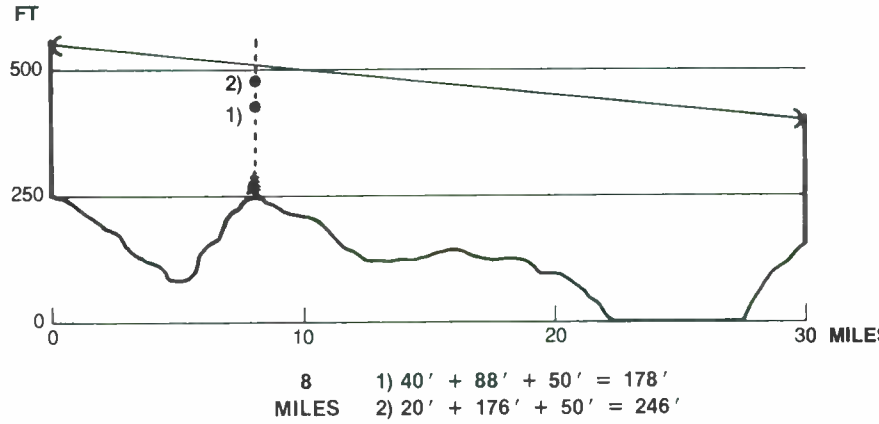


Fig. 7. Example of profile plotted on squared paper, with required clearances for (1) 0.6 × first Fresnel Zone when K = 4/3 and (2) 0.3 × first Fresnel Zone when K = 2/3 (50 foot tree allowance).

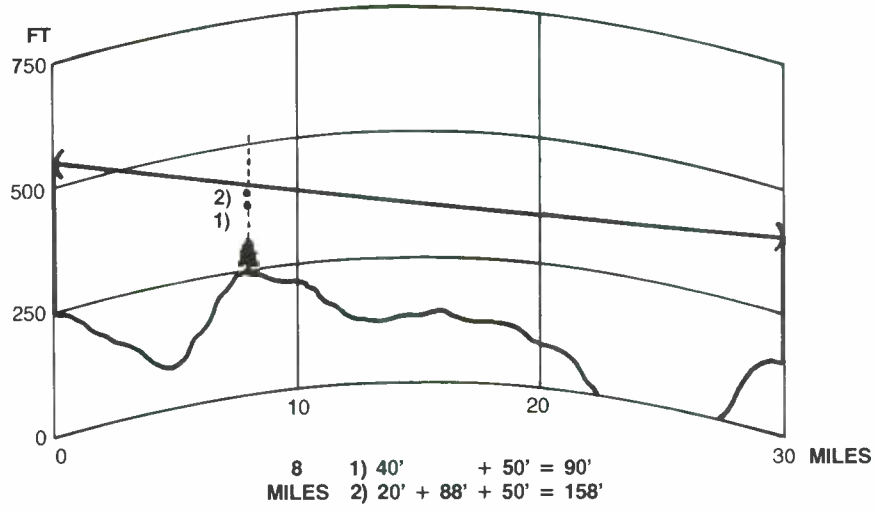


Fig. 8. Example of the profile of Fig. 7. plotted on K = 4/3 paper: (1) and (2) marked as on that figure.

reflector antennas are used for STL, intercity, ETV, and CARS systems. Corner reflectors and modified parabolas are sometimes used for 950 MHz STLs. Horn or shrouded parabolic antennas may be used for high front-to-back isolation ratios. Simple dipoles are often used for back pack and wireless microphone equipment. Selection of the antenna is usually based upon the application and the antennas available. The reader is referred to EIA Standard RS 195A for mechanical and electrical specifications.

Isotropic

As noted above, the isotropic antenna is a hypothetical antenna used as a reference against which the gain of other microwave antennas is measured. The term dBi denotes gain over an isotropic antenna. The isotropic antenna by definition has a radiation pattern which is a perfect sphere. The power density per unit area at a point in space due to the power PT radiated by an isotropic antenna is

$$P = \frac{P_T}{4\ \pi\ d^2} \qquad [4]$$

Where: d = Distance from radiator.
$4\ \pi\ d^2$ = Surface area of a sphere with radius d.

By definition, the effective area of an isotropic antenna is $\lambda^2/4\pi$ and the power received P_i is Equation 4 times the isotropic area, or

$$P_i = \frac{P_T \lambda^2}{(4\pi)^2 d^2} \quad [5]$$

Where:

λ = wavelength

Other Antennas

For other antennas of effective area A, the power received P_R is from Equation 4,

$$P_R = \frac{P_T A_{ef}}{4 \pi d^2} \quad [6]$$

The gain of an antenna is defined as the ration of its radiated or received power to that of an isotropic antenna. The ratio of Equation 6 to Equation 5 gives the gain (G) as,

$$G = \frac{4 \pi A_{ef}}{\lambda^2} \quad [7]$$

Where:

A and λ are in same units of measurement.

$$G = 12.77 A_{ef} f^2 \quad [8]$$

Where:

G = Gain
A_{ef} = Effective area in square feet
f = Frequency in Ghz.

Using Equation 8, the gains of various types of antennas are listed below:

Type	*Gain (dBi)*	
Parabola	10 log 5.5 $D_2 f^2$	[9]
Horn (optimum)	10 log. 10.3 Af^2	[10]
Omnidirectional (stacked array)	10 log 2 Lf^2	[11]

Where:

D = Diameter of parabola-feet
A = Mouth area of horn-feet^2
L = Length in feet
f = Frequency in GHz.

Parabolas

The parabolic antenna is available with several useful refinements. Radomes, heated and unheated, are available to prevent icing which rapidly reduces efficiency, especially at the higher frequencies. Special shrouds are available to improve the radiation pattern and increase front-to-back gain ratios. Dual cross-polarized feeds are available which provide 25 dB or so of isolation between two signals using the same reflector. Antennas at 1 and 2 GHz normally use coaxial dipole feeds while those at 7 and 13 GHz usually use waveguide horn feeds. Standard mounting structures are available for attaching the antenna to a 4.5-inch OD pipe, along with clamps which can be loosened for aiming the antenna after installation on a tower. Special light weight 950 MHz antennas sometimes mount to a 2-inch pipe. Special roof mounts are available for aiming the antenna upward when passive reflectors are used on the tower. Feeders must be airtight so that when pressurized moisture will not enter and reduce feed efficiency. At the lower frequencies, grid and mesh construction is often used to reduce weight and wind loading on the towers. Grid antennas cannot be used with cross-polarized feeds as they will only reflect signals which are polarized in parallel with the grids.

Horns

Several variations of the horn antenna are available for microwave use. They are characterized by better radiation patterns than parabolic reflectors but their weight and windage requires heavy towers and their use is limited to severely congested areas.

Omni

The omnidirectional antenna is characterized by a radiation pattern resembling a doughnut. Gain is achieved by reducing radiation in the vertical direction. They are often used to eliminate the need for tracking in mobile systems with typical gains of 6 dB on the vehicle or 10 dB at fixed points. The higher gain antenna is not used on helicopters or motor cycles as the signal loss when the vehicle banks during turns would be excessive.

Passive Reflectors

Passive reflectors are often used at 7 and 13 GHz instead of feeder waveguide to effect radiation at the top of the tower. The advantage of passive reflectors is the elimination of waveguide feeder loss and cost; the disadvantage is stray reradiation from the tower structure which limits frequency re-use by degrading the radiation pattern. The installation consists of a parabola near the equipment aimed at a reflector tilted about 45 degrees with the earth which reflects the energy away from the tower in a horizontal line. The efficiency of the reflector depends upon how well it is illuminated by the parabola. Curved reflectors are sometimes used to improve efficiency by 2 dB or so. All installations must meet FCC A standards.

Analysis of the "gain" of a parabola/reflector antenna system is complex, but useful relationships have been determined empirically which are shown on the transmission work sheet in Fig.

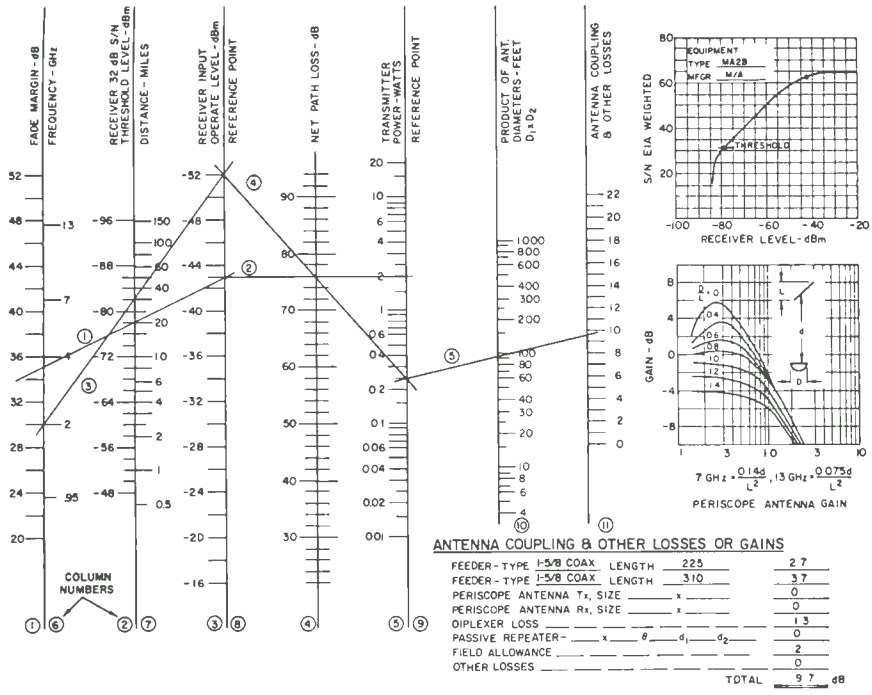


Fig. 9. Transmission calculation worksheet.

9. These curves may be used to determine gain of any size combination for use in system calculations. Gain here is defined as the increase in effective radiated power of the antenna/reflector combination over that of the primary antenna alone, had it been mounted at the same point; it can be positive when the reflector has significantly greater surface area than the primary antenna.

Adjustment of reflectors in the field requires skill but is accomplished with the assistance of surveying equipment for initial adjustment and trial and error for best received signal after the equipment is installed. Most popular sizes are 6 x 8, 8 x 10, 8 x 12, and 10 x 15 feet fed by 4, 6, 8, and 10 foot parabolas. The larger the antenna-reflector spacing the larger the antenna needed to concentrate the energy onto the reflector; over or under concentration leads to inefficient illumination of the reflector and loss of performance.

Antenna Feeders

Microwave equipment is connected to the antenna with either coaxial cable or waveguide. Coax is used for 1 and 2 GHz and may be either foam filled or air dielectric. Waveguide is used for 7 and 13 GHz and may be either rigid rectangular waveguide, elliptical flexible waveguide, or circular waveguide. Short sections of flexible rectangular waveguide are often used to simplify installation. In addition to the lines, various hangers, clamps, bending tools, hoisting grips, and pressuring equipment are required for installation. It is recommended that transmission lines be installed in continuous lengths to avoid potential problems with splices or joints.

The Andrew Corporation, Orland Park, Illinois, provides a wealth of information in its standard catalogue on the characteristics of feeder systems. Typical losses vary from 1.0 to 10.0 dB per hundred feet, depending upon the type of feeder used. Rather than list all characteristics here the reader is referred to vendor catalogues.

Care must be taken during installation to avoid pressure leaks, dents, and discontinuities, all of which will affect the system performance. Professional, experienced riggers are normally used with supervision by the equipment manufacturer. Foam-filled coax is the easiest line to install but has higher loss than air dielectric: it must only be used in conjunction with a foam-filled (non-pressurized) antenna.

When waveguide, or air-filled coaxial cable, is being used it must be maintained at a positive pressure (0.5-5.0 lb/ square inch) above atmospheric with dry air or nitrogen. Compressor/dehydrator units to supply regulated dry air can be fully automatic (the dessicant is dried out periodically by the unit) or semi-automatic (where the dessicant must be replaced or dried out by an operator). To avoid rapid cycling of the compressor the volume of air in the system should not be less than 1.5 cubic feet; this can

be achieved in small systems by fitting a regulating tank.

The typical loss per hundred feet of several types of feeder is listed below:

	Loss per 100 feet
At 950 MHz	
Foam dielectric (aluminum) coax:	
1/2 inch diameter	3.7 dB
7/8 inch diameter	2.0 dB
Air dielectric coax:	
7/8 inch diameter	1.6 dB
1-5/8 inch diameter	0.8 dB
At 2 GHz	
Foam dielectric (copper) coax:	
1/2 inch diameter	3.5 dB
7/8 inch diameter	1.9 dB
1-5/8 inch diameter	1.4 dB
Air dielectric coax:	
7/8 inch diameter	1.9 dB
1-5/8 inch diameter	1.0 dB
At 7 GHz	
Elliptical waveguide—	
Andrew type EW-63	1.4 dB
Rigid rectangular waveguide	
WR 137	1.8 dB
At 13 GHz	
Elliptical waveguide—	
Andrew type EW 127A	3.6 dB
Rigid rectangular waveguide	
WR 75	4.2 dB
At 18 GHz	
Elliptical waveguide—	
Andrew type EW 180	5.9 dB
Rectangular waveguide	
WR 42	14.0 dB

Passive Repeaters

On some hops a passive repeater is used to clear an obstacle rather than an active repeater. The passive repeater may be either a billboard type or two parabolas back to back. The flat billboard type has an efficiency near 55 percent.

Because the "gain" of a passive repeater of a given size is proportional to the square of the frequency, their use is mostly limited to frequencies of 6 GHz and above. The gain of a flat billboard is derived from Equation 8 as:

$$G = \left(12.77\, Af^2 \cos\frac{\theta}{2}\right)^2 \qquad [12]$$

Where:

A = Area of reflector in square feet (width x height)
f = Frequency in GHz
G = Gain in dB
θ = Angle between microwave beams extending to both adjacent stations.

Equation 12 is squared because the passive repeater has equal gain receiving and transmitting. Gain here is defined as the ratio of the power at a given (far-field) point relative to that which would be received at that point if the passive were replaced by a matched isotropic antenna fed with the same RF power. (This is the same definition as is used for a parabolic antenna.)

The performance of the hop may be calculated by considering 2 hops with a passive repeater with gain given in Equation 12.

When θ is too large to realize practical gain, a double billboard is often used, with one reflector illuminating the other. A loss of 1 to 3 dB is normally used for reflector-reflector coupling loss. The path is analyzed the same way as a single reflector except for the extra loss.

For transmission calculations it is simpler to consider a single hop equal in length to the sum of the two legs extending to the passive repeater. In this case the passive repeater is considered to have a loss given by:

$$\alpha = \frac{2.9 \times 10^7\, d_1^2\, d_2^2}{(d_2 + d_2)^2\, f^2\, A^2 \left(\cos\frac{\theta}{2}\right)^2} \qquad [13]$$

and in *dB*,

$$\alpha = 74.6 + 20\log d_1 + 20\log d_2 - 20\log(d_1 + d_2) - 20\log f - 20\log A - 20\log\cos\frac{\theta}{2} \qquad [14]$$

A solution to Equation 14 is given in Fig. 10.

When back-to-back antennas are used a coupling loss of 3 dB is included. To increase the gain of the two dishes a low noise amplifier is sometimes used between the antennas. Performance calculations are best left to the manufacturer because of possible overloading of the LNA. The path is analyzed in the same manner using Fig. 10 as a passive repeater except the πr^2 area of the parabola used is multiplied by 55 percent efficiency, and $\theta/2$ is zero degrees. It is important to ensure a good impedance match between the two antennas; failure to do this can lead to frequency-dependent performance.

The beam width of the flat billboard passive reflector repeater is given by:

$$\gamma = \frac{58.7}{fL} \qquad [15]$$

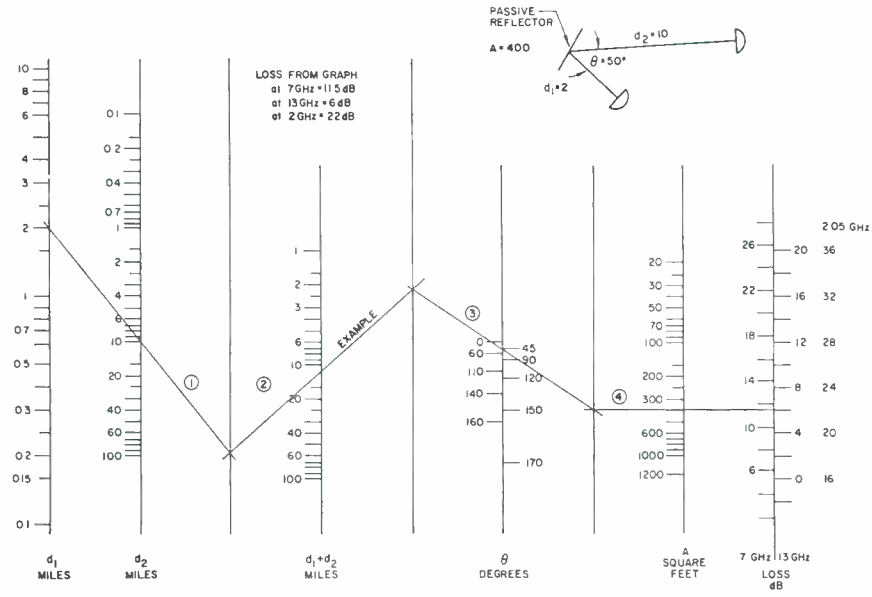


Fig. 10. Passive repeater loss relative to direct transmission over $D_1 + D_2$

Where: γ = Beam angle in degrees
f = Frequency in GHz
L = Projected length of a side in feet

$$(\text{width} \times \cos \frac{\gamma}{2})$$

Because the passive repeater does not require maintenance or operating costs, its use should not be overlooked when designing microwave systems. Passive repeaters are available in a wide range of areas from about 8 × 10 to 40 × 60 feet.

RADIO CONSIDERATIONS

Transmission of video and audio signals over the last 40 years has been almost exclusively carried out by frequency modulation of the microwave carriers by an analog signal (i.e. the exact waveform to be transmitted rather than a sampled and coded version of that waveform).

Since the broadcast television transmitter uses the analog signal it is probable that analog video transmission will predominate for at least another decade. Audio information also is usually frequency modulated onto a subcarrier, though digital modulation in the sync period or on a subcarrier is also used.

The microwave transmitter terminal thus comprises a baseband processor and frequency modulator (directly to microwave or via an intermediate frequency). The receiver terminal comprises a down-convertor, frequency demodulation (invariably at intermediate frequency) and baseband processing.

Repeaters

In a multi-hop system, two approaches can be taken at the intermediate repeater sites:

The received signal may be demodulated to baseband using a conventional terminal receiver and then this baseband applied to a conventional terminal transmitter thus regenerating the microwave signal at the desired output level. This is the remodulation approach. The second approach is to take the 70 MHz IF off the receiver and apply this to a transmitter, where it is mixed with a local oscillator 70 MHz away from the desired RF output. The correct side band is extracted by filtering, amplified at microwave and forms the desired repeater output signal. This is the heterodyne approach. The basic advantage to a remodulating system is cost. The heterodyne approach involves both microwave power amplifiers and tight RF (microwave) filters to reject the up-conversion LO and unwanted sideband. Both these items are costly.

Heterodyne systems have a significant advantage in preserving the purity of the video signal. Because the video is not demodulated and remodulated, no extra low-frequency corners are added to the video path. This improves the tilt and bounce performance, particularly over a large number of hops. Another feature is video gain stability. Since the signal is never demodulated and remodulated, the 4 MHz peak deviation is invarient over any number of hops. This directly

translates to video gain stability. Only the modems at the terminal transmitter and receiver affect the video gain.

In summary, in long-haul microwave systems, heterodyne repeaters are a necessity to keep end-to-end video degradation down to reasonable levels. In short-haul systems, the remodulating system offers comparable performance at a lower cost and with greater flexibility. For systems up to 8 to 10 hops, the remodulating system is normally used, while for longer systems, heterodyne equipment is normally used. Detailed descriptions of remodulating and heterodyne transmitters and receivers are presented below.

Transmitters

The basic remodulating transmitter consists of a video amplifier (with preemphasis), an oscillator which can be modulated, a crystal referenced AFC loop, a power amplifier and frequency multipliers when required to reach the desired output frequency as shown in Fig. 11. Various optional items are available to extend the usefulness of the transmitter. These include: Off-air demodulators to monitor quality of output at antenna feeder input; audio subcarrier modulators for transmitting program audio channels; a switch for rapidly changing frequency to different channels covering 5% or more of the output carrier frequency; output filters (wideband or channel width) to further reduce spurious outputs and operate with diplexers and duplexers; weatherproof housing for portable equipment; and ruggedized packaging for vehicular mobile equipment.

The baseband amplifier is wideband (10 MHz or so) for best linearity and incorporates liberal feedback for stability. A 13 dB preemphasis is used which together with the receiver deemphasis improves the overall signal to noise performance. Provision is also made for combining one or more audio program subcarrier modulators with the video before frequency modulating the voltage-controlled oscillator. The gain of the video amplifier is matched to the modulation sensitivity of the oscillator so that 8 MHz peak-to-peak deviation is produced on the RF carrier for a 1-volt peak-to-peak input video signal. The low-frequency response of the amplifier extends below 1 Hz as required for tilt performance.

The transistorized VCO (voltage controlled oscillator) typically runs at 2 GHz where transistors are available with enough power capacity to produce an adequate transmitter output level. As new transistors are developed, the trend will result in higher output power and greater power conversion efficiency (lower dc input power). A number of solid-state devices are available which operate directly at the output carrier frequency. The output power of the oscillator may be up to several watts, but it is usually lower followed by an amplifier.

The power amplifier consists of one or more broadband stages to provide a gain of 25 to 30 dB at a power output of 8 to 10 watts at 2 GHz falling to 1 watt or less at 13 GHz. As with other transmitter components, the mark of quality is linearity, wide bandwidth (10% or more of the operating frequency) and long-term stability. The amplifier should operate on any assigned frequency channel in the band without retuning.

Present generation solid-state equipments at 7 and 13 GHz use frequency multipliers and the degree of multiplication used depends upon the output operating frequency. This is typically x3 or x4 for 7 Ghz, and x6 for 13 GHz. These multipliers consist of varactors, impedance matching

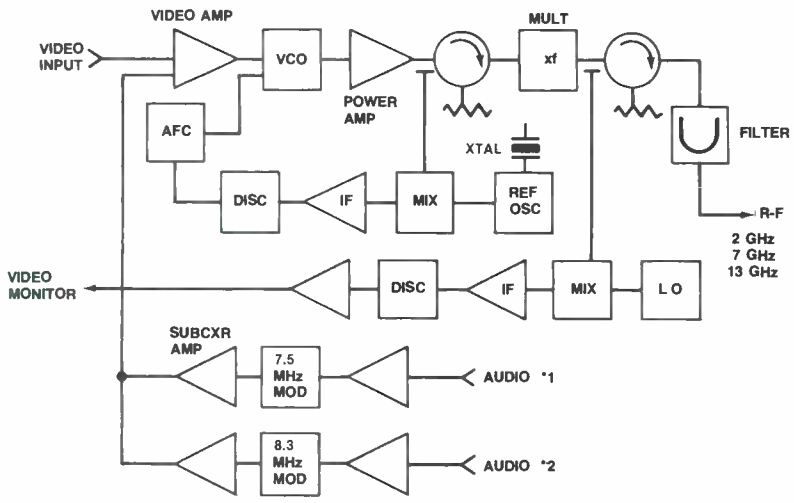


Fig. 11. Remodulating transmitter block diagram.

circuits, cavities, and filters to efficiently operate over a wide band of frequencies with minimum spurious output signals. No tuning is required to cover up to 10 assigned frequency channels in one of the three operating bands. Typical power output from the varactor multiplier is 1 to 2 watts at 7 GHz and 0.8 watts at 13 GHz. At the present time, operating frequencies of solid-state components are increasing so that the need for frequency multipliers will not exist for any frequency band in the near future, as they are not now required at 2 GHz.

Two approaches for AFC are common: Fig. 11 illustrates a crystal-controlled source which feeds one side of a mixer. The other side of the mixer is fed with a sample of the transmitter frequency. The mixer output is an IF signal which is amplified and demodulated by a temperature compensated discriminator. The dc output from the discriminator is the carrier frequency error voltage which, when applied through a dc amplifier to the VCO, keeps it on its assigned frequency. A more state-of-art approach uses a phase-locked oscillator as the microwave source. Here a microwave IC divider samples the oscillator output directly at 2 GHz. The output of the divider is at a frequency where standard PLL IC's and techniques can be used to lock the oscillator to a crystal reference. The phaselock approach involves less hardware and is thus less expensive.

The off-air monitor is essentially a microwave receiver which demodulates a sample of the transmitter output signal for monitoring. To be of maximum value as a transmitter test tool, the monitor signal should be of high quality even though this approach is slightly more expensive than slope detectors and other lower cost devices which are sometimes used.

The frequency switcher shifts the operating bias on the oscillator to change its frequency and, when AFC is used, switches crystals in the reference oscillator. Since all circuits are wideband, no tuning is necessary when frequency is changed.

The transmitter output filter is used when the transmitter is diplexed with another transmitter or duplexed with a receiver, or to reduce spurious levels. The filter may be broadband covering 5% or more of the spectrum, or narrow band covering a single assigned channel.

For portable applications, a weatherproof housing is required which is easily fitted, with an antenna, to a tripod. If remote control is used, special wiring and a connector are installed for mating with the remote control cable.

Equipment for mobile applications must be packaged in a rugged manner to withstand the high degree of shock and vibration experienced in most vehicles. Also size and weight become more important so special precautions must be taken to keep the high density packaged components from overheating.

To prevent interference to or from broadcast microwave equipment, special precautions must be taken for RFI filtering and shielding. The total unit is usually enclosed in an RFI resistant case with critical circuitry completely shielded. Additionally, all input and output electrical connections must be RFI filtered. Without these precautions, considerable difficulty can be expected, since broadcast microwave equipment often operates in close proximity to high powered transmitters.

Receivers

All TV microwave receivers are typically superheterodyne with a 70 MHz IF amplifier as shown in Fig. 12. For broadcast work, the local oscillator and mixer should be broadband to eliminate the need for tuning when switching to a variety of different frequencies.

Mixers are usually balanced mixers and often double balanced. If no low-noise amplifier (LNA) is used, the mixer determines the noise figure of the receiver which is in turn largely dependent on the diodes used. Noise figures of 8 dB at 2 GHz rising to 9 dB at 13 GHz are common. The mixer function is to produce an IF frequency by generating the difference between the local oscillator frequency and the received carrier frequency.

For superior noise performance and fade margin, a low-noise amplifier may be added to the receiver design (as in the figure). Using a LNA, receiver noise figures of 1.5 dB at 2 Ghz rising to 3 dB at 13 GHz are achieveable. Modern LNA designs are based on Ga-As (Gallium Arsenide) FETS. Previously, tunnel diode designs were used at 7 and 13 GHz while bipolar transistors were used at 2 GHz. The gain of these LNA's is typically 15 to 20 dB.

LNA's are also available separately for use outside the receiver. In this case, they are often mounted near the antenna and are provided with a weatherproof housing. In this case, the loss of the transmission line is eliminated and the system improvement is further increased. Another potential application of the low noise amplifier is between two back-to-back dishes operating as an active repeater. FCC action on this configuration is imminent. The low noise amplifier is a useful tool to the microwave design engineer, and its use in the system should not be overlooked.

The local oscillator carrier is usually crystal controlled to 0.005% or better of the output frequency. This eliminates the need for receiver AFC. Fundamental oscillators are usually used, but lower frequency oscillators followed by multipliers are occasionally used as well. For frequency agile equipment, up to 10 switch-selectable

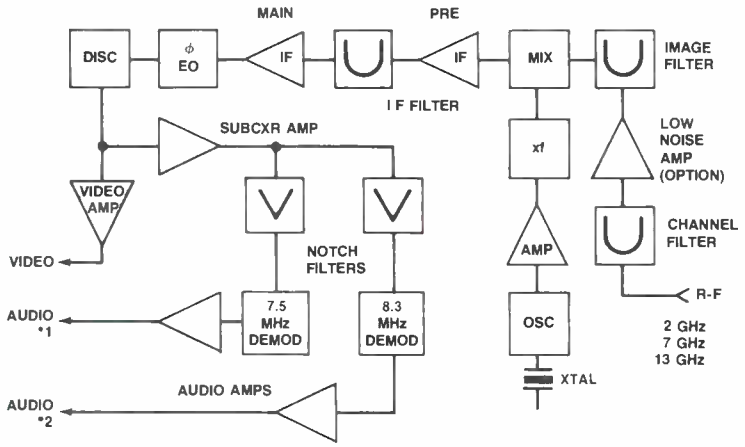


Fig. 12. Receiver block diagram.

crystal references may be used, or a suitable synthesizer employed.

The 70 MHz IF preamplifier is often mechanically integrated with the mixer to achieve best overall noise figure of the receiver. The preamplifier typically has 25 dB gain and is 50 to 60 MHz wide.

Optimum receiver noise performance is achieved when the minimum necessary bandwidth is used. This is typically 30 MHz to the 3 dB points for TV transmission. However in many metropolitan areas, frequency congestion is pushing usage to 20 MHz wide IF band widths. Since the basic IF amplifier circuits are 50 to 60 MHz or more wide, a lumped constant filter located between the preamplifier and the main IF is employed to reduce the noise bandwidth of the receiver to 30 MHz. The characteristics of this filter must be carefully controlled for good phase and amplitude linearity.

The main IF amp follows the filter and provides typically 65 dB of gain. In both pre and main IFs, discrete common-base transistor design had previously been used. This effectively isolates the transistor characteristics from the overall amplifier performance characteristics which are determined primarily by the interstage coupling circuits. With this design approach, the receiver characteristics are essentially independent of the transistor characteristics which may vary widely with temperature. However, current approach is to use special purpose IC's or RF modules to provide IF gain. The output level of the IF is typically +5 dBm. The input microwave level to a typical receiver may vary from −25 to −80 dBm during fading conditions. Since +5 dBm output is required, the gain needed varies from 30 dB to 85 dB. In order to keep the output constant, 60 dB of AGC is typically used to regulate the 90 dB gain in the two IF amplifiers between 40 and 90 dB. Since portable and mobile equipment operate over wide ranges of distance, it is important that receivers have at least 60 dB of AGC.

The limiters are an essential part of an FM receiver because they effectively eliminate the effects of AM variations on threshold performance. Typically 20 dB of limiting is used.

The discriminator demodulates the FM signal back to video. In a wideband TV system, it is important to keep the discriminator linear over a wide bandwidth, typically ±5 MHz or more about the center 70 MHz IF frequency. Nonlinearity will produce distortion and noise on the signal by increasing intermodulation between various components of the TV signal.

The video amplifier brings the discriminator output signal back up to one volt. It also includes a deemphasis network which is exactly matched to the transmitter preemphasis network so that an overall flat frequency response is achieved through the system. The video amplifier includes a low pass filter to reduce the level of the audio subcarriers at the video output. While the degree of audio subcarrier rejection is not extremely important in TV microwave signals, it is typically 30 to 40 dB below peak video levels. A high degree of feedback is used in the video amplifier to achieve maximum stability.

The preselect filter at the receiver input is used to improve selectively, prevent local oscillator radiation, and suppress image frequencies. It typically consists of five or more filter selections designed and tuned to cover several channels in switch tunable systems or a single channel in fixed signals. The passband characteristics must be closely controlled to avoid phase non-linearities in the system.

The same comments made for the transmitter regarding portable and vehicular applications apply to the receiver.

Basic Heterodyne TV Microwave

The receiver in a heterodyne system is almost identical to the remodulating receiver already discussed, the only difference being that the output is taken at 70 MHz from the IF amplifier and connected to the heterodyne transmitter. A second IF output may be used to feed an optional 70 MHz demodulator (limiter, discriminator and video amplifier) if a video drop is desired at the hop.

The heterodyne transmitter block diagram is shown in Fig. 13. It consists of an IF amplifier and a microwave source both of which feed an up converter mixer. The source is similar to that used in the remodulating transmitter except it need not be modulated. The mixer heterodynes the 70 MHz IF input signal up to a microwave signal ±70 MHz different from the source frequency depending upon the sideband selected. The sideband select filter passes the desired sideband while rejecting the undesired sideband and source frequency.

A microwave power amplifier is then used to restore the level of the signal to its desired value. Impatt diode (Avalanche diode) reflection amplifiers have been the norm and are still being produced, but the current move appears to be to Ga-As FET power amplifiers.

At a repeater the 70 MHz IF input to the transmitter comes from the receiver IF output at a level of +5 dBm. If the heterodyne transmitter is used at a terminal station, the video signal first modulates a 70 MHz FM transmitter (modulator) which then feeds the transmitter.

Power Supplies

Whether remodulating or heterodyne, microwave equipment uses several different voltages to power the various active circuit components. These are usually low voltages in the 12 to 35 range that must be highly regulated and filtered for best performance. The power supply function is to convert the ac or dc main supply voltage to those required in the equipment.

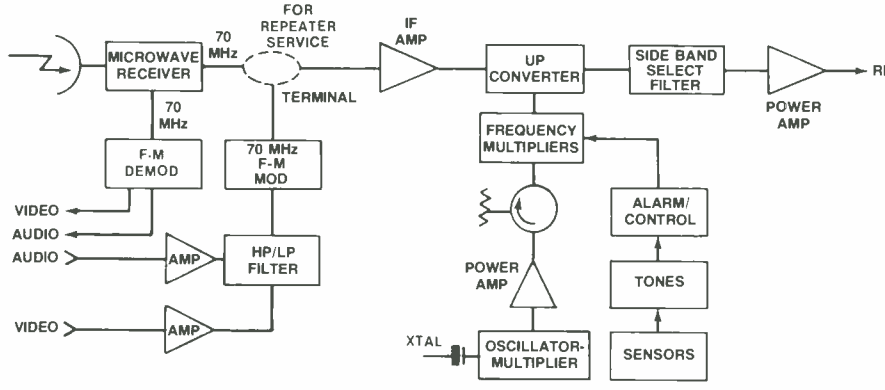


Fig. 13. Heterodyne transmitter block diagram.

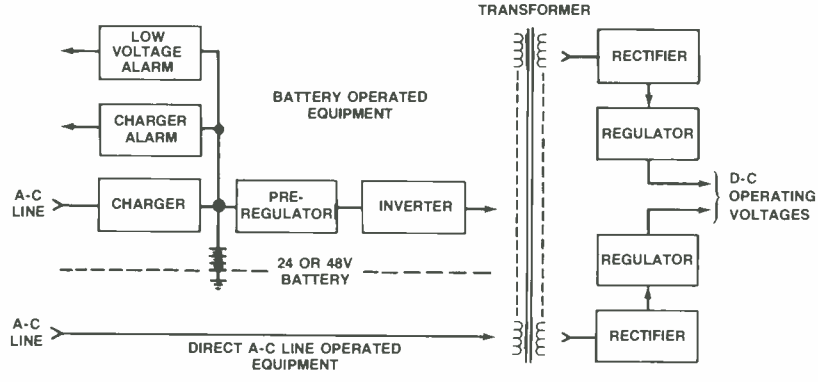


Fig. 14. Power supply block diagram.

Fig. 14 is a block diagram of a typical power supply system. AC units consist of a transformer and rectifiers to obtain the unregulated operating voltages. Various types of transistor regulators are used to keep the operating voltages within a narrow range of variation. In dc units, the battery voltage is first converted to ac by a chopper or inverter after which operation is similar to the ac. Good designs usually employ protection circuits on both input and outputs to protect the power supply from surges, load short circuits, and lightning. The power supply may be separate from the transmitter or receiver or it may be built in.

Subcarriers

In addition to carrying the video traffic, a microwave link can carry additional information above the video portion of the baseband. As the NTSC video bandwidth extends to 4.2 to 4.5 MHz, the area above 4.5 MHz, after allowing a suitable guard band, is available for other use. Four different uses are made of this baseband spectrum: Program audio subcarriers (multiple); engineering order wire; supervisory signals (alarms); and continuity pilot. In all uses, the deviation is generally 20 dB below the peak video deviation of 4 MHz.

The program audio subcarriers are generally modulated 75 kHz peak deviation at a 1 kHz test tone. Maximum audio bandwidth is almost universally 15 kHz. From Carson's rule the information bandwidth is thus 180 kHz. To allow adequate filtering of one subcarrier from the next, subcarriers are generally spaced at least 600 kHz apart (though occasionally a 400 kHz spacing is used.) Moreover, successive subcarriers are spaced at successively larger distances apart. This avoids a multiple difference beat of 600 kHz in the video baseband.

Up to four audio subcarriers are commonly used. But the more subcarriers used, the greater receiver bandwidth required, with its trade-offs. When 25 MHz wide channels (7 and 13 GHz bands), the four subcarriers are often located at 6.2, 6.8, 7.5 and 8.3 MHz. If 17 MHz wide channels are used, (2 GHz band) the four subcarriers might be located at 5.8, 6.2, 6.8 and 7.5 MHz. However, such a four subcarrier system in a 17 MHz bandwidth will show compromises in audio and video quality. Occasionally a subcarrier at 4.83 MHz will be used. However, this generally requires more severe video filtering, and the resultant degradation of video performance. The 4.83 MHz subcarrier is generally used in ENG systems (see Section 6), where a narrow IF filter is desirable due to transmitter power limitations and band congestion.

Often a single-side-band suppressed-carrier supervisory and control system is added to the baseband. If less than four subcarriers are used, this SSB system might be located at one of the above mentioned subcarrier frequencies. In four subcarrier systems, the SSB system might be located at 8.59 or 9.023 MHz. The supervisory and control system can include both an engineer's order wire and remote repeater alarming. The order wire allows two way communication among the terminals and the repeaters. The alarming allows automated fault reporting from these unattended repeater locations. The requirements for "partyline" transmission from multiple sites forces the use of a suppressed carrier, avoiding carrier beats which would otherwise occur.

In addition, a continuity pilot may be included in the baseband spectrum. Generally the pilot is the highest frequency in the baseband; 8.59 and 9.023 MHz are commonly used.

Descriptions of program audio modulators and demodulators are next presented. Note that depending on manufacturers and model, the program audio modulator and demodulator might be packaged separately or be integral to the microwave transmitter or receiver.

The subcarrier modulator is actually an FM transmitter operating in the range of 4.83 to 8.3 MHz. The subcarrier oscillator is generally frequency stabilized. Previous techniques had included AFC for the oscillator using a built-in FM discriminator as the frequency reference. Current practice is to phase lock the oscillator to a crystal reference using IC phase-lock components. Usually 75 μs preemphasis is employed in the audio circuit.

The subcarrier demodulator is similarly a FM receiver operating in the range of 4.83 to 8.3 MHz. These demodulators are available fixed tuned to one subcarrier frequency (analogous to a TRF receiver) or frequency agile, able to be tuned to several subcarrier frequencies (the superheterodyne approach). In either case, the "RF" or "IF" filters must be sharp enough to reject adjacent subcarriers as well as the 20 dB stronger video signal.

Due to residual non-linearity in the microwave modulator and demodulator, as well as in the path, sometimes cross modulation of the video appears on the demodulated audio. The most annoying characteristic is a 15.7 kHz buzz caused by the video horizontal scanning frequency. Subcarrier demodulator manufacturers often include a 15.7 kHz notch in their audio processing circuitry to suppress this tone. This notch requirement is difficult, as little attenuation at 15.0 kHz (top of the audio band) is allowed. In addition, 75 μs deemphasis and perhaps, noise low-pass filtering above 15 kHz is included in the audio circuitry.

Audio output level is generally +9 to +18 dBm, at a balanced 600 ohms; for multiple outputs a low-impedance option is sometimes available.

POWER PLANTS

Primary Power and Back-up

With improvements in equipment and systems engineering, the reliability of the main power source becomes more important. With solid state equipment which requires low power and voltages, batteries are the most popular form of standby power. If prolonged commercial power failures are anticipated, engine-generator sets are used to recharge the batteries. In some remote areas, gas fueled thermoelectric generators are used and solar power is now becoming an economic alternative except in the most northerly states where the necessary standby battery capacity becomes prohibitive.

Industrial lead-acid batteries are most often used. To give strength to the plate structure the lead is alloyed with calcium, antimony or selenium, and this gives each cell certain advantages or disadvantages depending on application.

Currently, industrial lead-calcium or lead-antimony acid batteries are most often used. Both types are reliable and the choice is often one of personal preference. The one advantage of lead calcium is that equalizing charges are not required which reduces maintenance. The float charge voltage is 2.15 volts per cell for lead-antimony, 2.2 volts per cell for lead-calcium, and 2.23 volts per cell for lead-selenium. Batteries should be installed in well-ventilated areas to reduce the possibility of explosion from escaping hydrogen gas. Battery banks usually consist of 12 to 24 cells (24 to 48 volts) and the positive terminal is grounded. Cell voltage typically varies over a range of 1.75 to 2.35 volts when completely discharged and when at maximum charging rate. The communication equipment must be capable of accepting this variation. Battery size is usually selected for a minimum 8-hour capacity with 24-hour capacity being about the economic limit. To arrive at the minimum ampere-hour capacity (AH) for a given standby period, the average station load (A) should be multiplied by the hours of standby required (H), typically 8-12.

To arrive at the minimum charger capacity (C) to recharge in R hours, the average station load should be multiplied by the factor:

$$\frac{A + H \times A \times 1.1}{R} = C \text{ amperes} \qquad [16]$$

When $H = 8$ and $R = 24$ this factor is 1.37. R should not be less than 2.5 times H.

Since charger failure would lead to station failure after H hours, a key repeater could require a duplicated charger for full protection. In this case each charger need only have a capacity equal to the station load A rather than C as derived above.

Present day batteries are quite reliable and require little attention for many years. Batteries are also effective filters to protect solid state equipment from power line surges, and act as a very large capacitor, so reducing ripple from the charger.

Battery chargers operate from standard commercial power and actually provide the power to the equipment with the battery floating as a standby device. Good chargers should incorporate protective devices to limit charging current and to protect against line surges and duplicated chargers should be designed to share the load. Alarms for charger and line voltage failure should also be available. Purchase of batteries and chargers from the same source of supply is recommended to insure compatibility.

Batteries and charges are sound investments which will add many hours of operating time to the average microwave system.

When diesel generators are the primary source of power they should not be run at less than 75% of rated load (after allowing for any de-rating

Fig. 16. A fixed solar powered TV station in Oman with a wind-powered generator. (Courtesy of Solarex Corporation)

due to altitude). This prevents oiling-up of the engines.

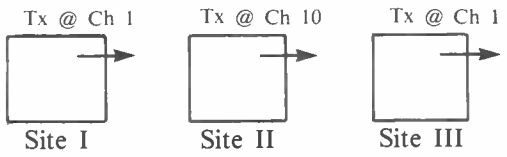
Solar power using photo-voltaic cells is attractive as there are no moving parts requiring maintenance. However the batteries required to maintain the supply during periods of darkness or heavily-clouded weather (which could be several days in some areas) can be the most expensive item in a solar installation. It may pay to have a small generator which can be cut in after 48 hours rather than a battery to give, say, six days standby when that capacity may only be required once or twice a year. The small generator can also power lighting and test gear during a maintenance visit to the site.

FREQUENCY PLANNING

Frequency coordination has been primarily a local case-by-case selection process through cooperation of the respective chief engineers. Most areas, through the local chapter of the Society of Broadcast Engineers (SBE), maintain an up-to-date log of existing licences.

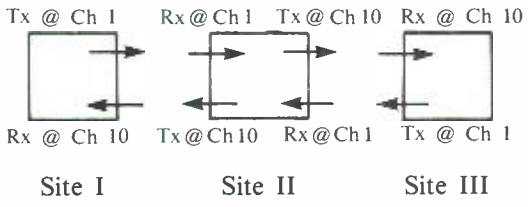
Ideally, frequency planning for future growth should follow the following basic parameters:

A. Multi-Hop System: High-Low Plan



Simplex System—One Way

B. Multi-Hop System: Duplex—Two Way



Future growth allows a second channel addition, diplexed on the same antenna system, with alternate channel selections.

With the High/Low Plan, channel additions can expand up from low end and down from high end.

Basic rules with standard transmitter and receiver designs sharing the same antenna network are:

Diplex—Channel Expansion—Same Direction—Alternate Channels

Duplex—Channel Expansion—Two Directions—Minimum two clear channels between transmitter and receiver at same end. When more than one transmitter is multiplexed onto a feeder, any receiver on that feeder must avoid 2A-B intermodulation products; this can be done by using even channels for transmitters and odd channels for receivers.

Cross polarization can be employed to interleave the channel plan, but care must be exercized in controlling the respective bandwidths through modulation control and RF/IF response.

Frequency Re-Use

Microwave antenna discrimination provides a degree of isolation that very often allows the re-use of the same channel as the same or a nearby site a number of times.

The EIA Interference Criteria, "Telecommunications Systems Bulletin 10D," specifies a carrier to interference (C/I) ratio of 60 dB. This is ideal, but in many cases very difficult to realize. Acceptance of a lesser C/I ratio has worked successfully in many cases.

Lowering the C/I ratio will raise the effective noise level and hence reduce the fade margin. Given a threshold of −80 dBm, say, the noise level will be appropriately −90 dBm and interference at −90 dBm will raise the threshold to −77 dBm. This may be acceptable in many cases.

Assume a well-designed path from Site A to Site B has, by design, a 40 dB fade margin from normal receive carrier level to Threshold—defined as 37 dB Video S/N. If another co-channel (same frequency) transmitter with same power output and antenna size is located at Site A, but aimed in another direction and the side lobe of the new antenna is only 50 dB down, relative to main beam, a 3 dB increase in the noise floor of the original receiver would be expected and undesirable. If, however, the side lobe can be made greater than 50 dB down, a lesser noise floor increase would be expected. Antenna patterns typically describe a worst-case peak envelope and in practice, the nulls can be well below the envelope and provide essentially no contribution to the original system noise floor. Many systems have been successfully built along this line. Fading over respective paths would be identical and the two systems could exist on the same frequency.

Same site re-use of receiver frequency can be considered in the same fashion with care exercized relative to fading differential.

FCC LICENSING

FCC Application

All broadcast microwave systems, portable or in fixed station operation, must be licensed through the FCC. The application is filed on FCC Form 313, with the pertinent characteristics and Type Acceptance Identification Number provided by the respective manufacturer.

Frequency coordination for clearance of the applied for frequency is the responsibility of the local area engineers. In contrast, licensing by Common Carriers, Industrial Service and CARS Band operators is supported by formal frequency coordination studies. The applicant provides detail analysis of use of the applied for frequency in the area with supporting technical details as to the acceptance of the use.

Broadcast engineers should be aware and careful when applying for channels in the 12.7 to 13.25 GHz Band. This band is shared with CARS—Cable TV Operations, and is in wide service in most areas.

The details in Form 313 are straight forward. However, some confusion may arise on Item 8 treating transmitter output. Subsection 8.B.1 is the typical output of the specific transmitter. Subsection 8.B.2 is the antenna input power and represents the actual typical power expected to reach the transmitting antenna after subtracting the losses expected from the length of connecting coaxial or waveguide transmission line. Subsection 8.B.3 is the Effective Radiated Power (ERP) actually transmitted and is the input power raised by the antenna gain. Subsection 8.C is the Emission Designator, 17,000 F9 at 2 GHz and 25,000 F9 at 7 and 13 GHz.

Portable frequency agile transmitters are typically licensed for all the channels that they can provide. For example, at 2 GHz, all seven channels are submitted on the single license applications.

Broadcasters and others using this Handbook should refer to the FCC Rules and Regulations and to their attorneys for complete, up-to-date information.

REFERENCES

1. Alvira, A., & Corbell, I. T., "Reliable Microwave System Parameters," *Power Apparatus and Systems,* Institute of Electrical and Electronics Engineers, December 1955, pp. 1101107.
2. EIA Standard RS-250-B, *Electrical Performance Standards for Television Relay Facilities,* Electronics Industries Association, Washington, D.C., September 1976.
3. *Television Signal Analysis,* Second Edition, American Telephone and Telegraph Company, Long Lines Department, April 1963.
4. C.C.I.R. Documents of the Fifteenth Plenary Assembly, Geneva, Switzerland, 1982.
5. *The Lenkurt Demodulator,* Second Edition, Lenkurt Electric Company, San Carlos, California, 1966.
6. *Reference Data for Radio Engineers,* Fifth Edition, International Telephone and Telegraph Corporation.
7. *Planning and Engineering of Radio Link Paths,* Sixth Edition, Siemens and Halske Aktiengesellschaft, Munich, Germany, March 1961.
8. Egli, J. J., "Radio Relay System Engineering," *Proceedings of the IRE,* January 1953.
9. Hogg, D. C., "Statistics on Attenuation of Microwave by Intense Rain," *Bell System Technical Journal,* November 1969.
10. Jakes, W. C., Jr., "A Theoretical Study of An Antenna—Reflector Problem," *Proceedings of the IRE,* February 1953.
11. *Engineering Consideration for Microwave Communications Systems,* by Lenkurt Electric Company, San Carlos, California, 1981.
12. *N.A.B. Engineering Handbook,* Sixth Edition, Section 21, I.T. Corbell, 1975.

4.3

Satellite Earth Stations

James Fitzgerald
Vice President,
Earth Station Services
Comsearch, Inc.
Reston, Virginia

INTRODUCTION

In less than a decade, satellites have become an essential part of the broadcasting industry. The rapid fall in the cost of satellite transmission has made satellites the vehicle of choice for program distribution. As the cost of satellite transmission continues to fall, we are fast approaching a time when many broadcasters will not only receive but also transmit programming by satellite as a natural extension of their role as communication centers. The local broadcaster may on a "shared use" basis transmit teleconferences for local corporations, distribute programming for LPTV networks or distribute its own "superstation" program material.

There are at this time two major developments that are changing the nature of satellite broadcasting. One is the introduction of the 14/12 GHz transmission, which provides channels with less interference from terrestrial microwave systems. The other is the introduction of 2° satellite spacing in the 14/12 GHz band and eventually in the 6/4 GHz band as well.

Satellite communication still has two primary advantages over terrestrial distribution—communication cost is independent of distance and many points can be served with a relatively small investment in terminal equipment. These characteristics make satellites an ideal means for delivery of broadcast programming over vast areas, such as the United States.

SYSTEM DESCRIPTION

A satellite communication system consists of a transmitting earth station, a satellite, (with a receive antenna, transponder and transmit antenna,) and a receiving earth station (Fig. 1 and 2). Since the characteristics of the satellite components determine the requirements of the earth systems, the analysis must begin with the satellite.

Satellite Frequencies, Channeling and Polarization

Satellites used for broadcast program relay are in an orbit 22,282 miles above the equator. In this orbit a satellite travels around the earth in exactly 24 hours, so that it appears stationary at a fixed point over the earth **(geosynchronous)**.

Like a microwave relay on earth, the satellite receives and transmits at different frequencies to prevent interference between incoming and outgoing signals. Current broadcast satellites operate in the C band (also known as the 6/4 or 4/6 GHz band) or the Ku band (also known as the 12/14 or 14/12 GHz band). C band uses uplinks from 5.925 to 6.425 GHz and downlinks from 3.7-4.2 GHz. Ku band uses uplinks from 14.0-14.5 GHz and downlinks from 11.7-12.2 GHz.

The satellite bandwidth is divided into channels. In the C band, 36 MHz channels have been standard (with two 2-MHz guard bands, so that

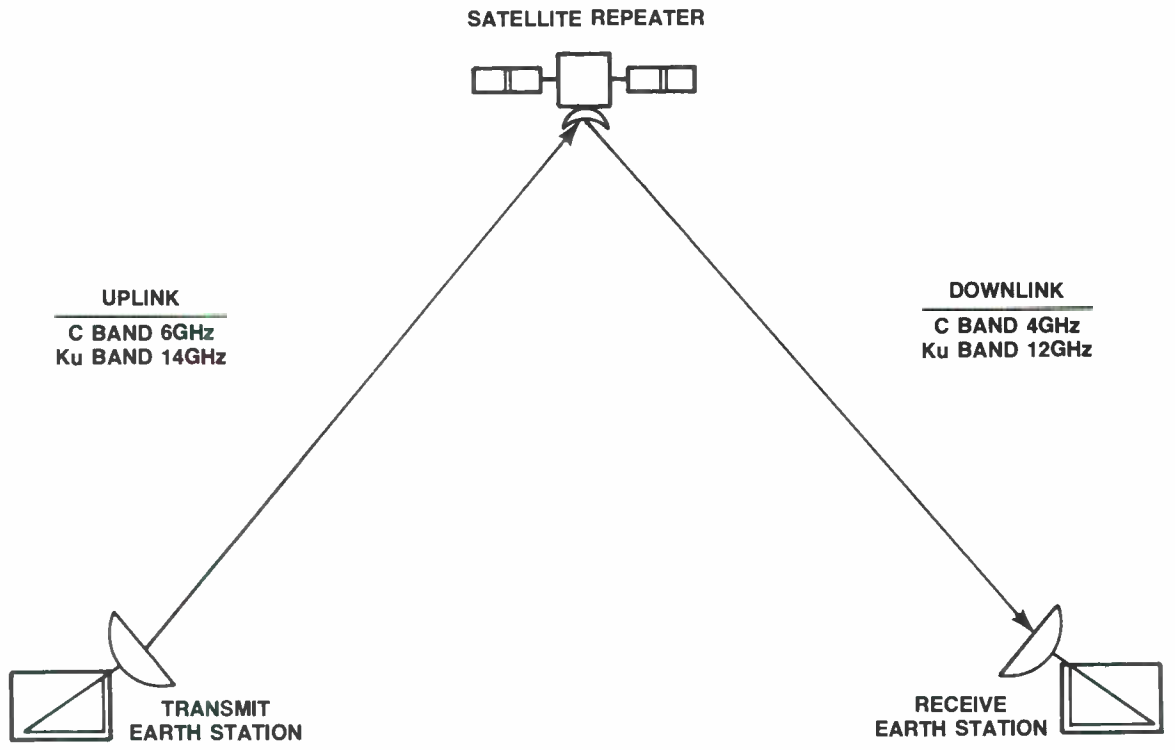


Fig. 1. Two hop satellite communication link.

channels are spaced 40 MHz apart). The 36 MHz bandwidth carries one standard FM modulated broadcast color television signal with sound (the 6 MHz signal used for broadcast has to be spread over 36 MHz to maintain a reasonable S/N in the received signal.) In the Ku band, channels of various bandwidths (such as 43, 54 and 72 MHz) permit combinations of broadcast quality video and other forms of communication.

Most satellites double their capacity by using two polarized channels in the same frequency range. In the typical C band scheme, alternate 36 MHz channels of opposite polarization are spaced 20 MHz apart.

Each channel on a satellite is served by its own transponder. The transponder receives the signal from the earth, converts it to the retransmission frequency, amplifies it and retransmits it.

Satellite Link Analysis

Satellite link analysis is the process of determining what characteristics of the transmitting and receiving station are needed to achieve specified system performance. For most systems used in broadcasting, the primary system performance specification is a signal-to-noise ratio (S/N). For digital systems, such as digital radio transmission, performance is specified as a bit error rate (BER).

Due to the importance of atmospheric conditions in satellite transmission, another significant specification for a satellite system is its performance over time. A system that exceeds a given S/N 99.99% of the time is a system that on average experiences an hour of degraded performance per year.

Once a system specification is established, the analysis generally proceeds in two steps. First is the analysis of system carrier-to-noise ratio (C/N) from transmitting earth station to satellite and from satellite to receiving earth station. The C/N ratio is independent of the type of signal to be carried. To simplify further, carrier-to-noise is referenced to a 1 Hz bandwidth (C/N_o) then converted to a full bandwidth figure.

The second step is to compute S/N or BER, taking into account the characteristics of the modulated signal.

The analysis of a C/N is dominated by the effects of transmitting a signal over vast distances and the limited power available for retransmission from the satellite. Thus the requirements for a transmitting earth station are set by the performance of the satellite's receiving system (measured by a figure called "G/T", explained below). The requirements for a receiving earth station are set by the transponder's EIRP (effective radiated power relative to an isotropic anten-

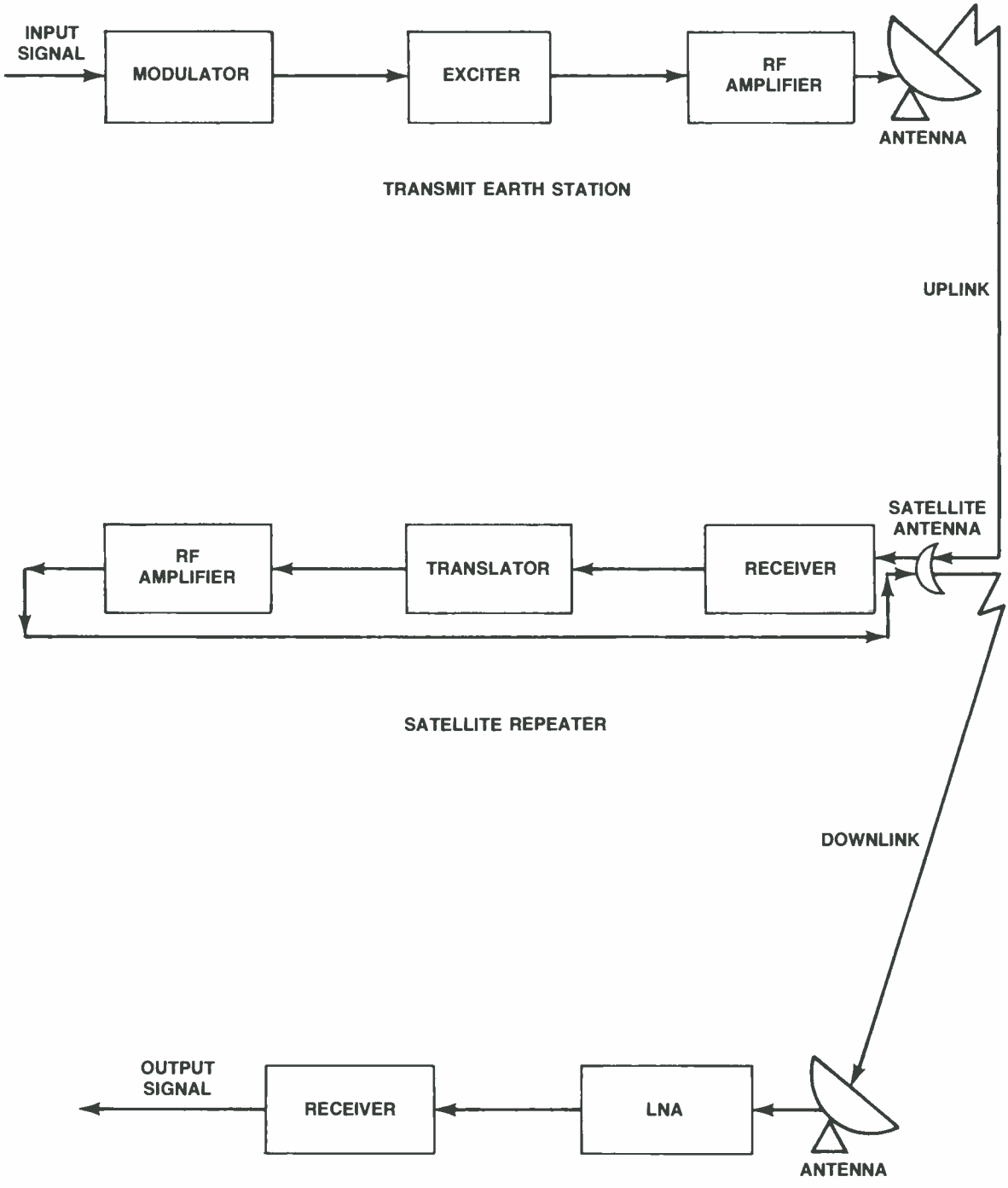


Fig. 2. Simplified block diagram satellite communication system.

na.) The G/T and the EIRP levels vary by location. "Footprint" maps (Fig. 3) show the contours of G/T and effective EIRP. These footprints vary by satellite and by transponder.

For either an unplink or a downlink, C/N_0 is computed using an equation like the following:

$$(C/N_o) = EIRP + (G/T) + 228.6 - L_{fs} - L_a \quad [1]$$

Where:

$EIRP$	=	effective isotropic radiated power from the transmitter (dBw)
G/T	=	figure of merit (see below) (dB)
228.6	=	Boltzmann's constant (dBw-Hz)
L_{fs}	=	Free space loss (dB)
L_a	=	Atmospheric loss (dB)

Of these figures, EIRP is the sum of antenna power and antenna again. Power at the antenna is a specification of the amplifier feeding the antenna. In the case of the earth station, amplifier power is on the order of 500 W (27 dBW) from a high-powered amplifier (HPA) for video services. The satellite power, supplied by solar panels, is limited to 5-10 W (7 to 10 dBW). Gain depends on the efficiency of the antenna and is proportional to the square of the frequency of transmission and the aperture area of the antenna. The larger the antenna, the larger the gain. EIRP is easily computed for a transmitting station given the power at the feed flange and antenna gain (from the manufacturer). Satellite EIRP is available from a footprint map.

G/T, also called "figure of merit", is a measure of the ability of a receiving system to amplify very weak signals, such as those of a transmitter 22,300 miles away, over background noise. The "G" is antenna gain. The "T" is a noise temperature, which is specified in degrees Kelvin for equipment used in satellite communications. For purposes of satellite link analysis, all noise is referred to an equivalent level of thermal noise, that is, the noise caused by random motion of electrons. As noted above, a footprint map of G/T for the satellite transponder supplies the figure used in calculating uplinks.

For downlinks, the gain figure is obtained from manufacturing specifications. The noise temperature, T, of the receiving earth station is the sum of antenna noise temperature and the noise temperature of the system's electronics, as shown in the following equation:

$$T_s = T_a + T_{lna} / G_{feed} + T_{receiver} / G_{feed} \times G_{lna} \quad [2]$$

Where:

T_s	=	total system noise temperature (°K)
T_a	=	antenna noise temperature (°K)
T_{lna}	=	noise temperature of the LNA (°K)
$T_{receiver}$	=	noise temperature of the receiver (°K)
G_{feed}	=	gain of the device coupling feed to LNA (dB)
G_{lna}	=	gain of the LNA (dB)

Antenna noise temperature, T_a, depends on the elevation of the antenna, since an antenna pointing to cold space faces less noise than one angled

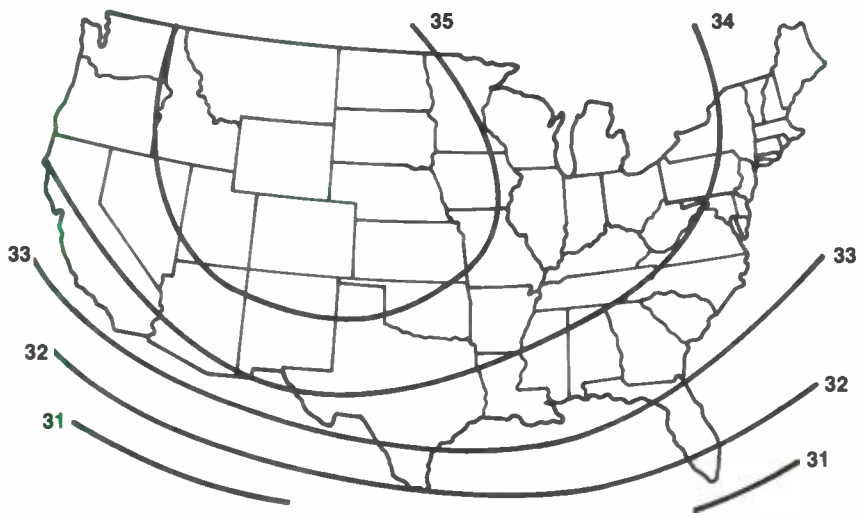


Fig. 3. Footprint showing assumed satellite EIRP in dBW at 4 GHz. (Figure actually shows average EIRP of RCA SATCOM f-1 at 135°W for transponders 3, 7, 11, 15, 19 and 23) (Courtesy J. Searcy Hollis, Scientific Atlanta, Inc.)

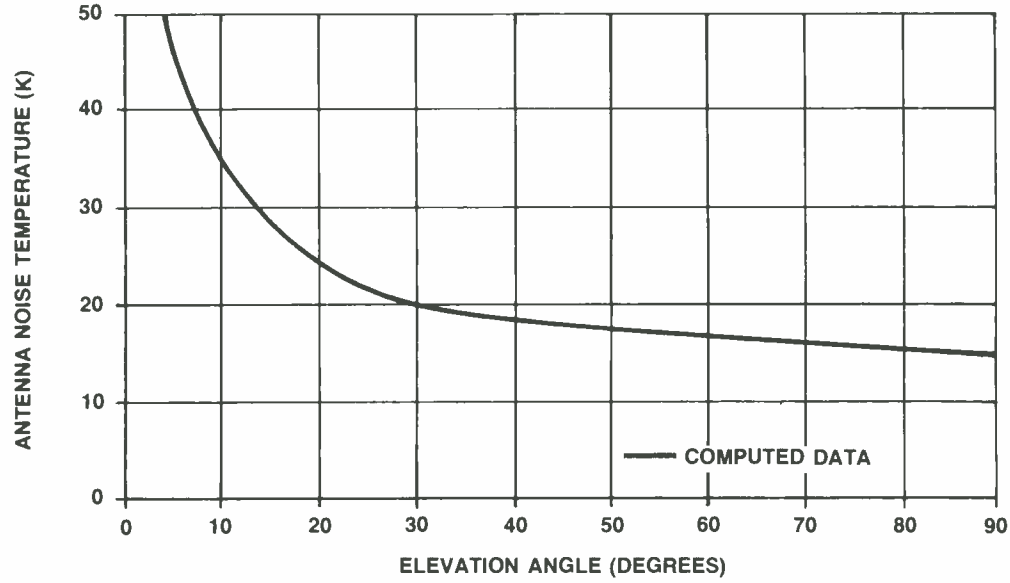


Fig. 4. Typical variation of the noise temperature of a satellite antenna as a function of elevation angle. (Courtesy J. Searcy Hollis, Scientific Atlanta, Inc.)

closer to the warm earth. Fig. 4 shows a typical relationship between antenna noise temperature and elevation angle.

Of the remaining terms in equation [2], only T_{lna} should make a difference. An LNA should be selected with a gain sufficient to overcome effects of noise temperature in the components that follow it.

The constant 228.6 in equation [1] is Boltzmann's constant (1.38×10^{-23} W/°K-Hz) expressed in decibels. This universal constant relates the noise temperature in G/T to power.

Free space loss, Lfs, can be expressed (in watts) as:

$$Lfs = (4 \times \pi \times f \times D / C)^2$$

Where:

f = frequency, Hertz
D = distance traveled, meters
C = the speed of light (2.99×10^8 meters/second)

The final term in equation [1] refers to atmospheric loss. This term can be neglected under most circumstances, particularly with C-band (6/4 GHz) systems. Ku band (14/12 GHz) systems are more likely to be affected by intense rain and heavy clouds. Atmospheric loss for all bands also increases with lower elevation of the earth station, since the station must look through more of the atmosphere.

Equation [1] calculates a single link from earth to satellite or from satellite to earth. To compute a two-hop link (earth to satellite to earth), the individual hops are calculated, then the two figures are combined by power addition. For power addition, decibel figures are converted back to ratios and then summed using the formula:

$$C/N_o = \frac{1}{\frac{1}{C/N_{ou}} + \frac{1}{C/N_{od}}}$$

The result is then reconverted to decibels. In this type of summation, the resulting noise level is higher than either of the links considered alone.

Types of Signals Carried

There are a number of types of signals that a broadcaster will encounter on satellite:

Full transponder FM video. This is a standard broadcast signal, including color and sync tips, using 36 MHz of bandwidth, in C-band systems.

Half transponder FM video is a video signal that uses 18 MHz bandwidth (whether or not the transponder actually has a 36 MHz bandwidth). Both the terms full and half transponder video are misleading, since not all existing or planned satellite transponders use 36 MHz. Half transponder video is used by Intelsat (the international satellite consortium) to transmit news video. It is not a broadcast-quality signal, but is used mainly for news programming.

Audio subcarrier is an FM signal modulated onto the video baseband. Audio subcarriers contain the program audio for video signals. In addition, audio subcarriers are used to distribute radio programming.

Other subcarrier uses. Subcarriers can also be used to transmit slow scan video (still photographs), teletext or other data.

Frequency Division Multiplexed/FM (FDM/FM) is a system by which a large number of limited bandwidth signals (such as voice-grade 4 kHz signals) modulate a carrier of much higher frequency. Using FDM/FM a transponder with 36 MHz bandwidth can carry 1200 telephone conversations.

Single-channel-per-carrier (SCPC) is an alternative to FDM/FM for sharing transponder bandwidth. SCPC transponder frequencies are divided up and assigned to various users, all of which can be transmitting at the same time. By contrast, in FDM/FM all the signals have to be modulated together and sent on a single carrier from a single transmitting station at any one time. SCPC links use more bandwidth per signal (for example: 50 kHz to 200 kHz for a standard radio signal), but they permit higher power on transmission and thus allow smaller, cheaper receiving antennas. News services are using SCPC to transmit audio feeds to radio stations using small antennas.

Digital radio The use of digital, time division multiplexing (TDM) techniques permits more efficient use of satellite transponders than analog techniques, because analog signals can not be compressed as well as digital signals without distortion. Current technology permits twenty 15 kHz audio channels where analog techniques would allow just 16 with very high quality and 15 dB more dynamic range than analog transmission. Digital signals can be sent by SCPC or as a subcarrier.

Data on blanking interval uses the vertical blanking interval in a television signal to send a burst of high-speed data.

SATELLITE EARTH STATION COMPONENTS

Antenna

The purpose of the earth station antenna is to concentrate the energy from a satellite signal at a single point. The critical characteristics of an antenna are its ability to increase the signal and its ability to exclude signals off the "main beam."

Gain is a measure of signal increase. Gain is typically given in dBi (decibels relative to isotropic). The gain of an antenna is dependent upon antenna size, frequency and its efficiency. In a given frequency range, the gain of the antenna increases by the square of the area. Thus the larger the antenna, the greater the gain, other things being equal.

The beamwidth of an antenna measures its ability to exclude signals in any direction other than where it is pointed. It is sometimes specified by the radius at which it radiates at 3 dB and 15 dB down from the main beam gain. Other times it is presented graphically by showing gain across a plane that includes the antenna's main beam.

The licensing of a transmit/receive earth station facility requires that the antenna beamwidth pattern must satisfy Paragraph 25.209 of the FCC regulations pertaining to sidelobe performance, to prevent a transmitter from interfering with adjacent satellites. While this performance is not required of receive-only earth stations, some consideration of beamwidth and sidelobe performance should be made, especially since the FCC has authorized closer spacing of satellites in the popular C band.

What follows is a brief description of antenna types used in satellite broadcasting.

Prime-Focus Antenna

A prime-focus antenna (Fig. 5) consists of a main reflector that reflects the signal energy to a single point, known as the focal point. The antenna feed and amplifiers are located at the focal point. At this point the transmission line is connected to carry the signal to the electronic processing components.

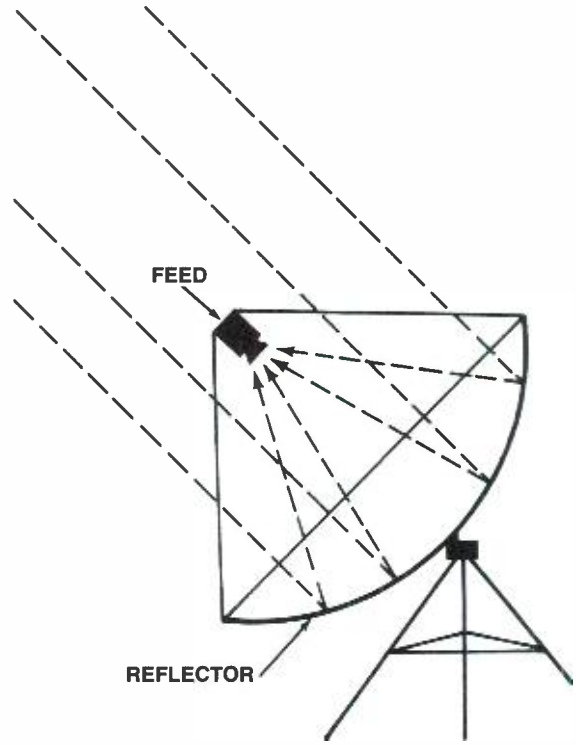


Fig. 5. Prime focus antenna.

Prime-focus antennas are generally used for receive-only services. Benefits of a prime-focus antenna are ease of construction and the fact that pressurization is not required because its design prevents rain and moisture from entering the amplifier. The major drawback of a prime-focus antenna is that the amplifier is located at the focal point and thus repair and maintenance are difficult. In addition, the electronics are exposed to the elements.

Cassegrain Antenna

The cassegrain or dual reflector antenna uses a convex and a concave reflector to direct signal energy to a feed horn. The system is shown in Fig. 6.

Dual reflector antennas like the cassegrain have distinct advantages. The most significant benefit is higher gain than that of a prime-focus antenna of equal aperture. In addition, the electronics can be located behind the antenna in a sealed housing.

The gain is slightly higher due to the fact that signal energy is being concentrated twice. The gain of a cassegrain is typically .5 - 1.0 dB higher than the gain of an equal size prime-focus antenna.

The disadvantage of a cassegrain system is the potential for sidelobe degradation and the need for system pressurization. Sidelobe degradation can occur because the subreflector lies in the main beam of the antenna. This potential problem is usually minimized by optimizing subreflector design and by achieving high manufacturing tolerances.

Cassegrain antennas require pressurization to keep moisture out of the system, since the feed horn is facing upward—exposed to the elements. The system is pressurized by a dry air pump regulated to maintain specific pressure within the feed assembly.

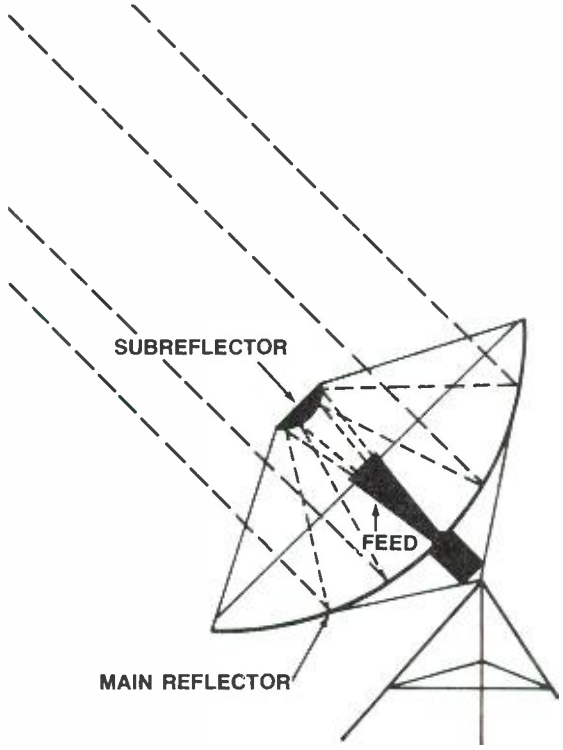


Fig. 6. Cassegrain antenna.

Offset Feed Antenna

Another earth station antenna design is the offset feed. The major benefit of this system is its excellent sidelobe characteristics, due to the fact that no obstruction of the beam occurs between the satellite and the focal point of the antenna. The path from the antenna feed to satellite is clear of subreflector, antenna parts or other support structures. This antenna design is becoming more widely used as a result of the FCC's recent decision to reduce the spacing between adjacent satellites. Its drawback is increased cost due to its nonsymmetrical shape, requiring demanding tooling to achieve its required performance.

Horn Antennas

Horn antennas similar in appearance to the type used in telephone microwave systems (Fig. 7) are sometimes used for satellite communication. They are extremely efficient and exhibit excellent sidelobe performance. However, they are large, expensive and difficult to mount. As a result they are only used in environments with exceptional interference problems.

Multiple Beam Antennas

Multiple beam antennas allow simultaneous communication with more than one satellite. These antennas are a variation on either the prime-focus or offset-feed designs. The advantage is the ability to receive signals from more than one satellite without installing an additional earth station. They are, however, more difficult to align, and the prime-focus types have to be carefully designed to minimize sidelobe degradation.

Orthogonal Mode Transducer (OMT)

As noted above, many satellites transmit frequencies with both horizontal and vertical polarization. To be able to receive both types of signals, an antenna must be equipped with an orthogonal mode transducer (OMT). The OMT is bolted to the feed coming out of the antenna. A system using an OMT will need two LNAs and cable runs, since signals will be on overlapping frequencies.

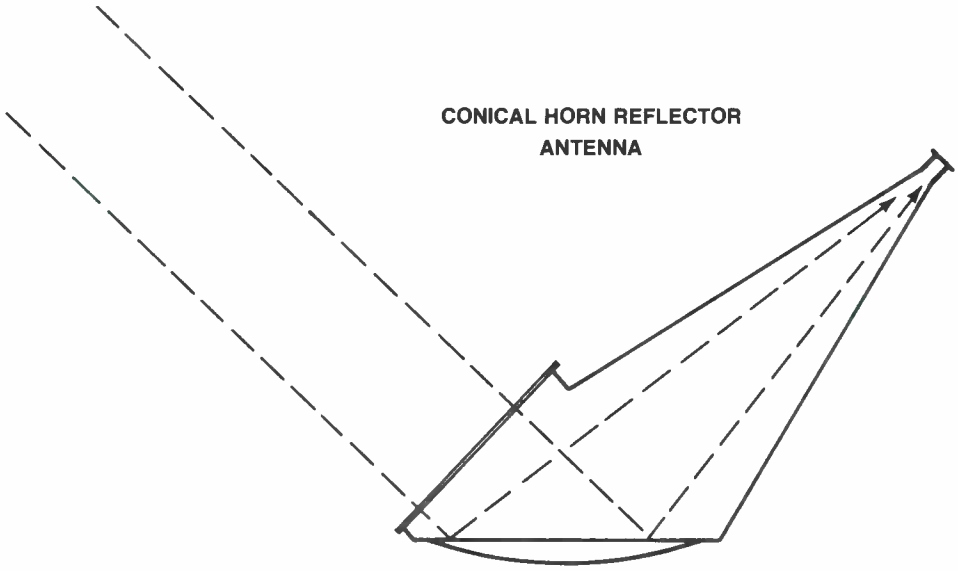


Fig. 7. Conical horn reflector antenna.

Low Noise Amplifier (LNA)

The low noise amplifier (LNA) amplifies the signal at the output of the earth station antenna. The most commonly used LNAs use gallium arsenide field effect transistors (GaAsFETs). Typical noise temperatures for this amplifier range from 75 °K to 120 °K. A thermoelectrically cooled amplifier reduces the noise temperature further, but at significantly higher cost. The selection of an appropriate LNA depends on antenna size and overall system losses.

There is a basic tradeoff between LNA noise temperature and antenna size (that is, gain), expressed by the system figure of merit G/T. Smaller antennas require a cooler LNA for equivalent system performance. A larger antenna allows use of an LNA with a higher noise temperature and lower cost.

The LNA is powered either by dc or ac current. A dc powered LNA can be supplied power through the output signal cable from the receiver or through a separate cable.

The LNA is a weatherized unit that provides sufficient gain to transport the signal from the antenna to the receiver. The LNA usually has waveguide input to connect the antenna feed assembly and a coaxial output.

Low Noise Converter

The low noise converter (LNC) combines the functions of an LNA and a down converter. It is usually located at the antenna which feeds the receiver. The low noise converter changes one channel of the 3.7 to 4.2 GHz frequency to an intermediate frequency. By downconverting first the LNC allows the use of low loss coaxial cable rather than waveguides to connect the LNC to the satellite receiver. However, local oscillator phase noise is introduced by the LNC, which makes it more difficult to maintain a broadcast quality signal. This along with the higher cost of an LNC means that LNAs tend to be the preferred choice for broadcasters.

SITE SELECTION

There are many factors that must be considered in the selection of a site for a transmit/receive or receive-only earth station. These considerations include:

- A clear view of the satellite arc
- Future building plans in the area
- Interference considerations
- Soil conditions
- Zoning, building codes and related regulatory issues
- Connection with ultimate destination of signals

The domestic satellite arc runs from 65° to 145° west longitude. For all practical purposes, an earth station used for broadcasting should have a clear view of the entire satellite arc, even if it may be receiving signals only from one or a few of the satellites now in use, to be able to make the most of the earth station in the future. No trees, buildings, terrain or other obstacles should obstruct the view. Even minor blockage can sig-

nificantly reduce or obliterate the very weak signal coming from a satellite.

When selecting the earth station location, future building plans near the earth station site should be researched and taken into consideration.

Rooftop locations are rarely desirable for a satellite earth station. The reduction in atmospheric attenuation is negligible and the station is not significantly closer to the satellite. The rooftop antenna faces a far greater likelihood of interference from terrestrial microwave systems which use the same 4 GHz and 6 GHz bands. Obviously, it also costs more to survey, plan, get permits for and construct a rooftop earth station.

Perhaps the most important consideration for a site after its unobstructed view of the satellite arc is its shielding from other signal sources. This issue is discussed in detail in the following section.

An additional consideration in site selection is its accessibility for maintenance and repair. It is desirable to have access by standard transportation at all times during the year.

A review of the local planning, zoning, environmental and building requirements should be made early in the evaluation process.

Finally, if a remote site turns out to be the only feasible alternative, consider the availability and reliability of electrical and telephone service from the site.

INTERFERENCE

Interference is a significant enough problem for satellite system operating in the C band to merit separate consideration. The C band is shared between satellite service and common carrier terrestrial microwave (telephone companies). The FCC requires new transmitters in the band to notify current users within a *coordination contour* defined by FCC rule and provide them with technical data on their proposed operation. The current users make an independent study of interference potential and report their objections, if any. The applicant must respond and get the objector's agreement—in writing—that no interference will result or if interference does result, it will be acceptable. After this process, called *frequency coordination* is complete, the new transmitter can apply for an FCC license.

For a receive-only earth station no prior frequency coordination is required. However, the interference potential affects receive stations as well as transmitters. The C band user has the right to license his receive-only earth station and thus the right to be heard when new microwave links are proposed.

The FCC will accept license application for transmit antennas of nine meters or greater for broadband (video) applications. For narrowband transmission (for instance, SCPC or digital radio), there is no limit on antenna size. Receive stations of any size may be licensed, although antennas smaller than 4.5 meters are only protected to the extent that a 4.5 meter antenna would require.

The 4 GHz band used for signals from satellite to earth is shared primarily with AT&T and the former Bell operating companies. They use horn reflector antennas with very good radiation characteristics, and thus only present a problem when they are nearby or if the receive station is directly under a path. Unfortunately, that happens fairly often, due to the number of paths involved.

The situation is more complicated for the transmitting stations at 6 GHz. Non-Bell common carriers and earth stations on this band generally use less discriminating antennas that allow more gain off the main beam of the antenna. In addition, there are more paths and the margin of protection for the terrestrial system is 10-16 dB greater than for an earth station.

Fundamental to an interference analysis is knowledge of how new and existing antennas emit and accept radiation off their "main beam." This information is available from the antenna manufacturer or standard FCC specifications are substituted. For any computation involving satellite earth stations, the analysis must take into account the fact that the antenna will be rotated to view a number of satellites and the fact that, unlike a terrestrial system, the earth station main beam usually points well above the horizon. The basic antenna gain chart in Part 25 of the FCC Rules is used as a basis for developing a horizon gain curve taking these factors into account.

Interference propagates along great circle paths. On unobstructed paths, free space loss is the primary factor reducing the interference level. If the path is blocked, diffraction or tropospheric scatter means that some interfering energy will nevertheless reach the antenna. The basic equation for calculating interference level is:

$$P_r = P_t + G_t - L + G_r$$

Where:

P_r = received signal power (dBw)
P_t = transmitted power (dBw)
G_t = gain of the transmitter in the direction of the earth station (dBi)
L = basic transmission loss (free space loss or loss from diffraction and tropospheric scatter effects) (dB)
G_r = gain of the earth station antenna in the direction of the transmitter (dBi)

This same equation determines interference caused by a transmitting earth station, with the role of transmitter and earth station reversed.

FCC rules establish the criteria that determine which microwave stations must be included in frequency coordination for a transmitting earth station. Similar criteria can be used to identify potential interference sources for a receive-only station.

Licensing for a transmitting or receiving earth station involves three steps. First, before coordination begins, the broadcaster conducts his own study of the interference environment. This can most easily be done using a computer study from one of the frequency coordination services with a data base of existing and approved microwave and earth station licenses. This study will include some consideration of terrain and may be augmented by field testing.

Second, once the user has satisfied himself that the station will operate without interference, he (or his frequency coordinator) issues the coordination notice. Then he responds to the objections of existing users.

Finally, once all parties agree on interference considerations, an FCC license application can be filed.

Often more than just an office study is needed to clear a proposed site, because many of the figures used in calculating expected interference are conservative estimates and because topographic map data usually underestimates isolation provided by buildings and trees. A field test will often clear a case showing marginal interference. For receive-only stations, the field test directly evaluates interfering signals. For a transmitting station, the test measures the isolation between the site and existing transmitters.

Field measurements are taken with a test antenna and a spectrum analyzer. The test antenna is scanned 360° in both vertical and horizontal polarizations, while the spectrum analyzer is set to display the full 500 MHz of either the 4 GHz or 6 GHz bands. Typically a daytime and a nighttime test is made and statistical models are used to estimate the results in the worst season and under the worst short-term conditions.

There are a number of things that can be done to prevent interference. Natural shielding remains the best and cheapest solution. If there is a choice between a hilltop site and a valley site with a view of the satellite arc, choose the valley. Trees can also reduce interference, but remember to take into account the loss of leaves.

Diffraction fences of hardware cloth, expanded metal or chain link fence with metal strips inserted in the mesh can also be used to shield. Prefab shielding material is also available for this purpose. It is often difficult to calculate in advance the precise effect of diffraction fences close to the antenna, since the fence must be considered as part of the antenna itself.

Pit shielding (building earthen mounds around the earth station) can provide more than 25 dB of additional isolation. Drainage should be provided if the pit completely surrounds the antenna.

A higher-performance (more directive) antenna can sometimes solve interference problems.

Because of the differences in channeling between terrestrial microwave and satellite systems, a good notch filter 10 MHz above or below the center of the desired receive frequency will sometimes resolve interference. This approach is only available for receive-only stations and only applies to interference from FDM/FM sources. It will not resolve interference from digital, single-sideband or FM video.

Finally, there is the option of choosing a completely different location for the earth station.

Early in the planning stages for an earth station, it is possible to obtain an interference intensity map. This shows expected worst-case interference levels at a number of equally-spaced locations within a large target area. This map can be used as a guide in finding a location with the right topography, zoning and price. The chosen site will still require detailed interference analysis, but the potential for unpleasant surprises is substantially reduced.

FCC LICENSE

The FCC requires licensing of transmitting earth stations and permits licensing of receive-only earth stations. It is desirable for a broadcaster to license a receive-only station, since licensing protects the station from future interference from domestic microwave systems.

The receive-only application is relatively simple. It is a narrative (there is no standard form) with the following information:

1. The nature of the proposed service.
2. A statement of public interest.
3. The name of a person to receive correspondence (usually includes a technical contact and counsel).
4. The applicant's technical qualifications.
5. A paragraph identifying that the application is a "minor" action for environmental considerations. Generally, the action is minor if the antenna dish is less than 30 feet in diameter and is not located in certain specific areas (e.g. historic districts, scenic areas, floodplains and some others listed in 47 CFR 1.1305(a)(6)).
6. Description of the site (plot plan) and its availability. This should include the eleva-

tion of the antenna base above sea level and the maximum antenna height above the base.

7. A functional block diagram of the system.
8. Description of the antenna mounting and range.
9. A statement of compliance with the requirements for antenna sidelobe performance.
10. A statement of FAA clearance, if required (the same rules apply as for any antenna).
11. The report of frequency coordination and interference analysis.
12. A technical showing that the antenna meets the performance criteria for a 4.5 meter antenna, if the antenna is less than 4.5 meters.
13. A completed FCC Form 403.
14. A technical summary of the proposed station including a description of the equipment to be used, major structures, the type of communication being received, the space segment being accessed, frequencies and polarities received, satellites and transponders being used.
15. A statement that the applicant will only receive program material for which it has obtained rights.
16. The applicant's certification.
17. The technical certification by a technically qualified person that the engineering data is complete and accurate.

These same items are required for transmitting stations, although naturally some of the items will be more involved (such as frequency coordination and technical description of the system). There are a few additional requirements for transmitting stations:

1. A completed FCC Form 430 (legal and financial qualification). This form is required if common carrier status is sought.
2. A statement of compliance with regulations for the protection of employees and the general public against excessive radiation.
3. A statement of compliance with FCC regulations regarding quiet zones.

INSTALLATION

This section consists of a checklist of considerations in constructing a satellite earth station.

Foundation

In selecting the precise location for the antenna, it is important to choose a level site, well drained and free from underground obstructions that might interfere with foundation construction. The foundation for the antenna will be substantial to maintain the pointing angle of the antenna despite substantial wind loading and possible ice loading. An evaluation of soil type and frost penetration is necessary to establish the foundation required.

There are two common types of foundation. In the mat footing, the load is borne by a single, large reinforced concrete mat. The alternative, a drilled pier footing, requires much less concrete and are more cost-effective if soil conditions permit their use. Further economies can be achieved with earth anchors supplementing concrete piers. Pier kits are available for smaller earth stations.

The mat foundation may be required if the ground is too rocky or the soil too loose for drilling holes for piers. Sometimes it is too expensive to transport pier drilling equipment to the proposed site. In some areas small contractors may be able to build a mat foundation at less cost.

As mentioned above, rooftop locations are not recommended for earth stations. If a rooftop location is required, it is necessary to construct a load frame to connect the antenna mount to the building columns. As height increases, expected wind load increases and the design of the antenna mount needs to be adjusted accordingly.

Note that a professional engineer may be required to approve a foundation design in some states.

Finally, before the foundation is poured, be sure that provision has been made for supplying ac power and RF interfacing, if it will pass through the foundation.

Mounting

There are a number of systems for mounting and pointing earth stations, some with two moving axes, some with one. As might be expected, the one-axis systems sacrifice some accuracy in the interest of simplicity.

The two-axis systems are elevation-over-azimuth (with one axis of rotation perpendicular to the plane of the horizon), X-Y (with one axis parallel to the ground) and polar (with one axis parallel to the earth's axis of rotation). Elevation-over-azimuth is an extremely flexible system, and initial mounting is not critical. It is more complicated than the other systems. X-Y requires that careful attention be given to the initial heading angle of the antenna.

The polar system has the advantage that it can maintain pointing at any point in the sky simply by rotating about its vertical axis. For this reason, the polar mount is the basis for the single-axis mounting systems. In a simple single-axis system, the vertical mount is exactly parallel to the earth's axis of rotation. In a declination-corrected polar mount system, a slight correction is made to ac-

count for the fact that the antenna is not in the same plane as the satellite arc (that is, the plane of the equator). In most parts of the continental U.S., a declination-corrected polar mount antenna can be made to point to any satellite between 70° and 135° west longitude with negligible error.

Heading

Accurate heading of the antenna center line is often essential for finding the desired satellites. With some mounting systems, an inaccurate foundation heading may require reconstruction, and the foundation contractor should be made aware of the importance of maintaining a surveyed heading. A competent surveyor can establish the proper heading by reference to known survey lines, by pole star observation or by compass. The last should take into account magnetic declination from true north and, in any case, should not be used near large metal structures or strong electrical fields.

Shelters

For receive-only earth stations in remote locations, the necessary electronics can often be located in a simple equipment shelter (8′ × 8′). Since the equipment generally does not generate a large amount of heat, it may be possible to avoid air conditioning.

Shelter requirements become significant for a transmitting earth station. Each HPA is about 2′ wide, 3′ deep and 7′ high, and a typical station will have redundant HPAs for reliability. Control equipment will occupy two standard 19″ racks. Sufficient space is needed for waveguides and cable runs. A 10′ × 18′ shelter is probably the minimum for accommodating the necessary equipment.

Any shelter should be as close to the earth station as possible to avoid long cable runs. If long runs cannot be avoided, additional amplifiers will be needed along the run.

Power

Power requirements for a receive-only station are modest, probably less than 1 kW for the LNAs, receiver and control equipment. Motorized antenna positioning would require additional power. For transmitting stations, HPAs demand large amounts of power, perhaps 12 kW of three-phase power for a 3 kW video amplifier. A hot backup HPA requires a doubling of the load. Antenna deicing represents the other major power requirement, with 3 kW for feed and subreflector deicing (sufficient in milder areas) up to 51 kW for full reflector deicing. Air conditioning is an additional power consumer.

Two kinds of backup power should be considered. Short outages can be bridged with an uninterruptible power system (UPS), a battery-based system. It is impractical for a UPS to protect anything but the electronics of the system. An engine and generator is needed for longer outages. This system should be sufficient to operate the entire system, with provision for enough fuel to maintain operation when conditions may hamper refueling.

Pressurization

A pressurization unit must be installed to keep moisture out of certain earth station antennas, notably cassegrains. Pressure may also be required for air dielectric cabling.

OPERATION

Operating an earth station antenna is above all a matter of correct pointing. The process should be one of pointing to the correct azimuth and elevation of the desired satellite and then fine tuning, first with the meters of the satellite receiver and then with a video monitor.

For a transmitting station, a scenario for starting transmission might follow these lines:

1. Position antenna on satellite (can use receivers to insure accurate pointing).
2. Check null on adjacent transponders to verify polarization angle.
3. Tune exciter, HPA and Receiver to the transponder frequency.
4. Check power levels with a dummy load.
5. Call the satellite technical operations center to initiate transmission.
6. Transmit low-power CW to check polarization.
7. Operations center clears full-power transmission.
8. Increase power.
9. Add modulation (test tone).
10. Check for interference on adjacent transponders.
11. Add source.
12. At the end of transmission, call operations center to inform them.

MAINTENANCE

Maintenance will usually be specified by equipment manufacturers. There are few moving parts or sensitive equipment with a receive-only station, so maintenance will not be a major item. Antenna bolts should be checked and tightened periodically. Waveguides should be checked for

leaks and kinks. Antenna motors should be checked and lubricated as required. Weekly inspection should identify impending problems.

For a transmitting station, HPAs require daily inspection. The klystron tube in an HPA will need to be rebuilt every two to three years, so that a redundant system with two HPAs will require 3 klystrons, two operating and one in repair.

A rule of thumb for maintenance is 3% to 5% of system cost per year.

4.4

Fiber Optic Video Transmission Systems

Pete Mountanos
Grass Valley Group
Grass Valley, California

INTRODUCTION TO FIBER OPTICS

Fiber optic technology is a dramatic step in the evolution of telecommunications. The heart of fiber optic communications is an optical fiber or waveguide, made of glass or plastic, through which light is transmitted. Light, being a part of the electromagnetic spectrum, follows the same principles we have employed in designing microwave, television and radio transmitters. The most common use of fiber is as a transmission link connecting the two electronic circuits of a transmitter and receiver. The central part of the transmitter is the optical source, either an LED or laser diode, which converts electrical signals into light signals. The source is modulated by a driver, which may, for example, convert a digital or frequency modulated voltage signal into a current source appropriate to drive an optical device. The receiver contains some form of a photodiode, which in turn converts light back into electrical signals, and an output circuit which amplifies and reconstructs the signal into its original form. Fig. 1 is a simple block diagram of such a link.

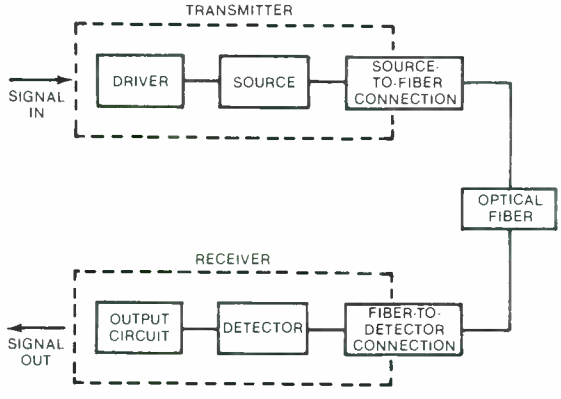


Fig. 1. Basic fiber-optic link.

As compared with discrete wire, twisted pair, coaxial cable, and even in some cases, over-the-air microwave and satellite transmission, fiber optic systems offer significant advantages for transmitting signals.

Advantages

The advantages of fiber optic systems warrant considerable attention from the communications industry. Among the most important are the following:

1. ***Bandwidth.*** Information carrying capacity of a carrier increases with the elevation of the carrier frequency. Since the signal is light with fiber optics, the carrier frequency is several orders of magnitude higher than the highest radio frequencies. (Fig. 2) Today's fiber optic systems easily surpass the information carrying capacity of more conventional methods and its future carrying capacity has only begun to be utilized. Fibers have bandwidths in excess of several GHz per kilometer, which allow high speed transfer of most types of informa-

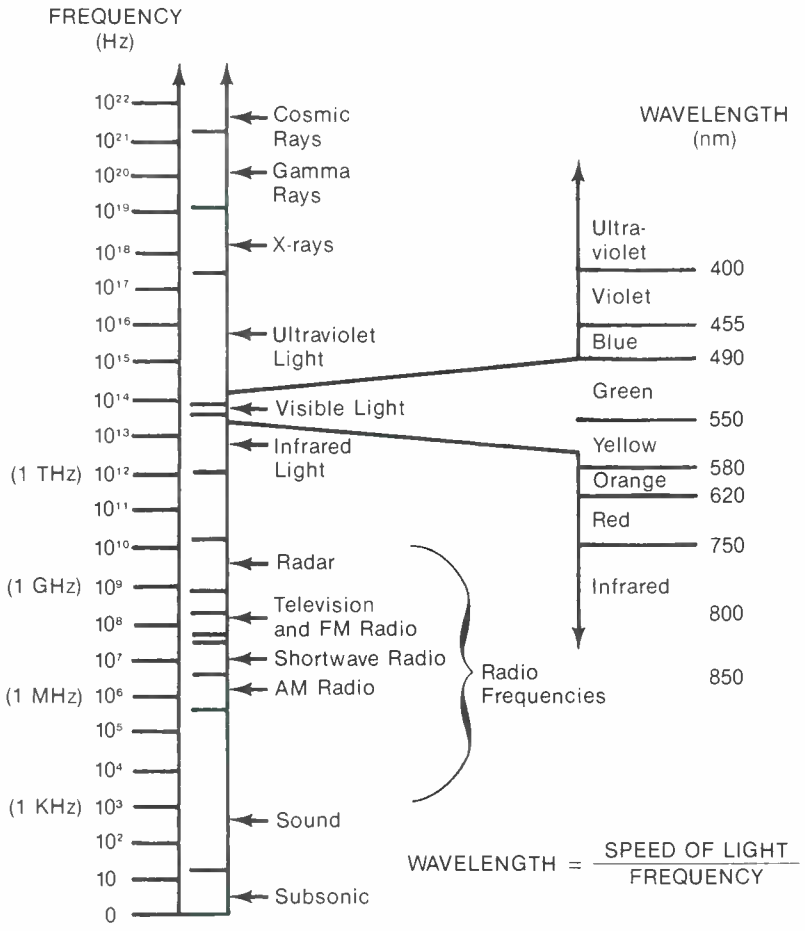


Fig. 2. Electromagnetic spectrum.

tion. With multiplexing, many signals can be sent over a single fiber. For example, the phone industry now transmits thousands of voice channels simultaneously over a single optical waveguide.

2. ***Low Loss.*** Fibers provide substantially lower attenuation than copper wires and require no equalization. In premium cables attenuation can be below .5 dB/km for certain wavelengths.
3. ***Electrical Isolation.*** Since the fiber cable is essentially dielectric material it is inherently isolated electrically. There is no spark hazard, and no risk of EMI emmissions. Fiber cable is a natural in hazardous environments, and its electrical isolation precludes ground loop problems. Fiber optic systems are immune to outside electrical noise as well.
4. ***Size and Weight.*** In general, the optical waveguide is the size of a human hair. As a result an equivalent copper cable is always much larger, stiffer and heavier than an equivalent fiber cable. Thus, installation costs, ducting, handling costs and the like are typically much lower for a fiber installation than for a similar coaxial system. This factor alone accounts for much of the rapid acceptance of fiber.

Disadvantages

Optical fiber as a transmission medium does have disadvantages, some of which are strictly due to the relative infancy of the technology. A major disadvantage is lack of fiber optic standards from industry organizations such as EIA. This lack of standards in both specifications and testing procedures makes comparison of various manufacturers' products difficult. It is expected that these problems will be addressed in the near future. Another drawback, most significant to the broadcast industry, is the difficulty of adapting fiber optics to existing systems. Most interconnections rely on linear analog amplifiers such as distribution amplifiers. Fiber optics is not suited for such implementation as it is preferable to operate in a serial pulsed fashion. As the cost of fiber optic components declines, and the use of digital components in television increases, the technology will become increasingly appropriate.

Economics

The economics of using fiber optic systems is a complex discussion. Direct comparisons between copper based, microwave or satellite based systems are difficult and open to debate. Each evaluation must be based on the user's needs. It is clear that widespread application of any technology depends upon providing superior performance at a lower cost to competing technologies. That fiber optics can meet such a criteria has been established by the telephony industry. As is the case with most new technologies, costs are rapidly dropping while more mature technologies continue to increase. As a result, fiber optics becomes more attractive every day.

LIGHT AND FIBER CHARACTERISTICS

Light is similar to radio waves, x-rays, and gamma rays in that it is a part of the electromagnetic spectrum. In general the frequencies of light used in fiber optic transmission are in the region of 300-400 terrahertz (10×E14), or several orders of magnitude higher on the electromagnetic spectrum than the highest frequency radio waves. Light waves are more generally described in terms of wavelength rather than frequency (Fig. 2). The region extending from 800-1600 nanometers is of greatest interest because today's fibers propagate these wavelengths most efficiently.

What we refer to as "the speed of light" (300,000 km/sec) is the velocity of any electromagnetic energy in free space or a vacuum. Light travels slower in all other media, and different wavelengths travel at different speeds in any single medium. When an electromagnetic wave crosses a boundary from one medium to the next it changes speed which results in a change of path called refraction.

The index of refraction, *n*. is a dimensionless number expressing the ratio of the velocity of light in free space, *c*. to its velocity in a specific medium. Thus:

$$n = c/v$$

Refraction of a ray of light as it passes from one material to the next depends on the refractive index of the material. When discussing refraction three terms are used. The normal is the line perpendicular to the interface of the materials. The angle of incidence is the angle between the incoming ray and normal. The angle of refraction is the angle between normal and the refracted ray.

When light passes from a high index of refraction medium to a lower one the light is refracted toward the normal. Fig. 3 shows that as the angle of incidence increases, the angle of refraction approaches 90 degrees with normal. This is called the critical angle. If the angle is increased past the critical the light is totally internally reflected.

Optical Fibers

A basic optical fiber consists of two concentric layers. The inner layer, the core, has a refractive index higher than the outer layer, the cladding. Light injected into the core and hitting the boundary at an angle greater than critical is reflected into the core. Light striking the interface at less than the critical angle is passed into the cladding and lost. This total internal reflection forms the basis for light propagation in optical fibers. The exact characteristics of light propagation depend on fiber size, construction and composition. Maxwell's equations show that light does not travel randomly through a fiber; but rather that it is channeled into modes. A mode is a possible path through a fiber.

Types of Fibers

There are many ways to classify fibers, however the most informative are by refractive index profile and number of modes supported. The two

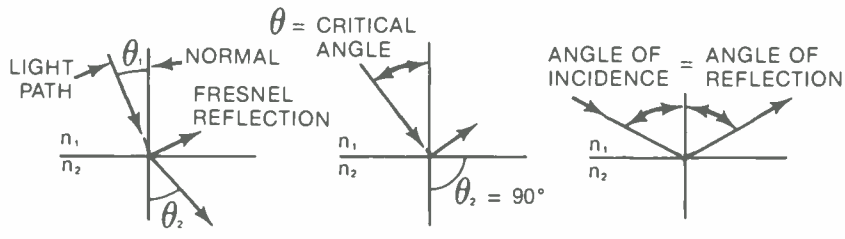


Fig. 3. When the refractive index, of the first medium (n_1) is greater than that of the second, (n_2) light is refracted away from the normal. If the angle of incidence is greater than the critical, the light is totally reflected.

main types of index profiles are step and graded. In a step index fiber, the core has a uniform index with a sharp change at the boundary of the cladding. In graded index fiber, the core's index is not uniform; it is highest at the center and decreases until it matches the cladding. There is no sharp break. Fig. 4 shows the paths and propagation characteristics of such fibers.

Multimode, Step Index

A multimode step index fiber typically has a core diameter in the 500-1000 micron range. The large core permits many modes of propagation. Since light will reflect differently for different modes some rays follow longer paths than others. The lowest order mode travels down the center while higher modes strike the core-cladding interface at angles near the critical angle and as a result, follow longer paths through the fiber. As a result, a narrow pulse of light spreads out as it travels through this type of fiber. This "spreading" is called modal dispersion.

Single or Mono Mode, Step Index

A way to limit modal dispersion is to make the fiber core sufficiently small to insure the fiber propagates only one mode efficiently. A single mode fiber has a core diameter small enough that the fiber propagates only one mode, efficiently. A single mode fiber has a core diameter of the order of 5-10 microns. This is of the order of 1/6th the diameter of a human hair. Its small size makes it very difficult to work with, however it is very efficient and suitable for high speed, long distance transmission.

Multimode Graded Index

A graded index fiber also limits modal dispersion. Its core is essentially a series of concentric rings, each with a lower refractive index. Since light travels faster in a lower index medium, light farther out from the axis travel faster. Since high order modes have a faster average velocity than low order modes, all modes tend to arrive at a point at nearly the same time. Rays of light are not sharply reflected by the core-cladding interface, they are refracted successively by different layers in the core.

Dispersion

Dispersion relates to the spreading of a light pulse as it travels down a fiber. A pulse measured at the output will be wider than it was at the input. This limits a fiber's bandwidth or information carrying capacity. Pulse rates must be slow enough that dispersion will not cause adjacent pulses to overlap. Consider the pulse shown in Fig. 5. Two trains of pulses, one faster than the other are injected into the same fiber. In both cases, the pulses are spread by dispersion. For

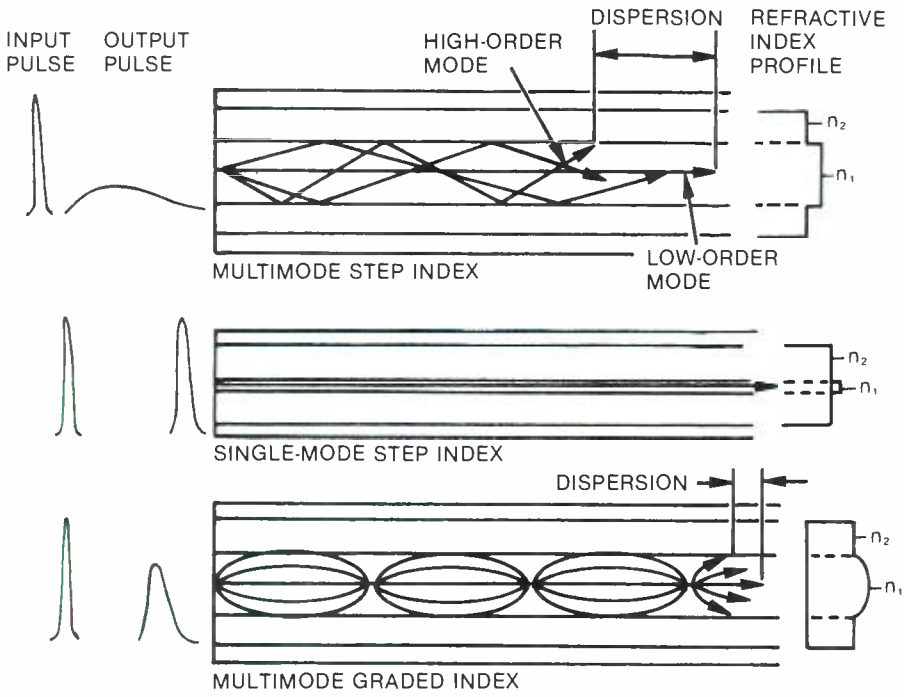


Fig. 4. The core size and refractive index determine the light propagation characteristics of the fiber.

Fig. 5. Dispersion limits signal frequency.

the slower train, the interval between pulses is sufficient to allow each pulse to be distinguished. In the faster train, however, the interval is so short that individual pulses merge into one long indistinguishable pulse. Dispersion, which can be related to pulse rise and fall times as in copper cable, therefore is the limiting factor in determining a fiber's bandwidth.

There are basically two types of dispersion: modal, resulting from differing path lengths already discussed; and material, arising from differing velocities of different wavelengths in the signal. In a single mode fiber there is no modal dispersion, only material dispersion limits its capacity for carrying information.

Material Dispersion is generally limited by either operating at lower frequencies, or using very narrow optical spectrum devices such as lasers.

Attenuation or Loss

Attenuation is loss of power. During transit some of the light is absorbed into the fiber or scattered by impurities. Attenuation for a fiber is usually specified in decibels per kilometer or dB/km. For commercially available fibers, attenuation ranges from around .5 dB/km for premium fibers to 100 dB/km for large core plastic fibers. It is important to remember that since we are measuring optical power, a 3 db loss represents ½ rather than the 6 dB we have become used to in dealing with voltages.

Fiber attenuation is closely related to light wavelength. Most fibers have a medium loss region in the 800-900 nm range (3-5 dB/km), a low loss region in the 1150-1350 nm range (.6-1.5 dB/km), and a very low loss region (less than .5 dB/km) in the 1550 nm area. As a result best performance is achieved by careful balancing of fiber, device and distance requirements.

OPTICAL DEVICE CHARACTERISTICS

Sources

An optical source is generally either a light emitting diode (LED) or an injection laser diode. The LED is an incoherent source, which when compared with a laser, provides less power and operates at slower speeds, but also costs considerably less. It is however, quite suitable for most applications requiring transmission less than 10 km and speeds less than 100 Mbits per second. A laser requires more electronics to operate, is more powerful, and costs more, however it can be used to transmit distances over 100 km before amplifiers are required. In general, an optical source must be evaluated to insure its speed is suitable to the bandwidth required, and that it provides enough optical power at a wavelength suitable to meet the distance requirement. Another important consideration is the fact that optical devices do not turn on with the linear characteristics we are accustomed to with electrical devices. Fig. 6 and Fig. 7 illustrate examples of characteristics for lasers and LED's. As a result, modulation techniques that rely on the linearity of the device are generally not suitable for fiber optic applications.

Detectors

A detector performs a complimentary function to the source: it converts incident optical energy back to electrical energy. Common detectors used in fiber optics are semiconductor photodiodes, including PIN and avalanche photodiodes.

The performance of a fiber optic system is generally limited by dispersion or attenuation. When a link is limited by attenuation distance, the detector must respond to weak incoming signals and its sensitivity will determine link performance.

In an ideal PIN diode, each incident photon creates an electron-hole pair in the semiconductor lattice. This in turn sets one electron flowing in the external circuit. If the received light is weak, the generated current may not be strong enough to overcome noise inherent in the diode and receiver circuit. In such cases, it is desireable to increase the detector output before amplification by the receiver. Such gain is inherent in an avalanche photo diode or APD. A reverse bias provides several electron volts of energy increase to each liberated electron, providing inherent amplification of the received signal. Once again, such amplification is not linear with received levels.

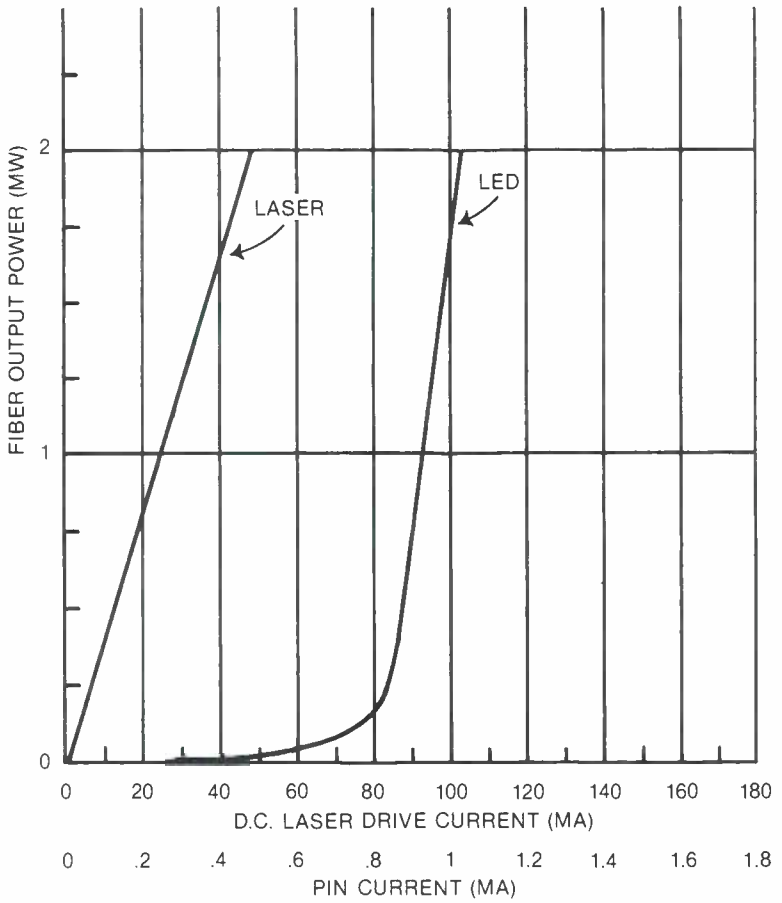


Fig. 6. Semiconductor laser turn-on characteristics.

VIDEO AND AUDIO TRANSMISSION TECHNIQUES

Modulation Techniques

In general there are three basic ways to modulate information onto an optical carrier. These are intensity modulation (light amplitude carries the information), frequency modulation (pulse speeds directly correspond to input signal levels), and digital pulse code modulation.

Intensity Modulation

Intensity Modulation (referred to as IM or AM) is the simplest form of modulation. Here an incoming signal such as video is used to directly drive an optical device. Thus, maximum amplitude of video being "white", would result in the most output light and bottom of sync the least. Unfortunately, as shown in Figs. 6 and 7, optical devices do not turn on in a linear fashion. As a result, linear distortions are introduced to the video signal when such modulation techniques are implemented. In addition, the signal-to-noise ratio of the signal is directly correlated to the optical power. As a result, attenuation in a system lowers signal to noise directly. Further, since most optical devices do not completely "turn off" (particularly lasers) there is always an optical noise floor present. For broadcast applications (EIA RS-250-B) such systems are not widely used.

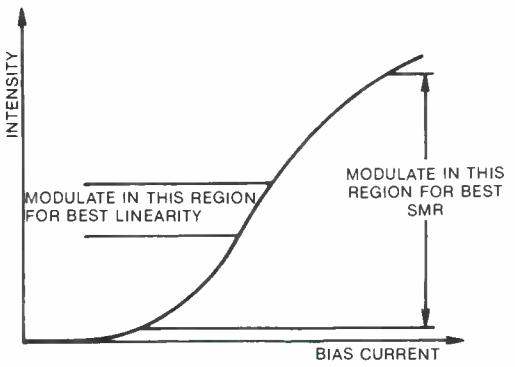


Fig. 7. Typical LED characteristics.

Frequency Modulation

Frequency modulation devices are often used to help overcome the limitations of optical devices. In general, an FM approach is more complicated and costly but removes the problems of signal quality from the optical domain to the electrical domain. Here an input signal (video or audio) is frequency modulated prior to driving an optical device. All problems related to required SNR or linearity are solved by proper design of the frequency modulator. The desired output being a square pulse train where the input signal information is carried in the time domain as pulse spacing. Audio information is generally contained as FM subcarriers added to the video; then the entire signal is remodulated to avoid non linearities in the devices.

PCM or Digital

As mentioned earlier, fiber optics is a technology intended to be operated in a pulsed mode, thus it is particularly suited to FM and digital approaches. In telephony applications, the relatively narrow bandwidth of a single voice channel can be digitized and multiplexed with thousands of other similar channels. Video on the other hand, is a much higher bandwidth signal and results in very high bit rates. In evaluating digital systems a user must keep in mind analog performance requirements. As a result, digital systems are generally evaluated end to end on the basis of the specific application. Two major factors affect digital systems performance: sampling rate and number of bits per sample. The Society of Motion Picture and Television Engineers (SMPTE) has done a very thorough job in correlating bits per sample (quantizing error) to equivalent signal to noise ratio. It is perhaps, worthwhile to provide a quick review.

In general, it has been shown that 8-bit sampling can provide excellent television pictures. This will generally result in bit rates (depending on sampling frequency) of up to 115 Mbits. However, this results in an equivalent signal-to-noise ratio of 56 dB. In general, most analog systems have allocations of performance to various portions of transmission that can require up to 67 db SNR. Unless the user can insure an entire digital transmission, higher sampling rates should be used. As a guide (again based on SMPTE digital publications), 9 bit sampling systems should be used where 60 dB SNR is required and 10 bit systems where 67 dB SNR is required. Such systems result in bit rates in excess of 150 Mbits per second.

Performance Requirements

In general, fiber optic transmission requirements must continue to meet the needs of existing transmission parameters. The EIA RS-250-B standard has served the industry well and continues to be the bench mark by which transmission systems are measured. It is a very comprehensive document but in general requires short haul systems (most fiber optic systems today) to deliver 67 DB SNR with 2% diff. gain and .5 degrees differential phase error. In applications for teleconferencing and CATV obviously lower specifications apply and cost-effective solutions exist for virtually all performance requirements.

Multiple Video Transmission

Because of the large information carrying capacity of fiber optic systems, they are frequently asked to send multiple video signals over a single optical fiber. Where required, there are several methods for accomplishing this. These are Wavelength Division Multiplexing (putting different wavelengths of light onto a single fiber), Frequency Division Multiplexing (putting multiple FM subcarriers through a single optical device), and Digital Multiplexing.

Wavelength Division Multiplexing

This multiplexing technique is primarily used to reduce the number of optical fibers required to meet a specific transmission requirement. Basically it requires two or more complete fiber optic transmission systems operating at different optical wavelengths. Utilizing a passive optical multiplexer (basically a prism) multiple optical wavelengths may be placed onto an optical fiber and then removed. Similar techniques can be used to accomplish bidirectional transmission. Several considerations are important in designing such systems.

First, adequate separation (measured in dB of each optical channel is required. Optical crosstalk between channels results in lowering the effec-

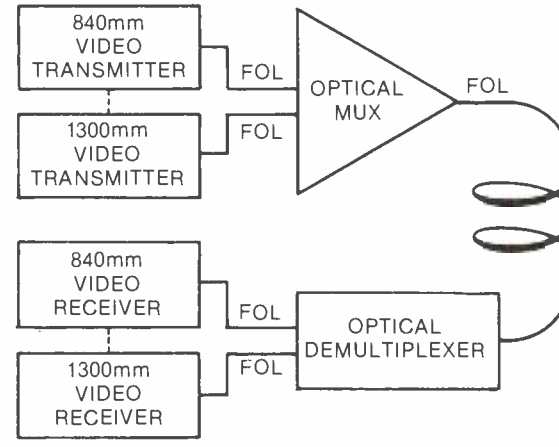


Fig. 8. Typical WDM configuration (FOL = fiber-optic link).

tive SNR of the link. Secondly, passive devices result in some optical attenuation when used (1-5 dB per device). As a result, effective transmission distances must be reduced when attempting to use WDM techniques. Lastly, most optical devices change output wavelength over temperature and the band pass of such WDM devices must be wide enough to accommodate the range. In general, fiber costs have dropped sufficiently that WDM is only cost effective when used to add capacity to existing installations. Furthermore, since optical separations are relatively poor, WDM techniques are only appropriate for FM and digital systems whose carrier-to-noise requirements are equivalent to or less than the WDM components.

Digital Multiplexing

As mentioned earlier, digital transmission rates for video are very high, particularly with regard to short haul requirements in an analog domain. However, even rates of 180 Mbits (243 for serial digital components) are less than current telephony rates. Serial transmission of 565 Mbits are now commonplace with demonstrations in the gigabit range occuring by numerous manufacturers. As a result such high speed transmission offers the promise of low cost high bandwidth channels. As these systems are proliferated it is increasingly obvious that multiple high quality video transmission will be most cost effective over fiber optics systems. In general, multiplexing applies equally to ancillary signals. Audio and data channels are similarly multiplexed together or with video using one or more of the above multiplexing techniques.

INSTALLATION CONSIDERATIONS

Installation of fiber optic systems is rapidly increasing. System design of each system requires numerous considerations, the following represents a guide to implementing a system.

Performance Requirements

First, the system engineer must determine what end to end performance requirements are needed. For video this can range from a very high performance entrance link to a low performance security camera. Determining performance requirements first can expedite equipment evaluation and insure the most cost-effective solution.

Once system performance of a link is determined, optical loss budgeting must occur. This is governed by the distance required and the manufacturer's specifications. In general, fiber optic systems specify an optical loss budget at a given wavelength. Subtracting from this number connector losses, splice losses, fiber losses, and future margins for additional splices and/or WDM components, will determine whether a particular system is acceptable and whether repeaters are required.

Optical loss affects the performance of a fiber optic system. Thus, it is worthwhile to minimize these wherever possible. In general, the optical loss of a link should always be measured to insure it meets calculations. There are basically two methods. First, an instrument called an Optical Time Domain Reflectometer (OTDR) is frequently used to measure attenuation or look for breaks in the fiber. It operates on the principle of sending a pulse of light and evaluating back scattered or reflected light in the time domain. This instrument provides a graphical representation of the fiber as a function of distance. It can literally pinpoint a break in a fiber to approximately a meter even over 10's of kilometers.

A simpler method is to use a simple optical meter and the system being installed. First, the user measures output power of the transmitter or launch power. This should be done with a patch cord to account for the first connector interface. Then, at the end of the fiber, received power is measured to insure it meets expectations. Once this is accomplished, the fiber optic system installation can be completed.

Frequency Division Multiplexing

This technique involves multiple FM modulators operating at different carrier frequencies and then summation of the signals. This is a widely used technique in coaxial cable distribution. Unfortunately, in optical systems the non-linearity of the optical devices results in large intermodulation distortions. As a result, wide spacing of carriers has been required in systems built to date. Further, insufficient experience has been gained regarding changes in device characteristcs with time that could result in long term increases in intermodulation distortions. This technique requires operation of the optical devices in an intensity modulation mode, which as discussed earlier, is not a desired application in fiber optics. This however, may turn out to be suitable for lower quality transmission requirements in the future such as CATV or teleconferencing.

Cable Specifications

In general, specifying cable for transmission applications is relatively easy. Step index fibers cost the same as higher performance multimode or single mode fibers but do not offer bandwidth. As a result, single mode or multimode fibers are

chosen. They are comparably priced and the selection criteria is based on other factors. Because multimode fibers are larger in core diameter they are easier to splice and connectorize. However, they have higher attenuation and lower bandwidth. As a result, in very long distance transmission (greater than approximately 25 Km), single mode is generally used. In shorter distances, (with the exception of telephony which is such a large user) standardization and large bandwidths lends itself to single mode) multimode cables are generally selected. In choosing a cable, numerous factors should be considered.

1. ***Attenuation.*** This will determine distance. It is specified in terms of dB/km. Thus if a cable has a specified attenuation of 3 dB/km, 4 kilometers will attenuate 12 dB of light. Remember attenuation is a function of wavelength. Short wavelength (800-900 nm) is used for short distance and vice versa.
2. ***Bandwidth.*** This only applies to multimode cables. It is generally specified in terms of MHz-km. Thus a cable specified as 800 MHz-km would have 80 MHz bandwidth end to end over 10 kilometers. There is a factor called concatenation which results in actual bandwidths greater than predicted by a specification. Cable manufacturers can provide additional specifications. In general the bandwidth requirements are only a consideration in FM and digital systems. With FM it is desirable to have sufficient bandwidth to pass the upper end of the FM modulators deviation including sidebands. Of course, in digital you must pass the bit rate.
3. ***Construction.*** Specific applications require specific types of cable. For example, for an aerial hang, UV resistant jackets are required. Similarly, for direct burial, rodent-proof jackets are required. In general, cables for every application and environment are available, however a user must insure he selects the correct cable for the application.

FIBER OPTIC SYSTEM PLANNING

In general, implementing a fiber optic system is in many ways similar to a coaxial system. After becoming familiar with connectors and cables, users find installations are actually simpler and easier. Several areas to consider are:

Loss Budgeting

THIS IS THE MOST IMPORTANT PART OF DESIGNING A FIBER OPTIC SYSTEM. In general, development of a loss budget is critical in installing a system that will meet the performance expectations of the user. It is a very simple process designed to insure that adequate light is received by the receiver to meet the performance requirements. First, it is important to learn to think of distance in dB. This is because of the number of variables that can attenuate light in a system. Light attenuation is a function of many factors thus manufacturers are loathe to guarantee a certain distance specification, but rather base their specifications on received light levels. Thus loss budgeting is a process of adding up all the known losses plus contingency and insuring the equipment being selected is compatible. Thus, such a process consists of:

Determining the launch power of the transmitter in dBm. From this value the following losses are subtracted.

a. Connector losses
b. Cable splice losses
c. Cable attenuation (This is dB/km and is wavelength dependent.)
d. Margin for future cable splices
e. Margin for future devices as couplers of multiplexers to be inserted. (This is generally important where future use of wavelength division multiplexing is anticipated.)

When all of the above values have been quantified in dB, they are simply added to obtain the worst loss likely to be incurred. This value is then subtracted from the launch power to determine the worst expected optical receive power expressed in dBm. This value is measured against manufacturer specifications to determine if system performance will be acceptable. If a specific system is weak on optical power, then light amplifiers can be employed to increase the total loss budget for a system.

Patching

Virtually all fiber optic connector manufacturers make "barrels" compatible with their connectors. Generally connectors which are used to terminate cables are "males"; barrels and device mount housings are "females". Bulkhead mount barrel connectors are used to construct patch panels for mass termination of fiber optic cables. Small, highly flexible patch cords are available to provide patching flexibility to large fiber optic installations. This is the generally used technique within common carriers to provide maximum flexibility. Virtually all connectors manufactured provide consistent performance even after hundreds of matings. As a general rule, after selecting a fiber optic connector, the manufacturer is the best source of information on such options.

Switching

No ideal optical switching solution has yet come out of the laboratory and found general acceptance. Optical switches are available which provide mechanical switching between fibers, however because of the mechanical nature of such a switch, and the extremely tight tolerances required, some optical losses are incurred.

Semiconductor switches are currently being evaluated as a preferred alternative. These devices promise switching directly analogous to semiconductor crosspoints used in today's electrical routing systems. Virtually all routing switching today is accomodated in the electrical domain by either decoding the fiber optic signals back to their baseband signals or more simply using an RF or Digital routing switcher. These latter approaches provide multiple passes without substantial signal degradation. Most major fiber optic systems manufacturers also provide compatible routing switcher equipment for large installations. When such installations are being considered, it becomes important to consider the electro-optic interfaces and insure compatibility between switching and transmission systems.

Cables

There are literally hundreds of types of fiber optic cables for virtually every application. The construction of the core glass or fiber is virtually identical in most cables (especially since there are only a few manufacturers of fiber), all of the variations result in differences in cable design. Cables come with many different characteristics, some of which are:

1. All dielectric construction
2. 1-144 fibers in cable
3. Suitable for direct burial with rodent proofings
4. Aerial hanging cable with U.V. resistant jackets
5. High moisture or underwater application
6. High pulling strength
7. Special cable for long vertical runs (glass does not support its own weight)
8. Hybrid cables with both copper and fiber capabilities

As a result it is important to work with a manufacturer in selecting a cable. Most installation problems result from cables being used in applications for which they were not designed. This problem is easily prevented by thorough discussions with cable and system suppliers.

In multiple fiber cables it is necessary to break out individual fibers with a "breakout kit". This is a simple junction technique generally done with a fusion splicer to break out individual fibers into individual cable for termination. Again, all cable suppliers provide simple solutions to such problems.

Installation

Installation of fiber cables is generally simpler and less costly than equivalent coaxial cables. Design of cables has reached the point where they have bending radii as small as an inch and can accept pulling loads of several hundred pounds. Because these cables are small and light for their information capacity, they come in very long lengths. As a general rule cables 2 km long are readily available with custom cables up to 5 km. Installation practices based on existing cable practices have been found quite acceptable. Again, working with a cable supplier can help point out the difference.

Connector Installation

Installation of fiber optic connectors has advanced to the point where it is a relatively simple process depending on the connector. Generally the installation of a connector consists of:

1. Cable preparation
2. Crimp or glueing of connector
3. Polishing
4. Final preparation

Specific installation instructions for a connector are available from all connector manufacturers. Generally, installation is accomplished with a connector kit available from the connector manufacturer. Once a cable is properly terminated, it is ready for connection to transmission equipment.

Test Equipment and Troubleshooting a Fiber Optic Link

There are many types of test equipment used in fiber optic systems evaluation and troubleshooting. Most of these pertain to ascertaining the optical performance of the link. Some of these equipment types are:

1. ***Optical Power Meter.*** Reads received optical power in dBm (preferably). Generally comes with connector adapters to permit direct connection to a fiber optic cable. These units are relatively inexpensive ($500-2000) and very easy to use. They are mandatory for any fiber optic user. Applications include verifying that received power matches manufacturers specifications, confirmation of calculated loss budgets, continuity verification; if no light is being received, the fiber may be broken.

2. ***Optical Time Domain Reflectometer.*** An instrument that measures the backscattered light down a fiber and based on its time after origination determines distance. These are used to precisely locate discontinuities in a fiber, evaluate the quality of splices and connections as well as characterize newly installed fibers. Such instruments provide a hard copy record of an individual fiber's characteristics which can be later remeasured to evaluate changes in performance. Generally this instrument is required by large volume users and installers. Priced in the $20,000 range, it is also available on a rental or service basis from many vendors.
3. ***Optical Attenuator.*** This is a variable attenuator capable of varying the amount of light through a fiber. It is generally used by equipment manufacturers to measure the range over which their receiver will operate. Fixed value versions are used in the field to "pad down" received light to meet manufacturers specifications.
4. ***Bandwidth Tester.*** This instrument is used to measure the bandwidth performance of individual fibers. Not required on single mode systems today and generally only needed by cable manufacturers to measure cable performance for grading.
5. ***Optical Spectrum Analyzer.*** Another rather expensive instrument used to quantify the spectral width of optical devices. Important for manufacturers of such devices but certainly not needed by a system installer or user.

As a general rule, we recommend a power meter as a mandatory tool for any use. It is inexpensive and easy to use and can provide useful information during installation. Again, before any receiver is connected a power meter should be used to verify received power is as expected.

Troubleshooting

There are many areas to look for problems if they occur, however the following procedures apply to virtually every case.

1. *Assume no or low received light level.* There is probably a squelch or alarm indication at receiver. First step is to check transmitter for launch light at appropriate level. If light out of transmitter is low then problem is in transmit card. If however, launch power is correct, then problem exists in fiber optic link.
2. *Verify received optical power level using a power meter.* If level is acceptable, then most likely problem is on the receive card. In some systems, it is possible that the transmitter can put out light with no modulation. Verify that receive card operates by direct connection to a transmitter, if not operating trouble shoot the receive card.
3. *In general, an OTDR is required at this point to measure performance of link and pinpoint trouble spots.* However, most problems (barring a backhoe digging up a cable) tend to occur very near the ends of cables. Patch cords get pulled on, connectors are bad, etc. Thus, the first place to look is the connections near the equipment before necessarily needing an OTDR. Failing this, an OTDR provides easy test of the link and will pinpoint the problem.

SUMMARY

In general, fiber optic systems and equipment have become very easy to use. The requisite test equipment is available and the technology has reached the point that newcomers can handle most installations. All vendors provide consulting service (generally free) and a large successful installed base of experience already exists.

REFERENCES

1. "Designers Guide to Fiber Optics" AMP Inc., Harrisburg, Pennsylvania. 1982.
2. P. Mountanos "How to Choose an Analog Video Fiber Optic System", Broadcast Engineering, June 1984.
3. "Digital Video" SMPTE publication, March 1977.

4.5

Aural Broadcast Studio Transmitter and Intercity Relay Service

John E. Leonard, Jr.
President
Gentner RF Products
San Jose, California

INTRODUCTION

The Federal Communications Commission (FCC) has defined an aural studio-to-transmitter link (STL) as a fixed station used to transmit the aural program material between a studio and transmitter of a broadcast station. Intercity relay service (ICR) is used for the transmission of aural programming between broadcast stations. In other words, an STL or ICR is a radio link used between two fixed points whose primary purpose is to carry program audio. In this chapter, STL and ICR will be used interchangeably, with emphasis on the STL application. The STL offers an alternative to the use of leased telephone circuits to the station with studio and transmitter at separate locations. The STL permits other signals to be carried in addition to the program material.

Currently, the radio links or microwave systems for this service use frequency modulation (FM) and operate in a band of channels at 950 MHz. Additional frequencies are available at 18 GHz, but at the time of the chapter's preparation the FCC reported that it had not received a single application for a license at these frequencies. For this reason, while 18 GHz will not be overlooked, the 950 MHz band will receive the major attention below.

In this chapter the current FCC requirements and procedures of licensing, as well as the available channels will be covered. Since Rules are subject to change, the information here should be checked with a current set of Rules. Typical equipment, its configuration and uses, and propagation characteristics are presented. At the outset, a review of the reasons for selecting the STL are presented.

STL SELECTION

The reasons for the selection of an aural STL in many cases are economic. With the deregulation of the telephone industry, the broadcasting industry is seeing major increases in the cost of program-grade circuits. It is anticipated that these costs will continue to rise in the future. There are a number of methods for assessing the economic viability of an STL. One of the simplest is to take the cost of the STL system and divide it by the monthly charges of the leased special access private lines it will replace. The resultant number is the number of months required to pay for an STL system with the money that would have gone for special access private line service. As an example, if the program circuits for a station are $475.00 and an STL system to do the same job will cost $8500.00, the payback period, without considering interest, would be 17.89 months, or just under one and one-half years. Even without adding the cost of financing the STL system or the loss of interest income by not using this $8500.00 for other investments, it can be seen that this would be a good investment for the station.

Another compelling reason for STL selection is the infeasibility of private line facilities. Constructing new lines in an area where there are no utilities and, possibly, no right-of-ways, can be very expensive. Moreover, in some parts of the U.S. program quality circuits are simply not available.

The quality of service is also a factor, as is having the interconnecting circuits totally under station control. With quality, the transient response characteristics of the typical STL system, most noticeably at lower audio frequencies, is a major contributing factor. For many users of STL systems, the factor of the reliability of the STL is of importance.

In summary, the factors favoring the selection an STL system are:

- Quality of Program Transmission
- Higher Reliability
- Total Control of Station Facilities
- Financial Consideration or Savings

FCC REQUIREMENTS

Aural STL and ICR service is controlled by FCC Rules and Regulations Part 74 Subpart E. No attempt will be made in this Chapter to fully reproduce these Rules, but important segments in effect at the time of writing are included. Under these, only licensed broadcast stations may hold an STL/ICR license. It is to be noted that this service is for AM and FM stations, with television aural only licensed on a secondary basis.

Available Frequencies

In considering the available frequencies or channels, some history may help in understanding the current situation for this service. The STL/ICR service dates from the early 1950's when, in 1953, there were some 47 licenses authorized. In this era the service had the spectrum from 890 MHz to 952 MHz available for all broadcast stations. Until 1961, TV stations had 41 channels in the 890-911 MHz band, 29 channels for AM stations in the 925-940 MHz band, and there were 23 channels in 940-952 MHz for FM stations. Only the 940-952 MHz spectrum was exclusively broadcast, all others were assigned on a shared or non-interference secondary basis. In 1961 the FCC altered the service such that separation by service was eliminated and the band was set as 942-952 MHz. Then in 1968 the Commission began a rule making that resulted in a reduction of the exclusive band to 947-952 MHz and 9 channels. 942-947 MHz was placed in a "reserved" status, with licenses issued on a secondary basis. The next change to available spectrum on an exclusive basis came late in 1984 when 944 to 947 was returned to STL/ICR service and increased the available channels to 15. New additional spectrum was allocated in 1983 at 18 GHz, but placed in a "hold" mode, until a rechannelization occurred in mid-1984. The 18 GHz channels are not available on an exclusive basis but rather on a co-primary basis with stations in the Point-to-Point Microwave Service operating under Part 21 of the FCC Rules and Regulations and stations in Private-Operational Fixed Service operating under Part 94. On October 31, 1985, the Commission revised the channelization and bandwidth criteria of the aural STL band, 944-952 MHz (MM Docket No. 85-36). The new rules "split" the existing 500 kHz channels into 25 kHz "segments" which can be "stacked" to form channels of varying bandwidths. The Commission also adopted RF bandwidth "criteria" for aural STL operation: 300 kHz for FM stereo stations using subcarriers, 200 kHz for AM stations and the existing 500 kHz bandwidth as a "wideband" criterion.

The fifteen 950 MHz channels available are:

MHz		
944.5	947.0	949.5
945.0	947.5	950.0
945.5	948.0	950.5
946.0	948.5	951.0
946.5	949.0	951.5

Each of these channels is 500 kHz wide, with the use of frequency modulation (FM) required. There is no transmitter power output restriction other than that necessary to render satisfactory service. And, no type approval or acceptance is necessary for the equipment used at these frequencies. These frequencies are for STL and ICR service, and are assigned for a specific path or hop, that is from one point to another. At 18 GHz two spectrum segments are available, 18.64-18.70 GHz and 18.88-18.94 GHz. These two segments are divided into 12 paired channels, each 5 MHz wide. A paired channel has one transmit channel and one receive channel for full duplex service.

The specific frequencies are:

Transmit (or receive)

MHz		
18,642.5	18,662.5	18,682.5
18,647.5	18,667.5	18,687.5
18,652.5	18,672.5	18,692.5
18,657.5	18,677.5	18,697.5

Receive (or transmit)

MHz		
18,882.5	18,902.5	18,922.5
18,887.5	18,907.5	18,927.5
18,892.5	18,912.5	18,932.5
18,897.5	18,917.5	18,937.5

A two-way system may be used or an application can be made for only one of the two frequencies making up that paired channel. These frequencies require that they be coordinated, with the users of them governed by Parts 21 and 94, and such coordination should use the procedures required in Parts 21 and 94. It is suggested that if use of these frequencies is being considered that a consulting engineer or others familiar with all the requirements be retained to assist. Section 1, Chapter 4 of this *Handbook* touches on these services. Transmitter power output at 18 GHz is limited to 10 watts and type acceptance of the transmitter is required. It should be noted that at 18 GHz, digital modulation, in addition to frequency modulation (FM), is permitted.

The frequency information presented above is for the continental U.S. and other states and possessions governed by the FCC. In Puerto Rico 942.5, 943.0, 943.5, and 944.0 MHz are available for licensing on a primary basis. Likewise, stations operating in the 942-944 MHz as of November 21, 1984 may continue to operate on a co-equal primary basis. It should be noted that in the Report and Order released January 18, 1985 (FCC 84-557) regarding aural STL spectrum, the Commission stated it would consider on a case-by-case basis a possible waiver for use of frequencies in the 2 GHz region in areas where 944-952 MHz operation is not possible because of the lack of sufficient spectrum.

One additional type of permissable service deserves mention. This is the aural broadcast microwave booster station. The booster station is a station that must receive and amplify the signals of the originating station and re-transmit them on the same frequency without significantly altering them in any way. With a booster, the licensee is responsible for correcting any condition of interference that results from the radiation of radio frequency energy outside the assigned channel. In essence, these Rules permit a repeater station to be created that must function as an on-frequency repeater, or what might be called a beam bender. A license is required for a booster station, and it can operate in conjunction with any STL/ICR system.

Frequency Selection

As noted above, frequency coordination is specifically required for use of the 18 GHz STL/ICR channels. At 950 MHz the procedure most commonly used is outlined in Section 1, Chapter 3, "Frequency Coordination." Specifically, Aural STL considerations are addressed beginning on Page 1.3-57. In essence, the procedure is to work with a local frequency coordinating committee to find a channel that can be used between the two points involved. As indicated above, consulting engineers or other service firms may also assist in this process. The desired end result is a channel that can be used for the required service and that does not receive interference from another station, or cause interference to any station already licensed.

With only fifteen channels available at 950 MHz and over 10,000 radio (AM & FM) stations in the country, great care must be taken in most cities to successfully use an STL or ICR system. This involves correct engineering of the system at the beginning and proper maintenance of it over time.

One technique used in many areas to make multiple use of channels is the cross polarization of antenna systems. With one system operating with horizontal polarization and the other vertically polarized, some 20 dB isolation is obtained in practice. Differences in the vectors of the actual paths and topography will also permit channel re-use or sharing.

Antenna Requirements

The Rules and Regulations place minimum directive requirements on the STL/ICR antenna at 950 MHz and both transmitting and receiving antenna minimums at 18 GHz. At 950 MHz, the current requirement is that a directional antenna is required. No specific parameters are placed on this antenna, but the requirement of narrower beamwidths and reduced sidelobe radiation in congested areas or to resolve an interference problem is contained in the Rules. See Section 1, Chapter 3, page 1.3-58, paragraph 6 for comments developed by one frequency coordinating committee.

At 18 GHz the requirements of the Rules and Regulations are more specific. First, the directivity requirement applies to both transmit and receive antennas. There is first a division based upon whether frequency congestion exists in the area the STL will operate. Ignoring this point for the moment, a minimum gain of 38 dB over an isotropic antenna is required for all antennas. The values presented in the two divisions below represent the suppression required in the horizontal plane without regard for the polarization plane of intended operation.

For areas not requiring frequency coordination, and without frequency congestion, the following "Standard B" applies:

Angle from Center of Main Lobe	Minimum Radiation Suppression (dB)
5 degrees up to, not including 10 degrees	20
10 degrees up to, not including 15 degrees	24
15 degrees up to, not including 20 degrees	28
20 degrees up to, not including 30 degrees	32
30 degrees up to, not including 100 degree	35
100 degrees up to, including 180 degrees	36

It must be noted that the Rules give the Commission the right to require replacement, at the licensee's expense, of a Standard B antenna with a Standard A antenna if there is an interference problem or the likelihood of interference.

The Standard A antenna requirements apply to areas with frequency congestion and as noted above. The "Standard A" is:

Angle from Center of Main Lobe	Minimum Radiation Suppression (dB)
5 degrees up to, not including 10 degrees	25
10 degrees up to, not including 15 degrees	29
15 degrees up to, not including 20 degrees	33
20 degrees up to, not including 30 degrees	36
30 degrees up to, not including 100 degrees	42
100 degrees up to, including 180 degrees	55

Licensing

To license an aural STL/ICR, the filing of a FCC Form 313 is required. It is noted that the Rules and Regulations at this writing permit operation of an STL/ICR transmitter for up to 720 hours without a license. This is to permit operation while an application is being processed. As a normal procedure, a Special Temporary Authorization will not be issued for this service. Completion of this Form is aided by the companion instructions.

STL EQUIPMENT

At 950 MHz there are currently two basic configurations of STL/ICR equipment being commercially manufactured for this service. These are:

A. Systems utilizing conventional inputs and outputs, but with two types:
   - Monaural
   - Composite

B. Systems utilizing conventional inputs and RF-type outputs.

An STL/ICR system is made up of a transmitter and receiver. In the 950 MHz service they must use frequency modulation (FM). At 18 GHz, FM or digital modulation techniques are permitted. Fig. 3 and 4 present block diagrams of several different systems.

Monaural STL/ICR Systems

As the name implies, this type of system accommodates monaural program audio, that is, it has a program or baseband frequency response in the range of 50 Hz to 15 kHz. All STL systems available today have the capability of relaying more information than the program audio. As will be seen below in more detail, an STL transmitter, much like an FM broadcast transmitter, will convey programming and subcarriers with a variety of information. Most systems available have the capability of several subcarriers. One configuration uses two monaural systems for stereo. Most monaural systems utilize pre-emphasis in the transmitter and de-emphasis in the receiver to obtain the FM benefit. This must be taken into consideration when setting audio levels.

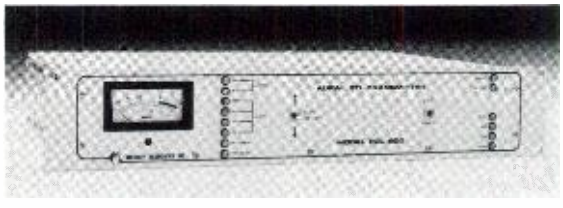


Fig. 1. Typical STL transmitter. (Courtesy Moseley Associates, Inc.)

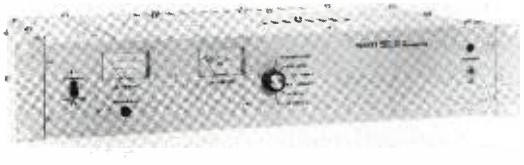


Fig. 2. Typical STL receiver. (Courtesy Marti Electronics, Inc.)

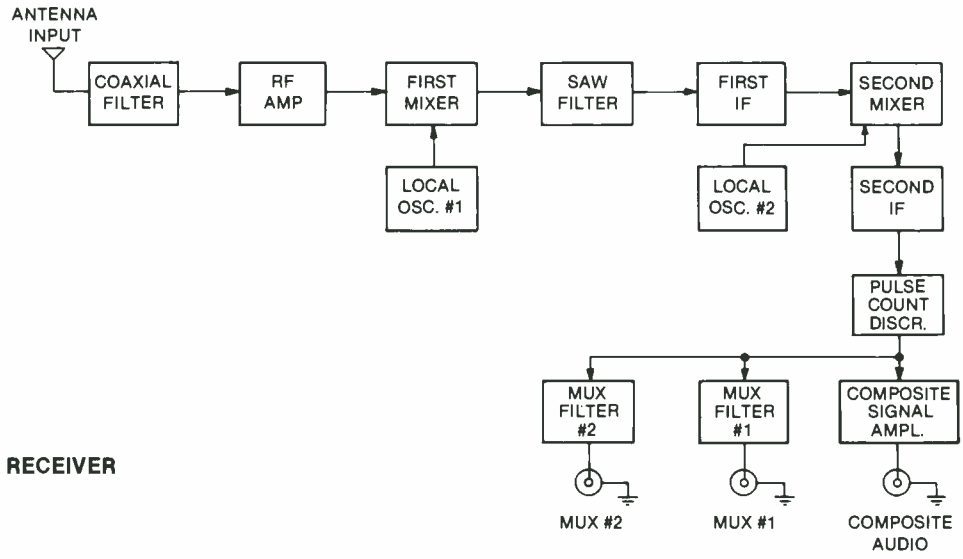


Fig. 3. Block diagram—composite STL system transmitter and receiver. (Courtesy Broadcast Engineering)

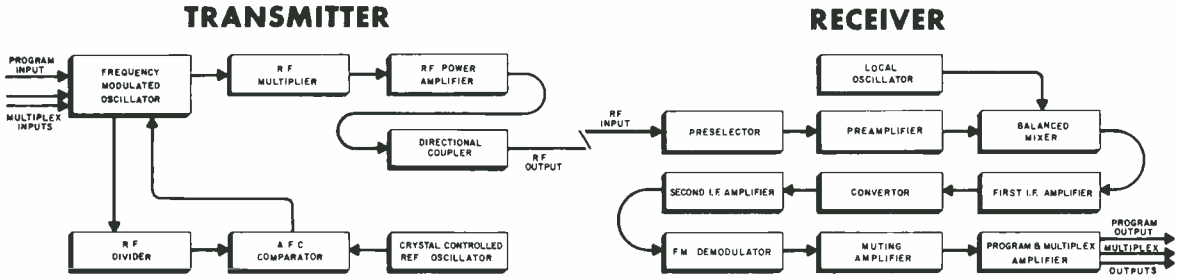


Fig. 4. Block diagram—monaural STL system transmitter and receiver. (Courtesy Broadcast Engineering)

Composite STL/ICR Systems

The composite system conveys the FM stereo waveform on one STL carrier. With this system, the baseband or program input and output has a frequency response of 20 Hz to 75 kHz, or slightly above. Some manufacturers offer composite systems with response through approximately 100 kHz. A number of subcarriers can be conveyed above the programming present in the baseband. As this is a wide band system, it does not utilize pre-emphasis or de-emphasis.

Transmitter

While there are differences between manufacturers on the exact techniques of transmitter design, there is a common theme. The input circuitry functions to provide proper level and impedance matching as well as any filtering necessary. As a general rule, STL transmitters do not include any audio processing. The modulator operates at a frequency less than the output frequency. For frequency control the use of phase-locked loops is common, referenced to a crystal oscillator. The transmitters manufactured today easily exceed the frequency tolerance required in the Rules. The modulator or modulated oscillator is then multiplied, mixed with another oscillator, or IF modulated to reach the final operating frequency. A final RF power amplifier stage then serves as the output. STL transmitters typically have an RF power output in the 7 to 20 watt range. Many contain a reflectometer permitting the measurement of forward and reflected power.

There are two basic types of STL transmitters, monaural and composite. With some manufacturers the differences lie more with the filtering in the receiver than in differences in the transmitter. This filtering is used to separate program audio from subcarriers. Some monaural trans-

mitters contain a 15 kHz low-pass filter to prevent audio excursions into the spectrum occupied by subcarriers. Composite transmitters have typically not contained filtering.

Receiver

As with the transmitters, there are common areas in STL receivers. Most employ several intermediate frequency (IF) amplifier stages. Double and triple conversion receivers are common. It is the receiver in the STL system that is the principal determinate of overall performance. As can be seen from the prior discussion on available frequencies, only 15 channels available at 950 MHz, extensive use of channel sharing has become the norm in many areas. It is the receiver that must perform to the utmost. Use of adjustable RF input attenuators, advanced techniques for obtaining selectivity such as surface acoustic filters (SAW), and high performance demodulation techniques are employed in many STL receivers. It is in two areas that the major differences between monaural and composite receivers will be found. These are the IF selectivity and the audio sections. In the audio sections, the filtering and amplification differs with the frequency responses necessary. With a monaural receiver, program audio is typically passed through a 15 kHz low-pass filter. This rejects any subcarriers that may be in use on the system. These subcarriers are in the 26 kHz to 100 kHz range. With a composite receiver, the program or baseband response is through 75 kHz, or as an alternative with some manufacturers through 100 kHz. Subcarriers are above this and normally have not been above 185 kHz.

STL Maintenance

With the advantages of the STL come responsibilities that include maintenance of the equipment. Routine maintenance is an important part of insuring proper and trouble-free operation of the system. Depending upon the equipment selected, this maintenance can be the simple observation of operating parameters and an occasional cleaning dictated by the environment of the transmitter and receiver. As with most electronic equipment, heat, or excess heat, is the major concern.

Test equipment should be kept at hand and in working order to take care of a failure if it should occur. Test equipment requirements are determined by the equipment in use, but a volt-ohm meter (VTVM or DVM) is the basic measurement equipment needed for observation of dc operating parameters, including power supplies, a principal source of failures. Should the transmitter not have a built-in VSWR bridge, a directional wattmeter will prove useful. Such an inline wattmeter is helpful for locating transmission line and connector problems. An oscilloscope is needed for audio and similar troubleshooting. For more information on audio testing please see Section 7, Chapter 9 of this *Handbook*. A frequency counter is needed for verification of operating frequency, but can be supplemented by a frequency measuring service. One item of test equipment that is viewed by some as mandatory is an RF spectrum analyzer. While it may be necessary in making certain types of repairs, it is not needed for satisfactory daily operation on an STL. On those occasions where a spectrum analyzer is required, one may be rented or borrowed.

STL EQUIPMENT CONFIGURATIONS

There are a multitude of ways that STL systems can be used to solve the interconnection requirements of the typical aural broadcast station. This section will explore various configurations. To enlarge or enhance the capabilities of an STL system, subcarriers are multiplexed on the carrier. This is the same process as multiplexing an SCA on an FM broadcast transmitter. Please see Section 3, Chapter 4 for a thorough presentation on the multiplexing of subcarriers on an FM carrier. The information presented there is directly applicable to the STL system, as to the characteristics of a frequency modulated carrier conveying subcarriers. In STL systems, frequency modulated subcarriers have been the most commonly used modulation technique. Amplitude modulated subcarriers have potential application but have not received wide use.

For the following sections, only the use of FM subcarriers will be discussed. The modulation technique used for the subcarrier determines the number of subcarriers possible and their frequency. Consideration must be given to the radio frequency bandwidth of the carrier in selecting the uppermost subcarrier frequency. STL channels are assigned a bandwidth of 500 kHz. To comply with bandwidth requirements, manufacturers use peak deviations of 40 kHz to 60 kHz and recommend the highest subcarrier center frequency to be 185 kHz.

Monaural System

The monaural STL is used as implied by its name, to relay the monaural programming for an AM or FM station. Fig. 5 shows the monaural system. This system has the capability of conveying two subcarriers. These subcarriers can be put to many uses, usually carrying the command information from broadcast transmitter remote control system and feeding secondary audio, such

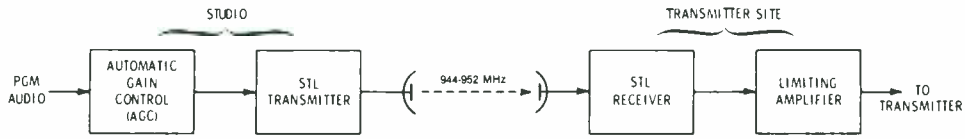


Fig. 5. Block diagram—monaural STL system, overview. Note portion of audio processing equipment. (Courtesy Broadcast Engineering)

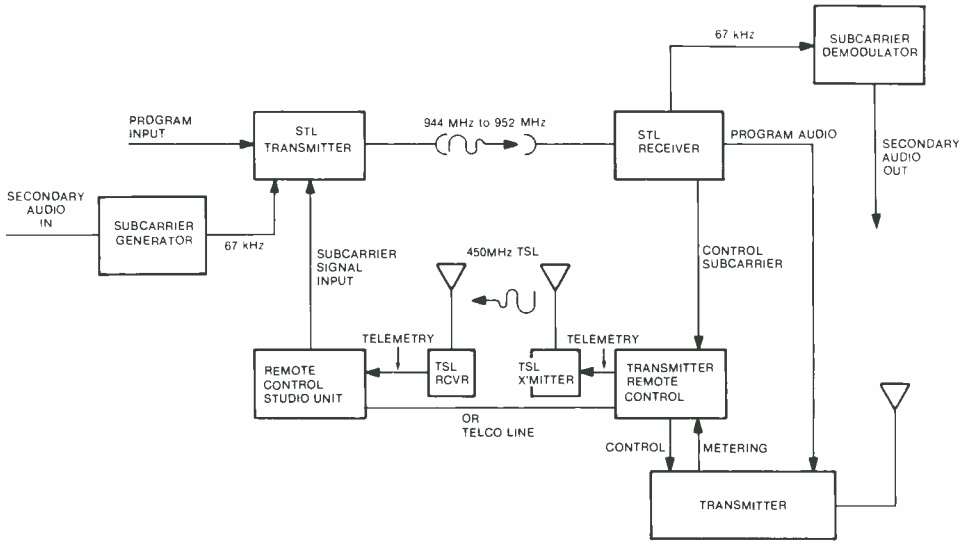


Fig. 6. Block diagram - monaural STL system, depicting use of subcarriers for command information of remote control system and second subcarrier for additional audio or other information feed. (Courtesy Broadcast Engineering)

as subsidiary program audio, data or intercom audio.

The subcarrier frequency used for the first subcarrier is in the 20 kHz to 30 kHz region, and the second subcarrier between 40 kHz to 70 kHz.

In Fig. 6, the first subcarrier is used to carry the command information for the remote control system to the transmitter site. For this remote control system, an SCA channel on the broadcast signal is then used to return the metering information. This would be representative of an STL system for FM use. The second subcarrier is carrying secondary audio, which in this example could be the SCA programming.

In using the monaural STL system it is important to verify if pre-emphasis and de-emphasis are employed. If this is the case, the same precautions that would be taken with an FM broadcast transmitter must be taken to prevent over-modulation from occurring. This is typically done by reducing the audio level feed to the STL transmitter by 10 dB, or placing all transmitter audio processing at the input of the STL rather than the input of the transmitter.

Stereo STL Systems

For stereo applications, there are three types of systems in use. These are:

- Dual Monaural
- Composite
- RF Output

Dual STL

The dual STL configuration consists of two monaural systems. Both systems are established on RF operating frequencies that enable them to operate within one 500 kHz STL channel. Given a channel center frequency of 950.0 MHz, with a dual system one system may operate on 950.125 MHz and the other on 949.875 MHz. This represents an offset from channel center of 125 kHz.

Fig. 7 depicts a possible dual STL configuration. This block diagram shows two transmitting antennas; however a transmitter combiner can be used to couple the two transmitters to a single antenna. A transmitter-to-transmitter isolation of at least 70 dB is desirable (see Section 1, Chapter 3, page 1.3-56).

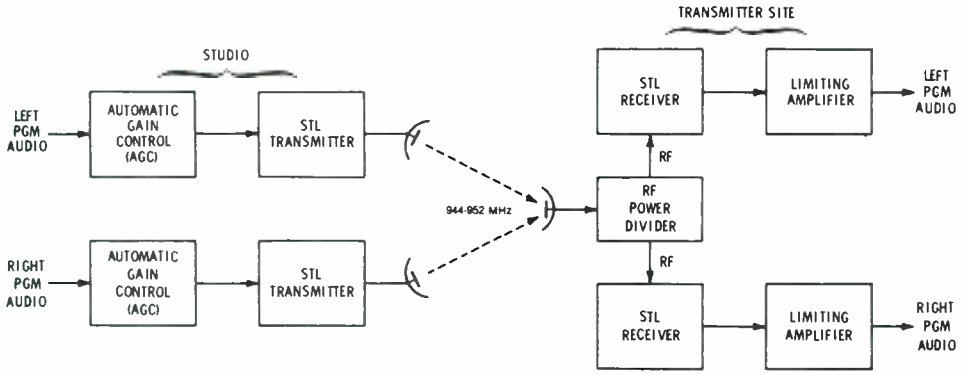


Fig. 7. Block diagram - dual Stereo STL configuration. Separate transmitting antennas are shown, with an RF power divider used to permit a single receiver antenna. (Courtesy Broadcast Engineering)

Because of the differences in STL transmitters, it is suggested that the manufacturer of the system be contacted for recommendations. A ferrite transmitter combiner is best suited for this use, because of the isolation provided between transmitters and the transmitter-to-antenna isolation. The subcarrier capability of most dual systems is that of two monaural systems. Because the dual STL consists of two monaural STLs, it permits switching to monaural transmission in the event of failure in one channel.

Composite STL

The composite STL system is designed to convey the FM stereo waveform on a single carrier. That is, the complete composite baseband that makes up the stereo signal. Attention is directed to Section 3, Chapter 4 for a complete definition of composite baseband, and specifically to Fig. 1 on page 3.4-115. The program or baseband frequency response of most composite STL systems commercially produced have the capability of accommodating, with acceptable phase and amplitude characteristics, frequencies through 75 kHz. This permits the composite STL to convey the stereophonic waveform and one subcarrier from the studio to the transmitter. Some STL manufacturers offer expansion of this response to 100 kHz permitting the system to convey stereo and two or more subcarriers.

The advantages of the composite system are that only one RF carrier is used to transmit stereo, and the stereo generation equipment can be located at the studio. This single site location of stereo generator and all associated audio processing equipment can simplify servicing and audio set up. Although some feel that the sound of a composite system is superior because of the elimination of additional audio sections, pre and de-emphasis, and filtering found in the monaural systems that make up the dual configuration, there is disagreement. Selection of a dual or composite component system should be based on a careful review of equipment specifications and costs in light of station requirements. Discussions with users of both types of systems may also be useful.

The composite system can convey additional subcarriers above the program or baseband information which makes bandwidth excessive. Fig. 8 presents a typical configuration. In this configuration one subcarrier is used for remote control command information and the other for secondary audio. Except for the specific subcarrier frequencies employed, the configuration for these subcarriers is identical to that shown for the monaural system.

AM stereo must be mentioned in regard to the composite STL system. Due to the nature of AM stereo (see Section 3, Chapter 2 for specific AM stereo information) a composite STL cannot be used for direct transmission of AM stereo. An RF output system, as described below for FM, could perform in the manner of a composite system. This leaves the dual configuration above or use of a composite configuration as shown in Fig. 9 for AM stereo applications.

RF Output System

Fig. 10 shows a system, where the transmitter is a conventional composite transmitter as described above, but the receiver is unique. This receiver functions as an FM exciter. The receiver output can be used to directly drive the IPA stage of the FM broadcast transmitter. As the block diagram shows, this receiver uses a phase-locked loop (PLL) that is tied to a TXO reference oscillator for the frequency control. This reference is used as the last conversion oscillator. At this writing the FCC is licensing this approach on a temporary authorization basis only. The system represents a unique approach, but system engi-

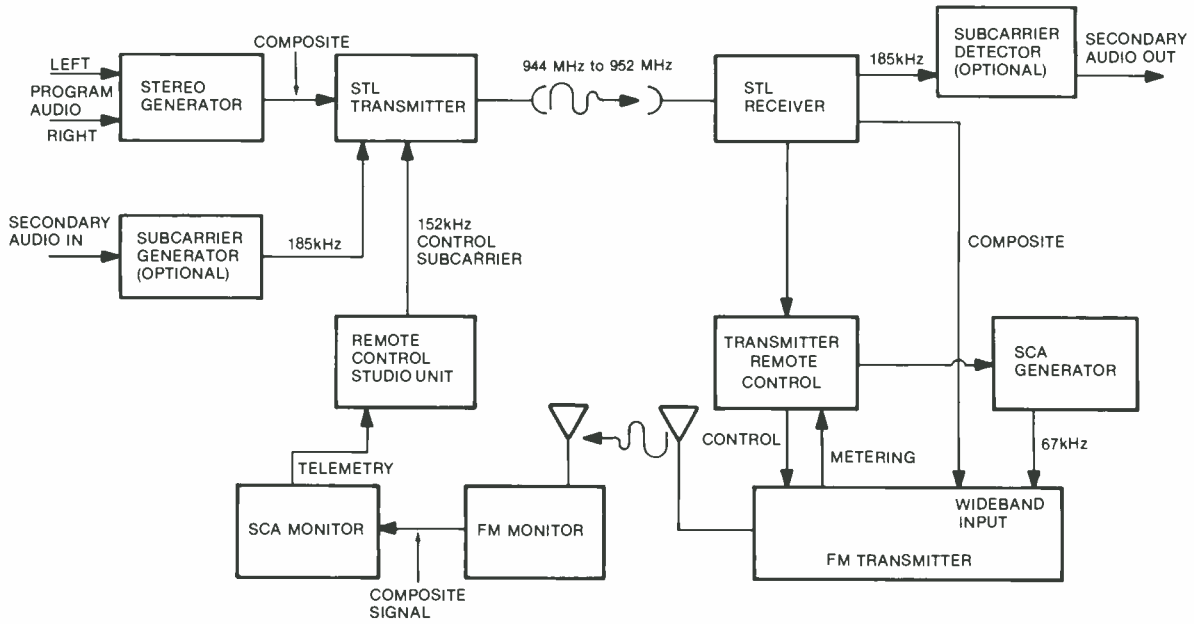


Fig. 8. Block diagram - composite Stereo STL configuration. While this depicts an SCA generator at the transmitter, it is shown for the return of metering information from the transmitter remote control system. An SCA generator operating at 67 kHz could be located at the studio and directly transmitted by the FM transmitter. (Courtesy Broadcast Engineering)

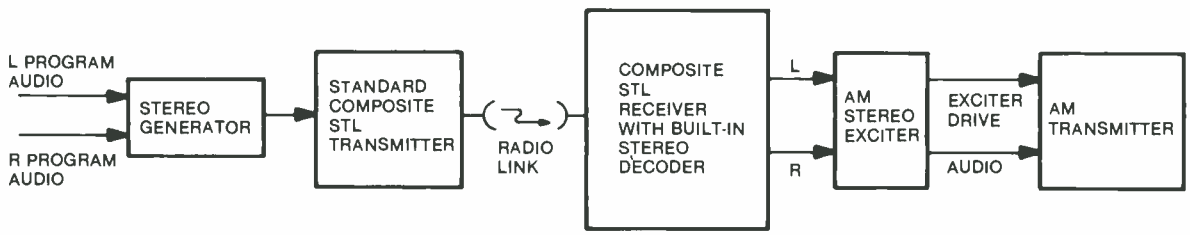


Fig. 9. A basic AM stereo STL configuration utilizing the FM composite STL. By converting the left and right audio channels to the FM composite waveform and then decoding them at the transmitter site, the FM stereo system is used as a multiplex scheme. (Courtesy Broadcast Engineering)

neering requirements go beyond the scope of this Chapter and consultation with the manufacturer is recommended if use of this system configuration is considered.

SYSTEM PLANNING

In the implementation of an STL or ICR system the most important thing to insure reliable and correct operation is the planning that is done at the start of the project. As stated in the introduction to this chapter, major attention will be given to the 950 MHz band. If 18 GHz operation is being considered the reader is referred to Section 4, Chapter 2, "Microwave Engineering for the Broadcaster" for information on path studies and considerations. While the information presented below can be applied to 18 GHz, it is directed mainly to the lower band. To evaluate a potential path the services of a consulting engineer may be employed or the user should perform an evaluation using the information presented below.

Path Evaluation

When planning the STL, the first point of consideration is the ability of a system to operate between the studio and the transmitter site: an acceptable path must be available for the system to function. This normally is interpreted to mean that a clear line of sight must exist between the two sites. If it is found that a line of sight does not exist between the studio and transmitter site, a repeater station may have to be used or the use

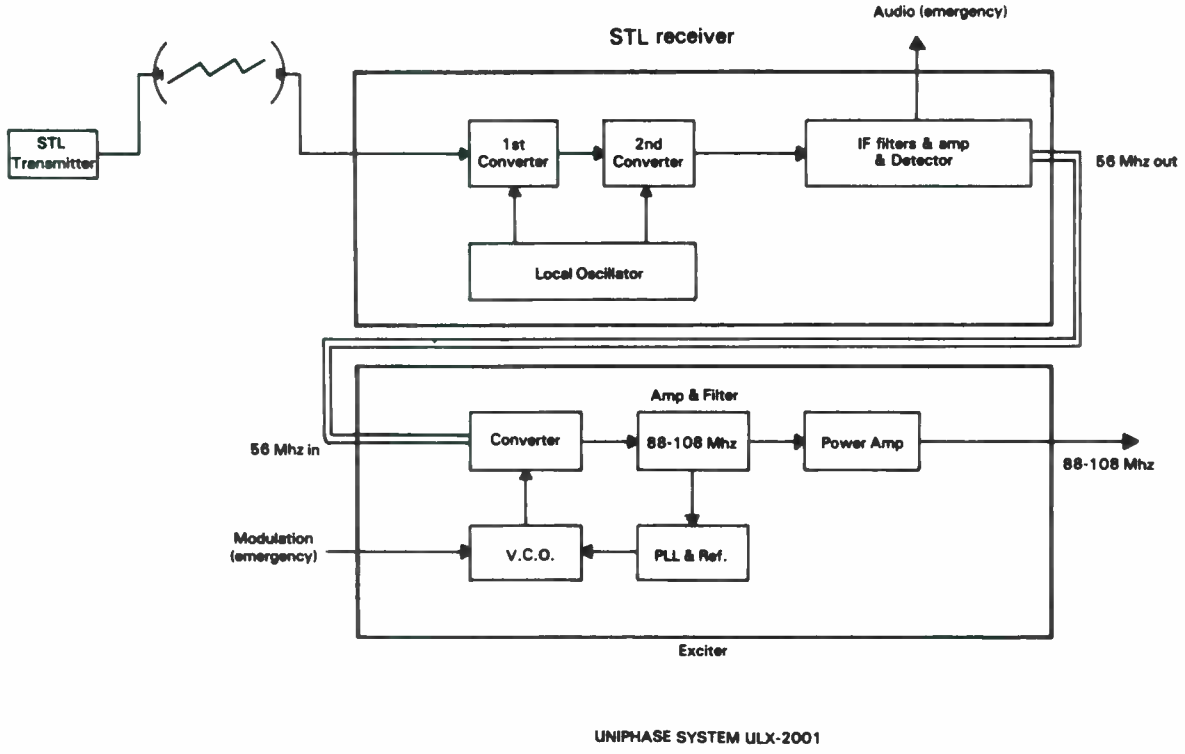


Fig. 10. Block diagram—RF output STL system. Micro Controls ULX-2001 system. (Courtesy Broadcast Engineering)

of an STL abandoned. While unusual propagation conditions can result in the operation of an STL system over a path that is blocked, it cannot be considered as being reliable over time. Exceptions to this are paths of short length over terrain that will not change. In this case, "short" means a distance of a few miles or less. When considering such a path, the opinion and recommendation of an engineer experienced in path evaluation at these frequencies should be obtained or an in-place test conducted.

Path Profile

To begin the evaluation, topographic maps showing the studio and transmitter locations and all terrain between these points are needed. After locating the two sites, a straight line is drawn on the map between these two points. From this information a chart is prepared that is a profile of the path on graph paper. The end result will look much like Fig. 11. The particular graph paper must be the type used for these purposes, and it can be obtained from engineering supply firms or from some equipment manufacturers. This graph paper reflects the curvature of the earth in a given way, as discussed below, and is referred to as K factor.

Following completion of the profile, the available heights above ground at each end of the path should be drawn on the graph. A straight line is then drawn between these two points to represent the center of radiation between the STL transmitting antenna and STL receiving antenna. For required antenna heights, see the discussion below on Fresnel zones.

K Factor

The relative curvature of the surface of the earth and the relation of propagation of an STL signal along that surface are considered in the creation of a K factor. The STL signal must be viewed as radiating in a straight line. Changes in temperature and water vapor cause the index of refraction to change. This can cause the signal path to curve toward the surface. The result is as if the earth had been "flattened" by increasing the radius by a certain amount (the K-factor). See also Section 4, Chapter 2, "Microwave Engineering for the Broadcaster," page 4.2-61 of this *Handbook*.

For this use the norm is to either use a K factor equal to the earth's radius (K = 1.0) or one that views the earth as slightly flatter (K = 1.33 or sometimes written as 4/3). When graph paper is produced using these factors they are referred to as true earth graph paper, where K = 1.0 and 4/3 graph paper, where K = 1.33.

The true earth paper can be viewed as being a pessimistic presentation with the 4/3 paper being optimistic. That is that the 4/3 paper antici-

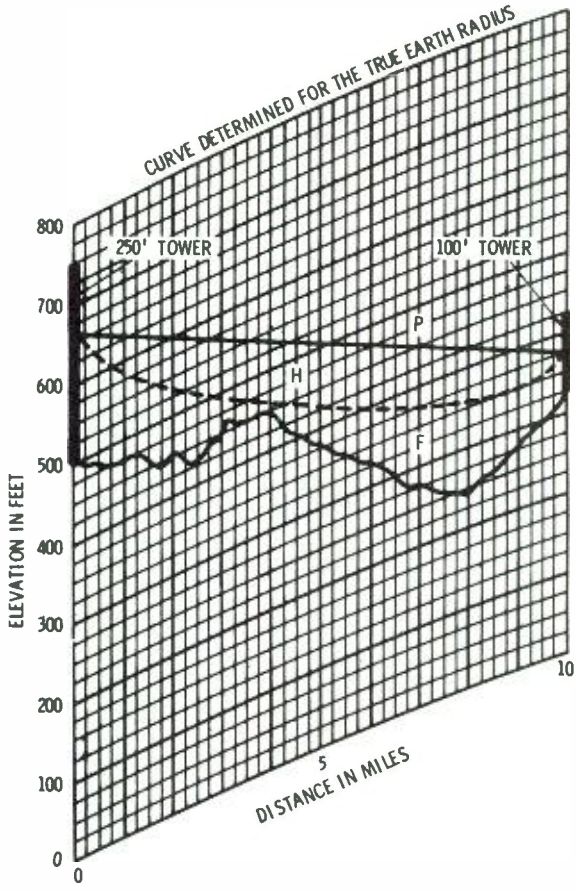


Fig. 11. Typical STL path profile drawn on true earth (K = 1.0) graph paper. P represents the center of radiation between transmit and receive antennas. The dotted line F depicts 0.6 First Fresnel zone. (Courtesy Broadcast Engineering)

pates that some positive refraction of the signal will occur.

Fresnel Zones

The Fresnel-Kirchoff theory was developed to explain the diffraction of light as obstructed by a diaphragm and the effects of transmission through an aperture of various characteristics. Light is an RF waveform of a high frequency, and thus these theories can be applied for microwave and STL purposes. As it will be used here, Fresnel zones can be viewed as various zones about the center of radiation, with the odd numbered zones possibly being additive and the even numbered being out-of-phase, and thus could be subtractive. It is the first fresnel zone that is of interest, and then only 60% (0.6) of that zone as it contains the energy that must be recovered.

All of this produces a formula that can be used to calculate the clearance needed above possible obstructions in an STL path. In fact, if viewed from the end, remember that the number produced is a radius from the center of radiation, and thus can be used to check clearance by objects that may be to either side, above or below the path center, such as a building.
This formula is:

$$H \text{ or } FR = 1316 \sqrt{\frac{d_1\, d_2}{f\,(d_1 + d_2)}}$$

In Fig. 13. note that d_1 is the distance from one end of the path to a possible obstruction in miles,

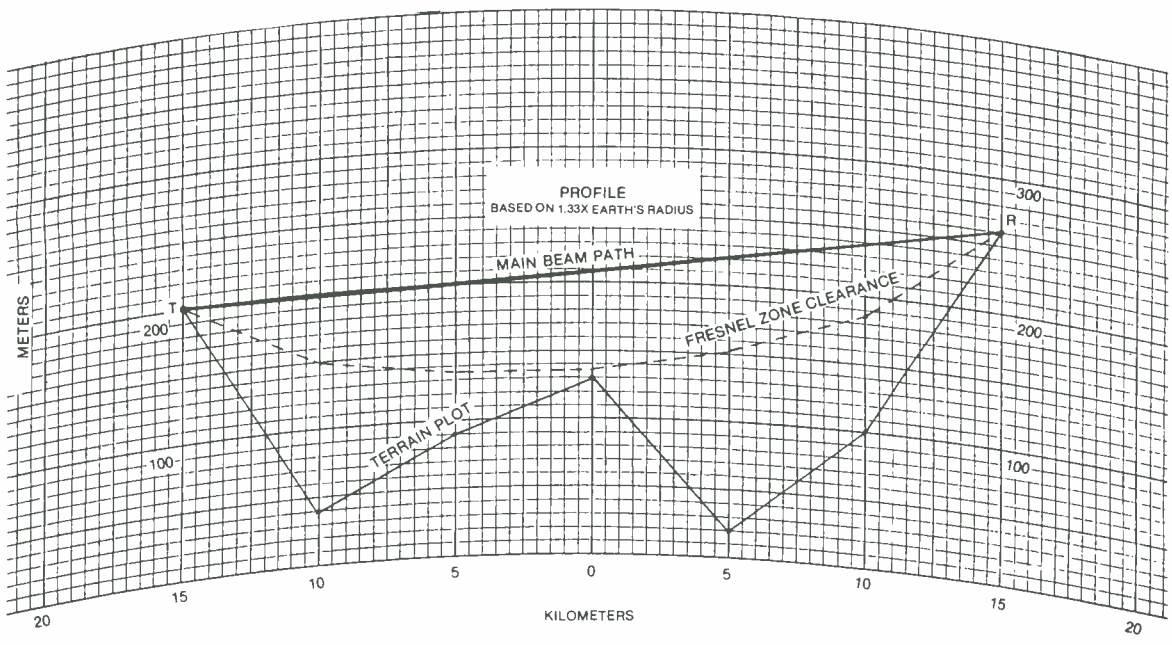


Fig. 12. Typical path profile using 4/3 or 1.33 profile paper. (Courtesy Broadcast Engineering)

and d_2 is the distance from that point to the other end of the path in miles. The f in the formula is the operating frequency in MHz. The resultant, H, is the radius of 0.6 of the first Fresnel zone in feet. It should be noted that this dimension is greatest at the center of any path, no matter what the path length. Also if plotted accurately, it is elliptical in shape. This formula can be used to check for minimum clearance above, or around any possible solid obstruction in a path. Thus this formula as applied to the path profile, will assist in determining the minimum height of the transmit and receive antennas for the STL system. It should be remembered that too much height can lead to unwanted reflected signals arriving at the receiving antenna, thus the desire is to have antenna heights that will produce a clearance equal to but not much greater than 0.6 first Fresnel zone over the entire path. Such unwanted reflections would come from even-numbered Fresnel zones that, after reflection, will change phase and reduce the signal.

It is advisable to calculate 0.6 first Fresnel zone clearance for any point in the path that is suspect. For many applications this will be no more than calculating this radius or clearance from the center of radiation only for the center of the path. Fresnel zone clearance is also discussed in Section 4, Chapter 2, "Microwave Engineering for the Broadcaster," page 4.2-61.

Field Survey

As the name implies, an actual observation of the potential path in question cannot be overlooked. This will verify that the data for terrain between the studio and transmitter are accurate. Often it is been found that data from topographic maps is in error. It may also be found that a building may be under construction which could block the path.

It is not necessary at typical STL frequencies to go to elaborate means to verify accuracy. A simple sighting of the proposed path will suffice. Existing obstruction lights on a tower can be useful for this purpose. Field glasses and a light source will do the job in most cases. The desire is, for the typical path of 20 miles or less, to verify that a clear line of sight exists, and to estimate clearance above or beside any possible obstruction. This permits verification of the profile prepared on paper.

Path Calculations

In the path evaluation above, the existence of a path was explored as well as the probable antenna heights necessary to obtain acceptable clearance over the path. In this segment the requirements of the antenna and transmission line will be determined.

Both antenna gain and transmission line loss must be viewed as controlled variables in designing an STL system. Only the loss between the transmitting and receiving antenna is fixed by the distance or length of the path.

Path Calculation Form

Before exploring the various aspects of a system path calculation, the following form should be reviewed.

LOSS

1. Path (___ miles / ___ km)	−____ dB
2. Transmission Line (total- ____ feet / ____ m)	−____ dB
3. Connectors (total)	−____ dB
4. Others _____	−____ dB
TOTAL SYSTEM LOSSES (Sum of 1-4)	−____ dB
5. Transmitter Power Output (____W)	+____ dBm
6. Transmit Antenna	+____ dBi
7. Receive Antenna	+____ dBi
8. Others _____	+____ dBm
TOTAL SYSTEM GAINS (Sum of 5-8)	+____ dB

Subtract System Losses from System Gains

TOTAL SYSTEM GAINS	+____ dB
TOTAL SYSTEM LOSSES	−____ dB
Expected Received Signal Strength (____ μV)	−____ dBm
Desired Signal Level (____ μV for ____ SNR)	−____ dBm
Fade Margin (Subtract desired signal from receiving signal line)	____ dB

Path Loss

Path loss is the atmospheric attenuation between the transmit and receive antennas of an STL system. For the purpose of this evaluation, free space loss will be used for these calculations.

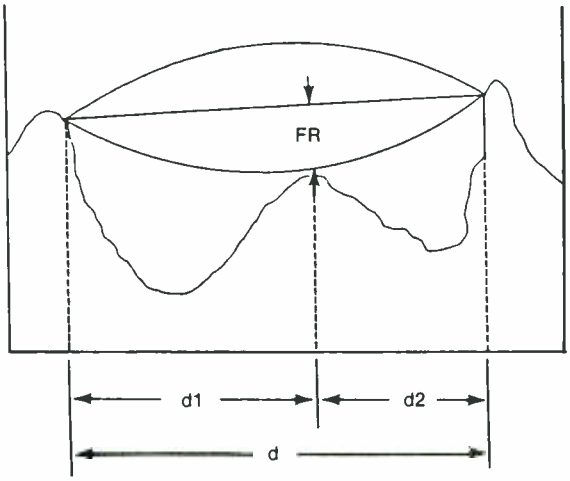


Fig. 13. First Fresnel zone radius, FR, depicts minimum desired clearance above obstructions. Note maximum clearance is required at the center of the path. (Courtesy Broadcast Engineering)

The nomograph in Fig. 14 provides an easy way of determining this loss as well as a formula that can be used to calculate this figure.

In some situations a clear line of sight path having 0.6 first Fresnel zone clearance may not be obtainable. If the obstruction is reasonably sharp in form, it can be anticipated that some refraction of the desired signal will occur over this obstruction. Fig. 15 provides a means of estimating this diffraction loss, and would be entered on the above form under Other Losses. This diffraction is referred to as knife-edging. As most obstructions are not sharp in form, it is advisable to add some additional loss possibly as much as 10 or 15 dB, to that obtained from this chart.

Transmission Line Loss

From the Fresnel zone calculations above, the needed height above ground at the studio for the transmitting antenna and the height above ground for the receiving antenna at the transmitter site have been determined. This in turn provides the

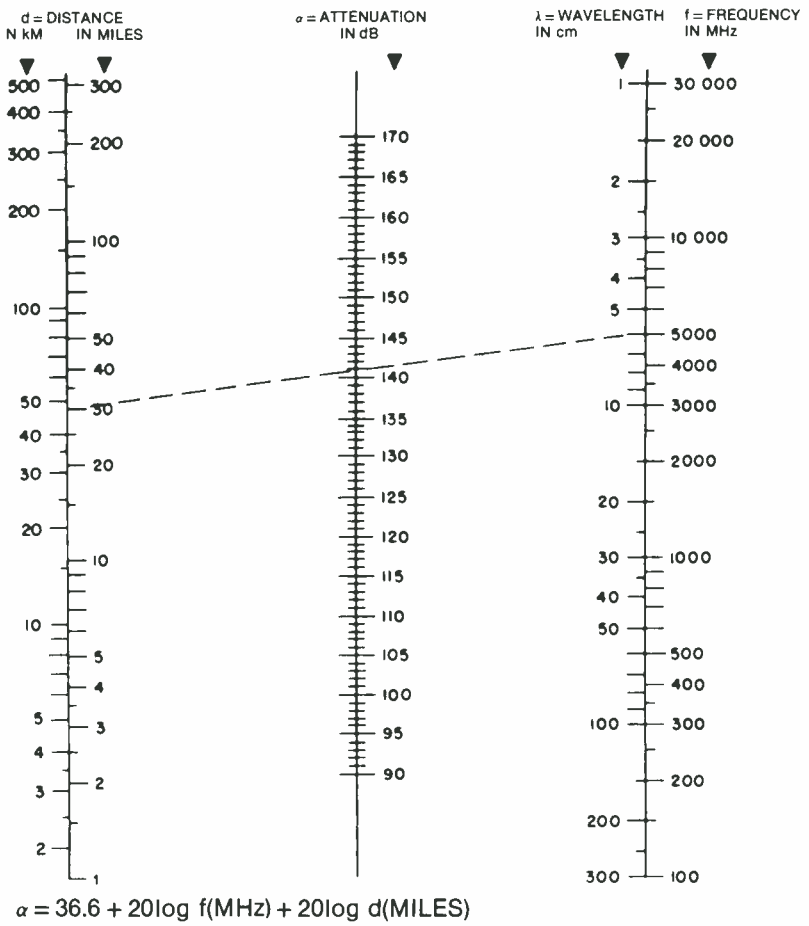


Fig. 14. Monograph for determining free space loss of an STL path. For distances under 2 miles, use formula shown. (Courtesy Broadcast Engineering)

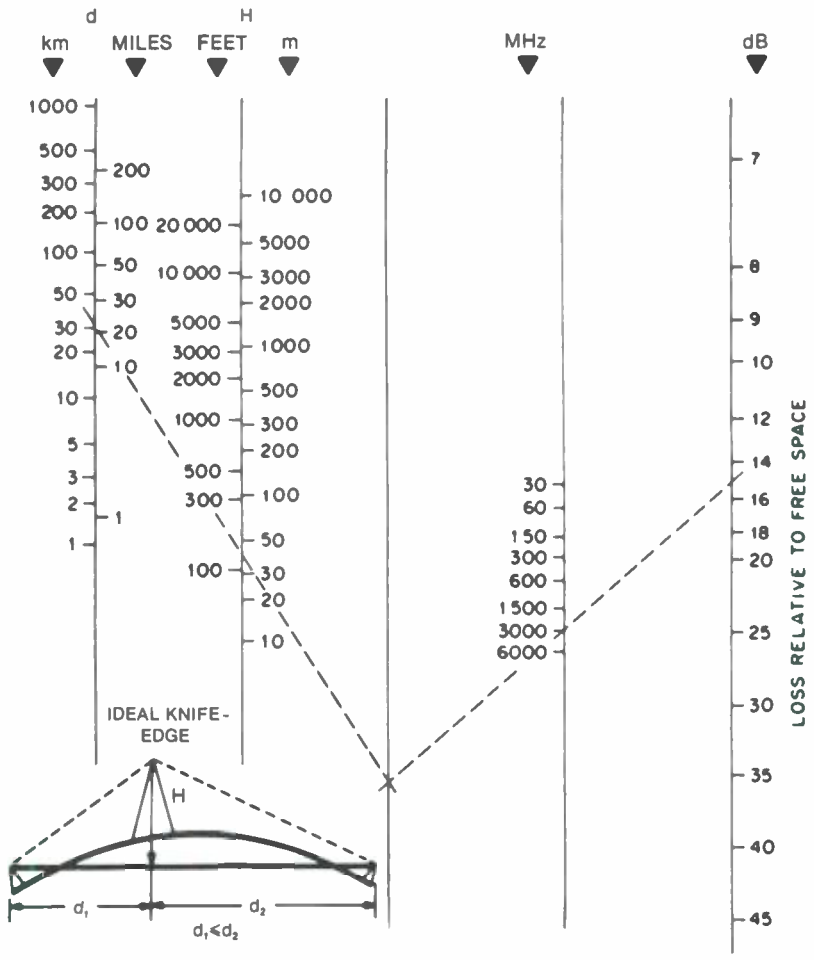


Fig. 15. Knife-edge diffusion loss can be estimated with above chart. (Courtesy Broadcast Engineering)

needed lengths of transmission line at both locations.

The transmission lines used for STL systems are half-inch or larger foam or air dielectric cables. These cables, while flexible, can be considered semi-rigid. In some installations rigid air dielectric transmission has been used to reduce this loss.

In designing an STL system there are three variables used in the path calculations to obtain an acceptable system. The loss in the path is a fixed parameter that cannot be changed. Transmission line losses are within the control of the system designer, by the transmission line selected. Fig. 16 gives typical losses for various transmission lines at 950 MHz. By the selection of transmission line, this loss can be controlled.

Connector Loss

This parameter is one that can be argued as being unnecessary. The designers of RF connectors state that connectors, when properly designed

TYPE	Loss per 100 feet (dB)
Standard Foam Dielectric Transmission Line	
1/2 inch diameter	3.0
7/8 inch diameter	2.0
1-5/8 inch diameter	1.4
Low-loss Foam Dielectric Transmission Line	
1/2 inch diameter	2.4
7/8 inch diameter	1.4
Air Dielectric Transmission Line	
1/2 inch diameter	2.7
7/8 inch diameter	1.4
1-5/8 inch diameter	0.7
Standard Coaxial Cable	
RG-8/U type	8.5
RG-218/U type	3.8

Note-Attenuations shown are typical for line types, at 950 MHz, 50 Ohms.

Fig. 16. Transmission line attenuation for commonly used transmission lines.

and properly installed have no loss. From actual observations it has been noted that some losses are typically encountered, and rather than debate, some loss is included here and is referred to as connector loss.

In practice, there are normally short (three feet or less) jumper cables, used between the ends of the transmission line and the STL transmitter and receiver and again between the transmission line and the antennas. These jumper cables are for ease of installation and to prevent connector damage. STL equipment employs Type N connectors. This connector, while correct for these frequencies, can be difficult to handle. The center conductor of the female connector is susceptible to bending and breaking. For this reason jumper cables have been used to make the joining of the connectors easier. Should jumper cables be used, care must be taken to select cables that will not contribute to intermodulation and related problems. To this end, it is recommended that RG-8/U and similar cables not be used, but rather flexible, solid-conductor outer shield cables, such as Andrew Corporation Superflex be used.

For the typical path calculations it can be assumed that approximately 0.5 dB loss will be seen at each end of the system, for a total of 1 dB.

Other Losses

Other losses will be used to account for a variety of possibilities. In areas with a large number of RF carriers it is advisable to use a ferrite isolator to protect the output of the STL transmitter. This device assures a constant impedance to the transmitter while providing isolation from outside influences.

Another loss will be encountered if, as in the dual system, a transmitter combiner is used to permit two STL transmitters to operate on a single antenna. Also in the dual system a power divider is used to feed the two receivers from one antenna. Such a power divider can contribute about 3.5 dB of loss.

In some situations, receivers may require the use of external preselectors or cavity filters for proper operations in congested frequency locations. Such devices have losses that would be accounted for at this point in the calculations.

Transmitter Power Output

This entry is self-explanatory. Fig. 17 provides conversion from watts to dBm power levels. The power output of the STL transmitter is the second area of control over the system design, following transmission line loss. The Rules and Regulations do not place an upper limit on power as is done in other services, but simply say that it should be not be greater than necessary to carry on the service.

Watts to dBm

P. Watts	dBm	P. Watts	dBM
5.0	+37	18.0	+42.6
5.5	37.42	19.0	42.8
6.0	37.79	20.0	43
6.5	38.12	25.0	43.9
7.0	38.46	30.0	44.8
7.5	38.75	35.0	45.4
8.0	39	40.0	46.0
8.5	39.3	45.0	46.5
9.0	39.55	50.0	47
9.5	39.78	55.0	47.4
10.0	40.0	60.0	47.8
10.5	40.2	65.0	48.1
11.0	40.4	70.0	48.5
12.0	40.8	75.0	48.8
13.0	41.1	80.0	49
14.0	41.5	85.0	49.3
15.0	41.8	90.0	49.5
16.0	42.0	95.0	49.8
17.0	42.3	100.0	50

Fig. 17. Table for conversion of RF power ouput in Watts to dBm.

With the advent of land mobile services in the 900 MHz spectrum solid-state power amplifiers exist to the 200-250 watt range, and are commercially available. As neither type approval or type acceptance is required of a 950 MHz STL transmitter, such amplifiers can be licensed for this service.

In considering the use of powers above the normal STL level, care must be taken to insure that undesirable interference does not occur to other users of the same channel (co-channel) or adjacent channels.

Transmit/Receive Antennas

The antennas used by a system represent the area where the most amount of control exists over the end result. Changes in antenna gain by selection of a larger antenna can make substantial changes in the received signal strength. With this goes, potentially, major revisions to the cost of the STL system if large antennas are used. Not only is the cost of the antennas a consideration, but also the cost of the supporting towers or structures.

Parabolic antennas are the most commonly used antennas for this service. Fig. 18 is an antenna that has been widely used in STL systems. In some parts of the country, antennas with a tighter pattern are needed because of the channel sharing that occurs in these areas. See Section 1, Chapter 3, page 1.3-58, paragraphs 5, 6 and 8 for comments on antennas from the viewpoint of frequency coordination. Other antennas that are in common use are both solid and grid full sized parabolic antennas see Fig. 19 and 20. Fig. 21 provides a summary of typical antenna gains.

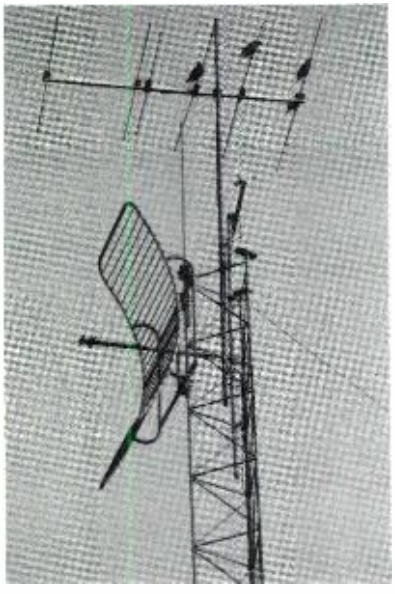


Fig. 18. Scala PR-450U STL antenna. A commonly used STL antenna. Antenna shown is in use at KPDJ-FM Eureka, California.
(Courtesy Broadcast Engineering)

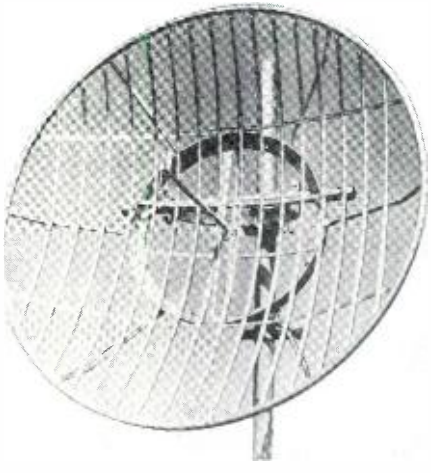


Fig. 19. Typical grid Parabolic STL antenna. Grid antennas provide gain without the wind loading of solid dish antennas.
(Courtesy Anixter-Mark)

Fig. 20. Solid parabolic STL antenna. This type of antenna provides excellent side and back lobe protection and is used in situations involving channel sharing.
(Courtesy Andrew Corporation)

TYPE	Forward Gain (dBi)
Grid Parabolic Antenna	
4 foot diameter	18.9
6 foot diameter	22.0
8 foot diameter	25.0
10 foot diameter	27.0
12 foot diameter	28.5
15 foot diameter	30.0
Solid Parabolic Antenna	
4 foot diameter	18.7
6 foot diameter	22.3
8 foot diameter	24.8
10 foot diameter	26.7
12 foot diameter	28.3
15 foot diameter	30.2
Parabloic, Single Plane, Grid	
a foot × 6 foot	20.1

Source - Manufacturers data sheets. Data to be considered typical, only.

Fig. 21. Chart of antenna forward gains for commonly used STL antennas.

Other Gains

While not common in many STL systems, there are devices that can be included that will result in further increases in total system gain. These include preamplifiers that may be used ahead of the STL receiver to lower the receiver noise figure and increase its sensitivity, thus adding gain but with a penalty of increased cross and intermodulation. In the dual STL or other situations where more than one receiver is located at the transmitter site, a receiver multicoupler may be used to couple these receivers to one antenna. Some multicouplers contain preamplifiers to compensate for the loss in the power dividers used for this division, and these can contribute gain to the overall system.

Expected Received Signal Strength

This number, expressed in dBm, is the end result of these calculations. It is, as the name implies, the anticipated RF energy entering the receiver RF input connector. As the microvolt (μV) is the unit of measure more commonly used in this area, the above form provides space to

enter the end result in this unit. Fig. 22 provides a table for conversion to μV from dBm.

Desired Signal Level

This parameter expressed in μV and dBm represents a given sensitivity specification for the selected STL receiver. As the desired service of the STL system is to deliver the program audio or signal to the transmitter site, a measurement of program signal-to-noise ratio (SNR) seems more appropriate than a quieting figure or other receiver sensitivity measurement. It is customary to use 60 dB SNR, but with the improving noise floors of program sources, transmitters, and other components of the program chain in FM service this figure may have to be increased to 70 dB. In a situation where there is co-channel sharing of the selected channel, the performance of the receiver to produce the desired SNR under co-channel conditions must be taken into consideration. Such co-channel operation will typically increase the desired signal level. In obtaining this number care must also be exercised to insure that the entire environment the receiver will see, be taken into consideration. This can be a consideration of all signals reaching the front-end of the receiver, levels of undesired signals in adjacent channels, in addition to any co-channel energy.

MICROVOLTS	DBM	MICROVOLTS	DBM
0.10	−127	35	−76
0.12	−125.25	40	−74.9
0.14	−124	45	−73.9
0.16	−122.9	50	−72.9
0.18	−121.9	60	−71.25
0.20	−120.9	70	−70
0.25	−119	80	−68.9
0.30	−117.25	90	−67.9
0.35	−116	100	−66.9
0.40	−115	120	−65.25
0.45	−113.9	140	−64
0.50	−112.9	160	−62.9
0.60	−111.25	180	−61.9
0.70	−110	200	−60.9
0.80	−108.9	250	−59
9.90	−107.9	300	−57.50
1.0	−106.9	350	−56
1.2	−105.25	400	−54.9
1.4	−104	450	−53.9
1.6	−102.9	500	−52.9
1.8	−101.9	600	−51.25
2.0	−100.9	700	−50
2.5	−99	800	−49
3.0	−97.5	900	−48
3.5	−96	1,000	−46.9
3.0	−95	1,200	−45.25
4.5	−93.9	1,400	−44
5.0	−92.9	1,600	−42.9
6.0	−91.25	1,800	−41.9
7.0	−90	2,000	−40.9
8.0	−88.9	2,500	−39
9.0	−87.9	3,000	−37.25
10	−86.9	3,500	−36
11	−86	4,000	−34.9
12	−85.25	4,500	−33.9
14	−84	5,000	−33
16	−82.9	6,000	−31.25
18	−81.9	7,000	−30
20	−80.9	8,000	−28.9
25	−79	9,000	−27.9
30	−77.25	10,000	−26.9

Fig. 22. Microvolt to dBm conversion table, at 50 Ohms.

Fade Margin

The last entry on this form may be the most difficult to determine. This represents the signal level above the acceptable minimum that it is desired to have as normal to the RF input to the receiver. It is this number that the calculations are to produce. By selecting a minimum fade margin, antenna gains and transmission line losses can be selected to meet the desired fade margin.

One way this may be addressed is the amount of time through a year that it would be acceptable for the performance of the system to drop below the established minimum. This may be expressed as a percentage of outage. Fig. 23 provides the relationship of reliability and outage time.

As the numbers imply, when reliability is highest the outages are the shortest. In the Chapter on Frequency Coordination (Section 1, Chapter 3, page 1.3-58, paragraph 4) it is suggested that 30 dB is a workable fade margin. For another point of view on this subject, Fig. 24 presents a nomograph relating distance to desired fade margin. It is the system design engineer's choice as to the level to be used for this entry in the calculations.

A Sample of Path Calculations

Fig. 25 represents a completed, typical path calculation. This theoretical path is some 10 miles in length, and uses parameters common to many situations. Having filled in the various gains and losses, they are totaled on the appropriate line. The Expected Received Signal Strength is obtained from the difference between Total System Loss and Total System Gain. The Fade Margin is the difference between this Expected Signal Level and the Desired Signal Level. It is to be noted that units of measure are not followed as an absolute with a mixing of dB, dBm, and dBi. As these are all relative, the desired end result is produced.

Repeaters

The above analysis may produce a situation that is not a workable STL configuration. If this is due to a blockage of the path than a repeater may be the solution. The two types of repeaters that may be considered at these frequencies are:

- Active
- Inactive or Passive

Reliability	Outage Time %	Outage Time per - Year	Month	Day
0	100	8760 hrs	720 hrs	24 hrs
90	10	876 hrs	72 hrs	2.4 hrs
99	1	88 hrs	7 hrs	14.4 minutes
99.99	0.01	53 minutes	4.3 minutes	8.6 seconds
99.999	0.001	5.3 minutes	26 seconds	0.86 seconds
99.999	0.0001	32 seconds	2.6 seconds	0.086 seconds

Fig. 23. Reliability vs outage time.

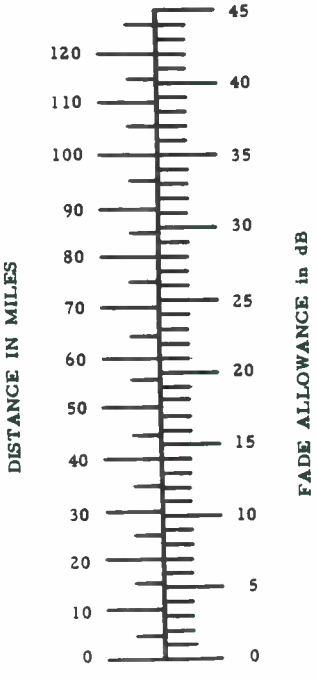


Fig. 24. Commonly used fade margin requirements versus path length. (Courtesy Broadcast Engineering)

LOSS	
1. Path (10 miles/16.1 km)	– 116.0 dB
2. Transmission Line (Total-400 feet/122 m)*	– 5.6 dB
3. Connector (total)	– 1.0 dB
4. Others-none _____	– ___ dB
TOTAL SYSTEM LOSS	– 122.6 dB
GAIN	
5. Transmitter Power Output (15W)	+ 41.8 dBm
6. Transmit Antenna**	+ 22.0 dBi
7. Receive Antenna**	+ 22.0 dBi
8. Others none _____	+ ___ dB
TOTAL SYSTEM GAIN	+ 85.8 dB
TOTAL SYSTEM LOSS	– 122.6 dB
TOTAL SYSTEM GAIN	+ 85.8 dB
Expected Received Signal Strength (3300 uV)	– 36.8 dBm
Desired Signal Level (100 uV for 70 dB SNR)	– 66.9 dBm
Fade Margin	+ 30.1 dB

Notes: * -7/8 low-loss foam transmission line
**-6 foot grid parabolic antennas

Fig. 25. Example of a typical STL path calculation, reflecting a path length of 10 mile.

Active Repeaters

This type of repeater can be subdivided into two types, that of a booster station and a full power repeater. The booster station is a station that receives and amplifies the signals of the originating station and re-transmits them on the same frequency without significantly altering them in any way. With a booster, the licensee is responsible for correcting any condition of interference that results from the radiation of radio frequency energy outside the assigned channel. In essence, this permits a repeater station to be created that must function as an on-frequency repeater, or what might be called an active beam-bender. A waiver is required for a booster station, that operates in conjunction with any STL/ICR system.

The second type of repeater is more conventional. This is normally a standard STL receiver feeding an STL transmitter, with different input and output frequencies or channels. For this, an ICR license is needed as it is an additional station. This repeater functions as a baseband repeater, with program output of the receiver feeding the program input of the repeater transmitter. Recently one firm offered a commercial I.F. or intermediate frequency STL repeater,

similar to those used in telephony microwave systems. In establishing a two hop system with a repeater, it can treated as two individual paths for purposes of path calculations.

Inactive or Passive Repeaters

At 950 MHz this type of repeater is used, but only under certain conditions. See Section 4, Chapter 2, Microwave Engineering for the Broadcaster, page 4.2-68 for details on true passive repeaters. With the billboard type passive repeater, normally the physical size at 950 MHz is so large making it not physically or financially viable. This is not to imply that the passive repeater should be ignored, as there are situations where it can be the ideal solution. Another passive repeater is back-to-back antennas. In considering the configuration, performance can be calculated as was done above, but using the expected received signal strength from the "receiving" antenna as the transmitter power output for the second hop calculations. From a mathematical viewpoint it will be seen that it will require a very short path for back-to-back antennas to function successfully as a passive repeater.

REFERENCES

1. Hamsher, *Communications System Engineering Handbook,* McGraw-Hill.
2. *Reference Data for Radio Engineers,* ITT—Howard W. Sams and Co.
3. Leukurt Electric Company, *Engineering Considerations for Microwave Communications Systems,* San Carlos, California.
4. Fink, Donald G., *Electrical Engineers Handbook,* McGraw-Hill.
5. Saveskie, Peter N., *Radio Propagation Handbook,* Tab Books.
6. Siemens and Halske Aktiengesellschaft, *Planning and Engineering of Radio Link Paths,* Munich, Germany.
7. Decible Products, *About Combiners,* Dallas, Texas.
8. Decible Products, *About Selective Cavities,* Dallas, Texas.
9. National Association of Broadcasters, *Engineering Handbook,* 7th edition sections 1, 3, and 4.

Chapter 1: Planning and Costs of Broadcast Facilities
Chapter 2: Planning and Design of Studio Lighting Equipment
Chapter 3: The Broadcast Television Camera System
Chapter 4: Video Signal Switching, Timing and Distribution
Chapter 5: Video Tape Recording
Chapter 6: Radio Studio Audio
Chapter 7: Magnetic Recording Media
Chapter 8: Film for Television
Chapter 9: 3/4" and 1/2" Video Recording System
Chapter 10: Video Tape Editing
Chapter 11: Audio Magnetic Recording
Chapter 12: Microphones

5.1

Planning and Costs of Broadcast Facilities

Malcolm M. Burleson*
RF Manager—Broadcast
NEC America, Inc.
Alexandria, Virginia

The information to follow may be used as a guide for general planning and cost estimating of facilities. Areas covered include the following:

- Checklists of items to be considered in any facility planning,
- Systems for television facilities,
- Acoustic considerations,
- Cost estimating and typical cost figures,
- Planning for AM and FM radio facilities.

Many factors determine the initial budget, as well as final cost figures at the time of actual completion. Proper planning and project coordination by the owner's representative is mandatory if a well-built, cost-effective facility is to be produced, by the date required. After many years of experience, the writer has been involved with numerous large and small broadcast facility projects, all having one major thing in common: the fact that time begins to run out before you are really finished. This may not actually be so bad, as otherwise, what else could ever stop the additional requests and change-orders, given the ever changing nature of our business.

*The author would like to thank both Alfred W. D'Alessio of Northeastern Communications Concepts for his contribution of the section on acoustics and Richard J. Anderson, Vice President of Engineering at Metromedia Television for his contribution of the section on construction examples.

GENERAL PLANNING CONSIDERATIONS

The early planning of a broadcast facility usually involves a number of factors such as: consideration of the market to be served; site selection; studio requirement; station programming and personnel; hours of operation; and available capital. First and foremost of the decisions to be reached is whether the studio and transmitter are to be combined under one roof or to be in separate locations. It is generally agreed that wherever practical it is most economical to combine the studio and transmitter. The initial equipment requirements are less, but more important is the fact that the day-to-day operating expenses are lower. With the plant "all under one roof" there are savings in heating, air conditioning, building maintenance, travel time, and personnel. A combined operation, however, is not always possible.

When a combined operation is not practical, the second approach is, of course, to operate the transmitter by remote control from the studio. By utilizing remote control, a transmitter site can be selected that is most advantageous from a coverage standpoint, and the studio can then be placed in the most convenient location. The building requirements at the transmitter can be the very minimum, requiring only space for the equipment, a small work area, and a small

heating unit. The studio then would contain both the programming and business functions.

Codes

Virtually any construction or alteration of a building may be covered by one or more codes. In addition to general building codes, there are electrical, mechanical, plumbing and other specialized codes. National associations have proposed model codes; however, it is up to state and local jurisdictions to adopt whatever codes, with variations, which they find appropriate. Reputable architects, contractors and subcontractors are familiar with local codes affecting their areas and should be involved in the work. Zoning is another consideration which is dependent on the local jusridiction.

FACILITY PLANNING

The initial step in station planning is to develop an outline of requirements that will form the basis upon which future decisions are made. Such an outline for broadcast facility planning may be developed as follows:

Outline for Broadcasting Facility

1. Site Selection

a. Adequate space for immediate building needs plus anticipated expansion.
b. Adequate parking space for employees, guests, and studio audience (if latter is being considered).
c. Trucking access and adequate loading area with loading dock, if possible.
d. Accessibility from high speed or uncongested roads (mobile units, audience, convenience of employees).
e. Transmission tower space or line-of-sight for microwave.
f. Zoning: use of towers, antennas, identification or advertising signs.
g. Possible use of helicopters for news and traffic reporting.
h. Relation of site to environmental elements: (i) noise, (ii) weather, (iii) drainage.

2. Building Program (Space Arrangement)

a. Proper flow and separation of studios, related technical spaces, craft shops and storage, programming and engineering, talent and dressing, administrative offices and mobile units.
b. Entrance arrangements for employees, guests, VIPs, and audience.
c. Relation of studios to loading areas.
d. Relation of parking areas to employee and audience entrances.
e. Security: inside, outside.

3. Building Construction—General

a. Selection of structural system, taking into account local conditions, codes, availability of materials, flexibility for future changes, special loading conditions and spans, degree of fire resistance and effect on fire insurance rates. Careful study of fire code requirements.
b. Partitioning: types to afford relatively good sound isolation, yet flexible enough for ease of removal or relocation. Better to make rooms larger in beginning and subdivide later if necessary.
c. Ceilings—high degree of accessibility for multitude of communications wiring; good acoustical value; cleanability, ease of electronic repairs.
d. Wall materials—extreme durability in technical and production areas, due to frequent moving of equipment and supplies.
e. Floor materials—durable yet resistant to traffic sounds and vibration. Raised computer floors may be used in control, video tape, and other electronic areas.

(Note: Floor slabs for TV studios must be extremely level for proper camera movement.)

4. Engineering—General

a. Availability of incoming HV power service from power company
b. Separate unit substations for: (i) air-conditioning, air handling and other facility motor loads, (ii) general illumination, (iii) studio production lighting, (iv) technical loads.
c. Lighting in general—fluorescent, 100-foot candles in working areas, dimmer controlled incandescent in control rooms.
d. Air conditioning—heavy studio loads (TV), low velocity for sound control, stand-by AC for master control rooms, separate exhaust system (air purging) for TV studios.
e. Miscellaneous systems—telephone (technical and commercial), public address, watchman's tour, door security, closed circuit TV and fire alarm.

5. Budget Estimate

The following Checklist and Project Budget Form are designed for estimating the scope and cost of station construction.

PROJECT BUDGET FORM

Call Sign _____ Start Date _____

Service _____ Finish Date _____
(Radio or TV)

Type of Facilities: (Check as applies)

Office _____ Studio _____ _____
Street address of project

Transmitter _____ Mobile _____ _____
City, State and Zip

Item #	Description	Estimate	Actual
1.	Land purchase/lease		
2.	Survey-property (and other)		
3.	Title search/insurance		
4.	Real estate broker/commission		
5.	Architects/engineers—fees		
6.	Permits and licenses (if separate)		
7.	Consultants-acoustic structural, etc.		
8.	Site preparation and demolition		
9.	General construction and finish		
10.	Optional construction items and finish		
11.	Special construction and finish		
12.	Furniture and fixtures		
13.	Decoration—interior		
14.	Landscape—exterior		
15.	Special equipment—electronic (and other)		
16.	Special equipment—installation of above		
17.	Contingencies (including price increases)		
18.	Other		
19.	Other		
20.	Other		
	Totals		

Prepared by _____ Checked by _____ Approved _____

Suggested Checklist for Planning

ITEM
- Land
- Land tests
- Site clearing
- Architects' and engineers' fees
- Permits
- Special consulting fees (include interior decorator)

GENERAL CONSTRUCTION
- Architectural
- Electrical
- Mechanical
- Heating and Plumbing
- Special in-house cabling (TV, Music, PA)

INTERIOR FINISH
- Wall covering (fabric or paint)
- Floor covering
- Special studio treatment

FURNITURE AND FIXTURES
- Decorative office furniture
- Standard office furniture
- Office area built-ins
- Working area counters, cabinets and built-ins
- Draperies
- Art work

TELEPHONE
- Broadcast line facilities
- TWX or facsimile
- Type of switchboard (owned or leased)
- Office interconnection needs
- Number of private lines
- System—owned or leased

SECURITY
- Control of public (where received)
- Control of all points of entry
- Closed circuit TV systems, watchman's tours
- Electrified gates and doors
- Separation of 9:00-5:00 areas from 24-hr. areas
- Night lighting

MISCELLANEOUS ITEMS (likely to be overlooked):
- Copier outlet (special power hookup)
- Special ventilation for odor areas
- Building maintenance equipment closets
- Drinking fountains and vending machine areas
- Space for air conditioning subdistribution boxes, fans, etc.
- Special waste water treatment for film darkroom processing, if local ordinances dictate
- Cable connection to roof for radio and television antenna system and two-way antenna
- Possible microwave antenna mounts

6. Electrical

General

The following is a sample specification for the electrical system of a large television station. It is based on the National Electrical Code and is intended to show how such a specification may be set up. Elements may be adapted to other applications, including radio station.

It is important that all state and local electrical, fire and safety codes be observed.

Area Classification

All electrical installations, materials and equipment shall comply with the classification "General Purpose" except for hazardous areas which shall be designed for Class I, Group D, explosion-proof conditions.

Incoming Power Service and Metering

1. Incoming power service may be high voltage (4.16 kv or 13.8 kv) due to high load requirements.
2. Standby incoming service shall be provided with automatic transfer when normal service fails.
3. One point of primary metering shall be provided to obtain best possible utility rates.

Primary Distribution

1. Distribution within complex may be high voltage (4.16 kv or 13.2 kv) from a primary switchgear to unit substations located as close as possible to the center of the loads served.
2. Separate unit substations shall be provided for different type loads, as follows:
   With secondary 120/208 v to handle equipment and motor loads and all fluorescent lighting;
   With secondary 120/208 v to handle receptacle, incandescent lighting and small equipment loads;
   With secondary 120/208 v to handle studio production lighting only;
   With secondary 120/208 v to handle technical TV loads only.
3. Each unit substantion shall include components as follows:
   Primary compartment with Hv fused load break switch;
   Open dry type transformer with Hv primary delta and secondary 120/208 v or 277/480 v, 3 phase, 4 wire. Sound rating of transformer shall be best possible;
   Voltmeter, ammeter, and selector switches;
   Main secondary air circuit breaker;
   Moulded case feeder circuit breakers and spares.

Secondary Distribution

1. Power shall be extended from unit substations with cable and conduit to automatic circuit breaker panels and motor control centers.
2. Motor control centers shall be Class I, Type B, with combination magnetic, full voltage starting, circuit-breaker-type motor starters or circuit breakers only for 480 v, 3-phase operation. Each starter shall have 3 thermal overloads.
3. Power panels shall be designed for 480 v, 3-phase, 3-wire service. Panels shall be of the dead front type with automatic circuit breakers of ampere rating as required.
4. Panels for receptacle and incandescent lighting loads shall be designed for 120/208 v, 3-phase, 4-wire service. Panels shall be of the dead front type with automatic circuit breakers of ampere rating as required.
5. Lighting panels shall be designed for 277/480 v., 3-phase, 4-wire service. Panels shall be of the dead front type with 20 ampere automatic branch circuit breakers. Panels shall be similar to Westinghouse Type NH1B-4.

Conduit

1. Rigid steel conduit asphaltum painted shall be used when installed in concrete slabs, below grade and outdoors above grade.
2. Rigid aluminum conduit shall be used for exposed installation in mechanical equipment rooms, damp locations and locations where exposed to mechanical damage.
3. Rigid aluminum or steel conduit shall be used for all feeder and subfeeder runs.
4. Steel EMT with compression weathertight fittings shall be used for all other branch circuit wiring indoors and above grade.

Wire

1. HV cable shall be single conductor crosslinked polyethylene insulated and shielded.
2. Building wire shall be Type THW rated at 600 v-75 degrees C No. 12 AWG and smaller shall be solid copper. No. 8 AWG and larger shall be stranded.
3. Fixture wire shall be Type AF, 300 v insulation.
4. Minimum wire size shall be No. 12 AWG, except No. 14 AWG for control wires. Maximum wire size shall be No. 500 MCM.

Grounding

1. Electrical grounding shall be provided in accordance with the National Electric Code. Equipment enclosures, electrical service, transformer neutrals, outdoor lighting standards, and cable shielding shall be grounded.
2. Insulated bushings and double lock nuts shall be provided at all panel boards and pull boxes in feeder runs and pull boxes shall be bonded through with bare copper wire.
3. Separate technical equipment ground system shall be provided as required.

Switches, Wiring Devices, Wall Plates and Special Enclosures

1. Single pole switches shall be 20 amperes, 120/277 v, ac, quiet type.
2. Duplex receptacle shall be 20 amperes, 125 v, 2 pole plus U-slot ground.
3. Special outlet to be provided as required.
4. All wall plates for switch, receptacle, and telephone outlets shall be .06 in. stainless steel.

Telephone System

1. Two incoming underground services are required, one for technical use and one for commercial use.
2. Equipment room for the technical service shall be located close to Master Control and there shall be a cable-tray tie between the equipment room and Master Control.
3. The commercial system shall be complete, consisting of conduits from equipment room outlying telephone closets and interconnecting panels and thence to the various outlets as required. All installations shall be in accordance with the requirements of the local telephone company.
4. Interconnecting panels shall be of steel with plywood backboard, full opening door, latch, cylinder lock and trim.
5. Telephone closets shall be furnished with plywood backboard.
6. Conduits shall be ¾ in. minimum.
7. Telephone outlets shall be 4 in. sq. with bushed hole cover plate.
8. Equipment instruments and wiring shall be by the telephone company.
9. Some recent trends are for the broadcast station to actually own the telephone equipment. Should this be true, Items 1 through 7 are still to be used as a guide.

Public Address System

1. A complete PA system consisting of amplifiers, loudspeakers, and microphone shall be provided.
2. Loudspeakers shall be located in corridors throughout the complex and calls shall originate from the telephone operator's desk.
3. System shall be zoned as required.

Fire Alarm System

1. The fire alarm system shall be closed circuit zoned, consisting of control cabinet, gongs,

manual stations and automatic fire detectors.
2. Manual stations shall be provided at each stair on each floor and at all ground level exterior doors.
3. Automatic thermal or smoke detector shall be provided in all areas except where sprinkler heads are installed.
4. Each sprinkler alarm valve shall indicate on the fire alarm panel zone annunciator as a separate zone when activated.

Video Cable Trays and Audio Signal Conduits

1. A system of cable trays and signal conduits originating from Master Control shall be provided to studio control rooms, studios, microwave rooms, electronic shop, program computers, etc.
2. In addition, a separate cable tray with antenna cables shall be provided from Master Control to all areas where antenna outlets would be required.

Studio Production Lighting System

1. Unit substation and dimmer board shall be located as close as possible to studio served.
2. Unit substation shall include the following:
   a. Electrically operated main circuit breaker to permit remote control from studio floor.
   b. Transformer with 6-2-1/2 percent taps, 3 above and 3 below rated primary voltage, to compensate for possible secondary voltage variations.
3. Other work shall be as follows:
   a. Wireaway with wiring from load size of dimmers to studio floor patch panel.
   b. Studio grid wireaways with load wiring to studio patch panel;
   c. Wiring under studio floor from studio floor "pockets" to studio patch panel;
   d. Control wiring from studio control console to dimmer board.
4. In sizing unit, substantions serving dimmer boards, a 50 percent demand factor may be applied to connect dimmer load.
5. An "on-air" studio warning light system be provided as required.

Security

1. The following security systems shall be provided:
   a. Supervision of all exterior doors on ground level, with control cabinet in guard room;
   b. Closed circuit TV cameras at key positions, with monitor in guard room;
   c. Manual nonwired watchman's tour stations located throughout complex;
   d. Electrically operated gates to control automobile traffic.

Emergency System

1. Power for the emergency system shall be provided with a water-cooled diesel generator set with generator voltage 277/480 v, 3-phase, 4-w. The installation shall include all accessories such as automatic transfer switch, output switchboard, battery starting set, oil storage tank, fuel pump, mufflers, vibration isolators, etc.
2. Generator set shall automatically sense power failure or 80 percent undervoltage, start engine, attain and maintain speed, and transfer emergency load. Manual override of start and transfer of load controls should be provided.
3. Provide local transformer with primary delta 480 v, 3-phase and secondary 120/208 v loads on emergency supply.
4. Loads on emergency supply shall include stair lights, exit signs, selected corridor lights, PA system and all technical lighting and heating, ventilating, and air conditioning loads required for transmission of live news programs and taped programs.

Lighting (277 v for Fluorescent, 120 v for Incandescent)

1. Lighting fixtures shall be completely installed with all required outlet boxes and accessories.
2. Lighting levels shall be in accordance with IES latest recommendations, with minimum 100 FC in working areas.
3. Fluorescent fixtures shall be used for general illumination. Fixtures shall be with 40 w RS lamps and HP factor ballast, with best sound rating. Fluorescent fixture types shall be as follows:
   a. Recessed with acrylic lens diffuser to be used in areas with hung ceiling;
   b. Surface or pendant mounted with wraparound acrylic lens diffuser to be used in stairs and other selected areas with exposed ceiling;
   c. Industrial RLM with porcelain reflector to be used in mechanical equipment rooms, storage rooms, etc.
   d. Executive offices and conference rooms shall be provided with dimmer-controlled incandescent lighting using recessed fixtures.
5. Selected walls and art work shall be illuminated with recessed ceiling-mounted incandescent wall-washing fixtures.
6. Make-up room mirrors shall be illuminated with special bracket wall-mounted fluorescent fixtures. Dressing room mirrors shall be illuminated with special wall-mounted strips with incandescent bare lamps.

Outside Lighting

1. Outside lighting shall include illumination of audience concourses, entrances, parking lots, signs, building exteriors, planters, etc.
2. Lighting levels for all outside area illumination shall be strictly in accordance with IES latest recommendations.

Miscellaneous

1. Wall-mounted clocks operating on 120 v shall be provided complete with outlet in designated areas.
2. Clock system for technical use with master clock in Master Control and indicating clocks in studio control rooms, offices, etc., shall be provided as required.
3. Local office intercommunication systems shall be provided as required.
4. Local sound systems shall be provided for large conference rooms.

Mechanical

General

Color television studios require special consideration in solving the many problems entailed in the mechanical design due to the high-lighting capacity, noise criteria, air distribution and emergency stand-by operation. Black and white, color television studios, and radio broadcasting facilities would require the same consideration, but some of the problems would not be as severe.

Design Conditions

1. The optimum summer and winter design conditions to be maintained by the air-conditioning system is 75 degree F dry bulb bulb and 50 percent relative humidity. However, these conditions should be checked (in respective area with the owner's) since they may require slightly different criteria.
2. The outside design conditions are dependent upon the geographical location from data established by the US Weather Bureau.

Air-Conditioning Loads

1. Studio and production lighting for color television constitute the major portion of the heat gain and can exceed 75 percent of the total cooling load requirement. The unit lighting load requirement in the production area of the studio can equal 50-60 watts per square foot of floor area and in many cases this load can occur in any part of the studio since the production area and audience accomodations are flexible.
2. Transmission and solar heat gains are minimal since the exterior walls are well insulated and windowless.
3. Another contribution to the cooling load results from occupancy heat gain and the fresh air load. The fresh air requirement should be based on either 15 CFM per person, or the equivalent of one air change of fresh air, whichever is greater. It is also important to check and insure that the fresh air quantities conform with all code requirements.

Method of Air Distribution and Noise Control

1. Proper air distribution and air movement are of critical importance. Systems should be designed so that within a zone of 12 ft. above floor level, an air movement of 25 fpm is not exceeded. Air velocities exceeding the 25 fpm can cause movement of performer's hair, clothing, and stage props, which are usually highly expendable and flimsily built of thin canvas and light plywood.
2. The air supply should be introduced at a level above the movable lighting grid system to prevent interference with the closely spaced batten strips. Low-level return grilles located at the perimeter of the studio, in principle, would be desirable. However, due to the nature of studio operation, the grille could be blocked off by the cyclorama curtain or by studio props, which would result in an ineffective return air system. It could also be a possible source of noise generation. Locating the return air outlets at a level above the air supply will tend to relieve the neutral zone before it can heat the ceiling and radiate heat downward. Proper location of return air grilles and maintaining low velocities will eliminate any possible "short circuiting."
3. Noise criteria are of utmost importance and unless proper consideration is given to this problem, it can result in a nonproductive studio. Noise level should be within a range of NC 20 to NC 25, so as not to interfere with studio performance, particularly during scenes where there is no conversation and no background sound effects. Duct velocities should be designed for approximately 400 fpm within 10 ft. of diffuser or register opening, 525 fpm within 10-30 ft. from opening, 700 fpm within 30-50 ft. of opening, and 800 fpm within 70-90 ft. of opening.
4. All ductwork (supply and return) should be acoustically lined for sound attenuation and the sound power level of all outlets should be carefully checked to insure that it does not exceed the decibel rating at the end of the duct run, otherwise it will become additive (logarithmic) and negate a portion of the acoustically treated ductwork.
5. All piping should be insulated and all ductwork should be externally insulated to

eliminate reflected sound in studios. Where ductwork and piping pass through walls or floor, the openings should be sealed with acoustical sound-deadening material. Ductwork and piping should be suspended from vibration isolators. Where ductwork and piping pass through studio walls, flexible pipe and flexible duct connections should be provided. Piping should be sized so that velocity of the medium transmitted is low enough to be inaudible.

6. Mechanical equipment should be located remotely from studio to eliminate transmission of sound and vibration. All equipment should be properly supported from vibration isolators. Sound traps for sound attenuation and flexible duct connections to prevent transmission of vibration should be provided for all air-handling apparatus.

Type of System and Control

1. Each studio should be served by its own air-handling apparatus and should consist of supply and return fans, filters, heating and cooling coils, sound traps and a purge exhaust system.
2. There are several schemes that can be utilized in the arrangement and selection of the component parts of the system, and this is somewhat dependent upon the economics, space conditions, and geographical location of the project. An "economizer" cycle utilizing 100 percent fresh air during intermediate season or a fixed percentage fresh air system can be used. The application of preheat coils is also dependent upon the percentage of fresh air and geographical location. Heating coils can be either steam or hot water type and cooling coils should be of the chilled water type. In areas where freezing outside temperatures are experienced, special conditions have to be considered to prevent possible "freeze-up" of preheating coils and chilled water coils.
3. A separate purge exhaust system should be provided to permit studio to be evacuated during periods when it is not in operation. During purge operation, the system should handle 100 percent outside air without attempting to maintain studio design conditions. Where an economizer-type cycle is provided, purging of the area can be accomplished by resetting controls to 100 percent outside air.
4. Control system should be arranged to control studio temperatures and where facilities are provided for audience participation, additional humidity control should be provided.
5. The installation of a Supervisory Data Center would provide operational supervision of the project and would include remote control for resetting of space temperatures and humidity, starting and stopping of air handling system, "read-out" of other pertinent air and water temperatures and alarm indication.
6. Pneumatic temperature control system should be provided with standby air compressor with automatic cut-in features.

Stand-By Operation

1. Due to the critical operation of the Master Control Room and Videotape Room, a separate air-handling system shall serve these areas with provisions for standby equipment in the event primary equipment fails. This can be accomplished by interconnecting the ductwork (properly dampered) with another air-handling system serving a noncritical area in the building (i.e., office areas), thereby permitting the Master Control Room and Videotape Room to be satisfied during an emergency period. Another desirable feature to be incorporated in the system is provision for handling 100 percent fresh air in the event refrigeration equipment becomes inoperative.
2. Multiple refrigeration equipment and boiler equipment should be provided so that in the event a single unit becomes inoperative, partial operation can maintain conditions in critical areas.
3. Compressed air system serving videotape machines should be provided with standby compressors to insure continuous operation. Compressors that are water cooled can operate off the chilled water system and arranged so that in the event there is a loss in chilled water pressure, the cooling system will automatically switch over to city water.
4. In the event of an electrical power failure, an emergency generator should start automatically to maintain operation of the boilers, heating pump, air-handling system serving the Master Control Room and Videotape Room, pneumatic temperature control air compressor and air compressor serving videotape machines.

ACOUSTICS

Studio Planning

When a microphone is opened in a studio or combo control room, it is expected to pick up the voice of the talent. But if it is also subjected to building rumble, office noise, air conditioning noise, hissing radiators, and unwanted reflections from the room walls; the resulting air signal, YOUR PRODUCT, can sound cheap and hollow. It can actually diminish intelligibility, and possibly invite listener fatigue in severe cases. There is no complete electronic fix for poor acoustics.

Creating the "ideal" studio acoustic is an expensive undertaking. It requires the expertise of an acoustical consultant and an architect, who are both familiar with studio construction. Retaining professionals who specialize in unrelated fields within their professions should be avoided, because of the special nature of broadcasting requirements. Good designers will often find it necessary to recommend types of construction which are two to five times as costly to execute than standard office construction. However, the resultant studios and control rooms will be well isolated from intrusive noise and vibrations, and will project a clean and crisp On-Air signal from live talent, free of unwanted resonances and echoes.

Costs of Acoustic Treatments

Many factors affecting the final costs of construction are actually under the station's control. First, determine whether your needs require the "ideal". A Top 40 station whose talent works only a few inches from a single microphone, relies far less on room acoustics for its live "sound" than does an All Talk format station requiring five open microphones to pick up guests at any variety of distances. Because of their wider frequency response and greater dynamic range, and the fact that their listeners may tune in on sophisticated high fidelity receivers, FM stations generally require more closely controlled studio acoustics than their AM counterparts. Remember that the more a station employs signal compression and limiting, the more evident will be the annoyance of poor studio acoustic characteristics. Conversely, compression on stations with better studio acoustics will be less noticeable during live broadcasts.

When planning new studios, significant cost reductions can be realized from selecting a site which is far removed from noise generating sources such as pumps and air conditioning equipment; street, rail and air traffic; and manufacturing equipment. Be sure to consider ceiling height. Large HVAC ductwork is required to keep air flow noise at a minimum; and if insufficient space exists for the simple installation of the ductwork, expensive alternatives will be required. Likewise, when roughing out the details of a floor plan, don't draw walls as single pencil lines. All partitions have some thickness which will take up floor space; and it is not uncommon for some acoustic partitions employing internal air spaces to exceed a 16" thickness. If space is not a premium, such constructions are generally more economical than thinner partitions with similar transmission characteristics. Absorptive surface treatments can easily add an additional 4" to 6" to each side of the wall profile.

The control of the transmission and reverberation of sound are two disciplines in acoustics which apply to broadcast environments. They are virtually independent and require completely different methods and materials in creating studios suitable for broadcast use. It is important that each be understood, since confusion between the two can result in aggravating an existing problem.

Controlling Sound Transmission

Sound Transmission results when a source of sound is carried from one area to another. The vehicle of transmission may be a direct path, a flanking path around an object, or a path carrying vibration. The most economical and practical means of limiting the transmission of noise usually requires the control or reduction of it at the source. Disturbances with low frequency components are the most difficult and expensive to contain. Completely enclosing the noise source in a highly absorptive room, and isolating its vibrations from the building structure will limit the ability of noise to intrude upon other areas. For example, if footfalls on a cement floor adjacent to or above the studio are causing problems, try carpeting those areas before attempting to increase the transmission loss of the studio construction.

Where treatment at the source is not practical, the most effective way of isolating an area against the intrusion noise is to employ floating construction. With floating construction as shown in Fig.1, the noise sensitive area is actually a room built within a room. The most important aspect of this type of construction is that mechanical contact between the inner room and outer room is kept to a minimum, with the construction of both rooms creating as complete and uninterrupted an envelope as possible. This is most commonly achieved by resiliently supporting the floor and suspending the ceiling of the inner room on springs or neoprene isolators. Hence the term "floating". Usually in radio studios the walls have no connection between them; but in television studios, where the ceilings are significantly higher, resilient sway brace connections between the inner and outer walls may be required to stiffen the construction, and prevent buckling.

Depending on the intensity and proximity of the noise source, and the degree of residual noise which can be tolerated, some or all of the aspects of floating construction can be employed in designing a broadcast studio or control room. The resiliently isolated floor and ceiling is necessary to prevent structure borne sound and vibration from entering the interior space. The double walls with the resulting air cavity between them are actually more effective than a single partition of the same mass. In order to preserve this advan-

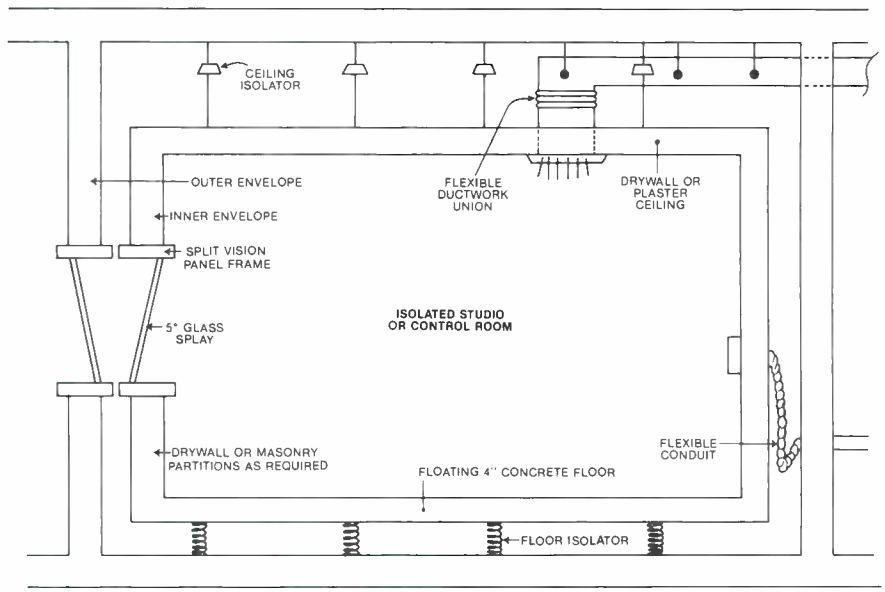


Fig. 1. Floating construction schematic showing mechanical isolation between inner and outer rooms.

tage, no service such as air conditioning ductwork, plumbing, or electrical conduit should be allowed to make a solid mechanical contact between the outer and inner rooms. The use of flexible connections within the cavities is extremely important.

When spring or neoprene isolators are employed for vibration isolation, the effectiveness of the isolator is measured by its nominal deflection, the relation of its natural period to that of the disturbing vibration, and the stiffness of the structure supporting it. It is important that isolators with the proper characteristics be specified. Isolators which are too lightly loaded will provide little isolation, while isolators which are too compliant may cause instability, or bottom out. If the isolation system exhibits a natural resonance equal to the disturbing frequency, the transmission of the disturbing frequency will be amplified.

One often overlooked source of vibration which may induce unwanted disturbances into adjacent areas is the control room monitor speaker system. Resiliently suspending the loudspeaker enclosure from the wall or ceiling will significantly reduce the structure borne transmission of sound from the monitor.

The materials used for the reduction of sound transmission in walls, ceilings and floors, are typically heavy, dense, and thick. Designing a barrier for maximum transmission loss would include practical considerations for the stiffness, resonance, mass, isolation, cost, and construction details of a partition. Typical partitions may be composed of brick or masonry block, poured concrete, lead, multiple layers of gypsum board supported by metal studs, or a combination of these. Regardless of the materials used, the most efficient barriers employ an integral airspace or cavities filled with a damping material such as fiberglass batts. Isolation at the lower frequencies becomes increasingly difficult and expensive, requiring stiffer, thicker and heavier construction than that needed for higher frequencies.

Perhaps the single most important aspect in the construction of acoustical barriers is sealing. Regardless of the materials used, the fit of the individual components with each other and the existing structure must be tight. All joints should be filled and sealed with a resilient, non-hardening caulk. The smallest openings can have disastrous results, and render otherwise expensive construction no better than a far cheaper counterpart. As an example, the TABLE 1 shows the reduction of the sound insulation (R) value of a hypothetical partition at some mid frequency, due to acoustic leakage through various size openings.

Once the design of the partitions has been decided, an entrance with the same sound insulation characteristic will be needed. No practical doors are commercially available which meet or exceed the R values of the most common partitions used in broadcasting. Therefore, a soundlock entrance scheme is required, which will attenuate sound through two doors and an intervening air space. The soundlock is a small vestibule between the studio and a hallway or other room requiring access to the studio. A small soundlock is detailed in Fig. 2. By entirely covering the walls of the soundlock between the studio and exter-

nal doors with absorptive material, the efficiency of the soundlock will increase, decreasing the effect of opening one door. The use of a soundlock not only reduces the insulation requirement for each door, but also provides passage in and out of the studio or control room without exposing it to the full noise and disturbance of an adjoining area. Doors with good acoustic characteristics are available either in metal or wood, both of which feature a sound retardant core.

Like the partition requirements, the door must seal tightly within its frame. Lack of a good seal wastes whatever investment is necessary to procure a good sound rated door. Commercially available compression and/or magnetic type seals are recommended at the head and jambs of the door, while a mechanical drop seal and step saddle should be employed at its threshold. Some expensive pre-hung doors feature integral seals and can lift hinges, which actually lower the entire door into place tightly against the threshold saddle when it is closed. The greatest advantage of these doors results from the fact that they never have to be pushed shut to make a good seal all around the door. All other types require an oversize door check (pneumatic or hydraulic closer), and a latch to properly compress the seals when the door is closed.

In order to match the transmission loss characteristic of the partition, most installations will require double glazed vision panels. The two panes of glass should be of different thicknesses to minimize the coincidence of each pane's deficiencies. The glass should be mounted in a resilient neoprene or felt lined channel, and caulked tight. Some provision should be made for removing either piece of glass for replacement or cleaning. The glass should be mounted with a 5 degree outward splay at the top to reduce acoustic and visual reflections. Where a high degree of isolation is required, acoustic laminated glass should be employed. Each pane of this glass consists of alternating layers of plastic and glass; and it is lighter, less resonant, and a better acoustical barrier than standard plate glass.

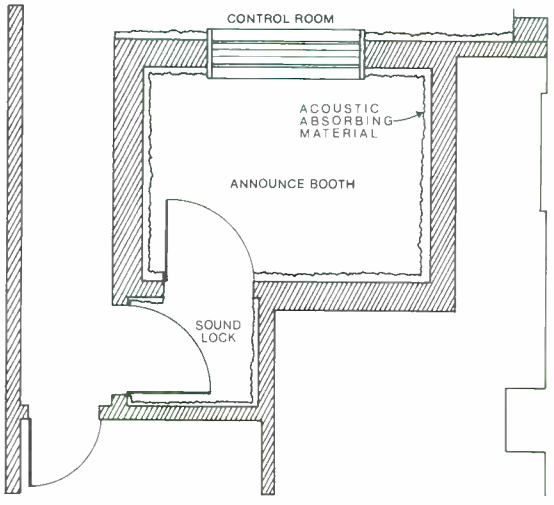


Fig. 2. Soundlock entry to a small announce booth.

Welded hollow metal frames are preferred over wood for both doors and windows for their stability. However, the void within them should be packed with either a cementitious or mineral fiber filler. It is important that the frames not connect the vertical partition sections in floating room or double wall construction.

In large cities where the cost of construction labor is high, small studios and control rooms may be economically built from modular components. The modular rooms are constructed from 4" thick, prefabricated hollow steel panels. A modular room usually includes a self supporting ceiling and an integral floor. The entire room is assembled on rails which can be isolated with springs or neoprene from the building structure. Most companies offering modular rooms also include double and triple partitions, doors, windows, conduit, ventilation ductwork, and a performance guarantee as available options. Because modular rooms can be disassembled and relocated, they are not usually considered leasehold improvements, and may offer certain financial benefits in addition to being somewhat portable.

Regardless of the design, the installation contractor must be familiar with the stringent requirements of acoustic construction. The efforts of the general construction, electrical and mechanical trades will have to be coordinated by the architect both in the design and execution of the studio project, to assure that no conflicts compromise the acoustic plan. The job should be inspected during construction by the acoustical consultant, to check for any potential leakage paths brought about by existing field conditions, and conformance to acoustical details.

If the station is to be situated in an office building, or other shared location, don't forget that other tenants may be annoyed by high level monitoring, tape rewind noises, and other sounds peculiar to broadcasters. So during the design phase, if the acoustic consultant recommends protection for adjacent building tenants, it may avoid a future embarrassment.

Controlling Reverberation Time

Separate and distinct from providing sound and vibration isolation, is that part of acoustics which governs how a room "sounds" when a sound originates in it. This is almost entirely a function of the room size, proportion and the ability of its contents to reflect, diffuse or absorb sound

of differing frequencies. To complicate matters, all these parameters interact with each other in determining the reverberation characteristic of a room. The major measurable characteristics are a combination of the time that it takes a sound to decay 60 dB within a room, once the source of that sound is terminated (T 60), how the T 60's differ with frequency, how uniform the decay rate is, the ratio of early and late reflections, and the natural room resonances (modes). Room tuning is both an art and a science, which requires more research to fully understand. However divergent the philosophies involved, most consultants agree on several guidelines for radio and television studios.

The smaller and more symmetrical a room is, the more noticeable will be its undesirable resonances. This is why many television announce booths sound more like stuffy little phone booths. Avoid exceptionally long and narrow proportions, square rooms, rooms with concave walls, or rooms with a ceiling height equal to the height or width. Splayed walls and ceilings are dramatic, but necessary only as opposing surfaces which cannot be covered with mid and high frequency absorptive material, such as large vision panels and glass doors.

Controlling the T 60 of a room yields the most dramatic results. Most medium size radio studios having a T 60 of approximately 0.3 to 0.4 seconds from 100 to 6 k Hz yield a pleasant acoustic environment. Unlike the massive solids that are used for acoustic isolation, the most common absorptive materials are light and porous. The most common materials that are commercially available for absorbing sound are carpeting, acoustic tile ceilings, and fiberglass or polyurethane foam wall panels. The difficulty in using these materials in broadcast studios, is that they provide only mid and high frequency absorption. Exclusive and excessive use of these materials can cause a studio to become "boomy", by causing it to have too long a T 60 at low frequencies in proportion to the short T 60 at the higher frequencies which they can absorb.

An acoustic consultant can specify the design of resonant slot, hole, and panel absorbers, as well as extra thick mineral fiber materials to absorb low frequency sound. Boominess can also be decreased by adding a thick fiberglass blanket above a lay-in tile ceiling; and using commercial absorptive materials in their thickest available form. Applying 3 or 4 foot widths of these materials with 2 or 3 foot spacings between them may also help balance the T 60s at low and high frequencies. However, to avoid reflective echoes, no hard untreated surface should ever oppose another either parallel or at an acute angle to it.

In combination control rooms, mechanical equipment such as broadcast cartridge machines and reel to reel tape decks should be surrounded with as much absorptive material as practical. This will help absorb some of their mechanical sounds which might otherwise be reflected toward the host's microphone. Also, try to avoid placing the console microphone position too close to a vision panel. Whether omnidirectional or cardioid, any conventional microphone requires a free field behind it; and will color the sound it picks up from the front, if a reflective surface is present behind it.

Large television studios often derive their acoustic characteristic more from their sets and backdrops, than from any materials purposely installed for acoustic purposes. Since any portion of a studio wall may be exposed at one time or another, it's a good idea to cover the walls with absorptive mineral batts. The batts should be protected by a wire mesh, to keep them from disintegrating when props and sets are stored up against them. The ceiling, above the lighting grid, should also be heavily absorptive, especially since large portions of the floor will remain reflective. It is important to keep the T60 of the television studio quite low to minimize the transmission of camera and crew noises, and to permit greater talent to microphone distances without an "off-mike" quality. Hard, concave, acoustically reflective sets should be avoided, since any combination of these tends to reflect unwanted sound toward the talent microphones in front of them.

The most reliable rule of thumb in acoustics is that treating low frequency problems is always more difficult and expensive than mid and high frequency work. If the budget is tight, always assign top priority to sound transmission considerations. Once the facility is built, little can be done to make up for economies made in the basic construction, while considerably more flexibility for improving interior room acoustics will remain.

TABLE 1. Reduction in the sound insulation, (*R*) of a partition due to acoustic leakage through various size openings.

Example: Partition with R = 60 dB

SIZE OF OPENING	RESULTANT R
0%	60 dB
0.1%	30 dB
1.0%	20 dB
10.0%	10 dB
50.0%	3 dB

ESTIMATING COSTS

During the last few years cost increases have been been continuous and are unpredictable. They

must be examined carefully by competent architects and construction engineers for the specific structure and area involved, if there is to be any accuracy in budgeting the project.

Two major factors contributing to cost overrun on projects are inadequate initial plans and the resultant change orders during construction. Also, there must be an owner's supervisor highly involved in the project on a daily basis.

In each case, a general contractor was retained and coordination was handled by staff engineering personnel.

Electrical costs include power to all equipment, but not wages paid to staff technicians who installed the broadcast equipment.

Architectural and consulting fees are for outside help only. No attempt was made to estimate.

TOTALS

New studios and offices (complete new structure)	$82 to $138/sq. ft.
Conversion for studios & offices (in existing structure	$40 to $65/sq. ft.
Transmitter building (new structure)	$61 to $98/sq. ft.

SEPARATE ELEMENTS

Demolition and site work	$1.80 to $3.00/sq. ft.
Structural	$9.00 to $14.00/sq. ft.
General construction	$18.00 to $50.00/sq. ft.
Heating, ventilating and air conditioner	$9.00 to $16.00/sq. ft.
Electrical	$5.40 to $18.00/sq. ft.
Plumbing	$1.35 to $4.00/sq. ft.
Arch & Engineering fees	$2.25 to $7.00/sq. ft.
Special acoustical	$2.70 to $5.00/sq. ft.
Woodwork and built-ins	$1.08 to $3.00/sq. ft.
Office furniture	$2.70 to $7.00/sq. ft.
Decoration	$3.60 to $7.00/sq. ft.

Note: Electronic equipment installation and wiring not covered by any of above. A good general rule is to allow 15 to 25 percent for this in addition to basic equipment cost. Variation is due to location, personnel, working rules, etc.

CONSTRUCTION EXAMPLES*

The examples that follow illustrate construction for TV facilities. The stations are in large cities, with construction being completed between 1980 to 1983.

Note: See Tables 2 and 3 at end of chapter for labor costs and conversion factors.

EXAMPLE A

BOSTON:

There were three basic requirements which the addition had to meet.

1. Provide Corporate and Television Division offices
2. Provide expansion for the WCVB-TV News.
3. Provide a studio and ancillary facilities capable of producing syndicated shows as well as increased local station production.

The available area to build was limited since the property was divided into two types of zoning. This required the expansion to be planned for the area in which the zoning would allow such construction. We were able to meet the codes for parking, but the lack of Public Transportation presented a requirement of additional parking which has not totally been met.

The timetable for the construction of the addition was dictated by the fact that the corporate and Television Division personnel were sharing space with the station. This, as well as wanting to enclose the building before winter set in, pretty much established the schedule of construction. For all practical purposes the construction took approximately 9 months not including engineering and construction drawings.

NOTE: See Fig. 3 & 4

EXAMPLE A (Cost)

New Building—Studio
25,000 sq. ft.

New England Area (Boston)

Demolition & Site	$ 111,000.	/$ 4.44
Structural	255,000.	/$10.20
General Const.	1,694,600.	/$67.68
Decoration	93,700.	/$ 3.75
Heating/Ventilating	315,000.	$12.60
Electrical	225,000.	/$ 9.00
Plumbing	119,000.	/$ 4.76
Architect, Elect. & Mechanical Engrg.	396,000.	/$15.84
Special Woodwork & Built-ins	55,000.	/$ 2.20
Special Acoustical (incl. ceilings)	172,300.	/$ 6.89
		$137.46

NOTE: See Fig. 3 & 4

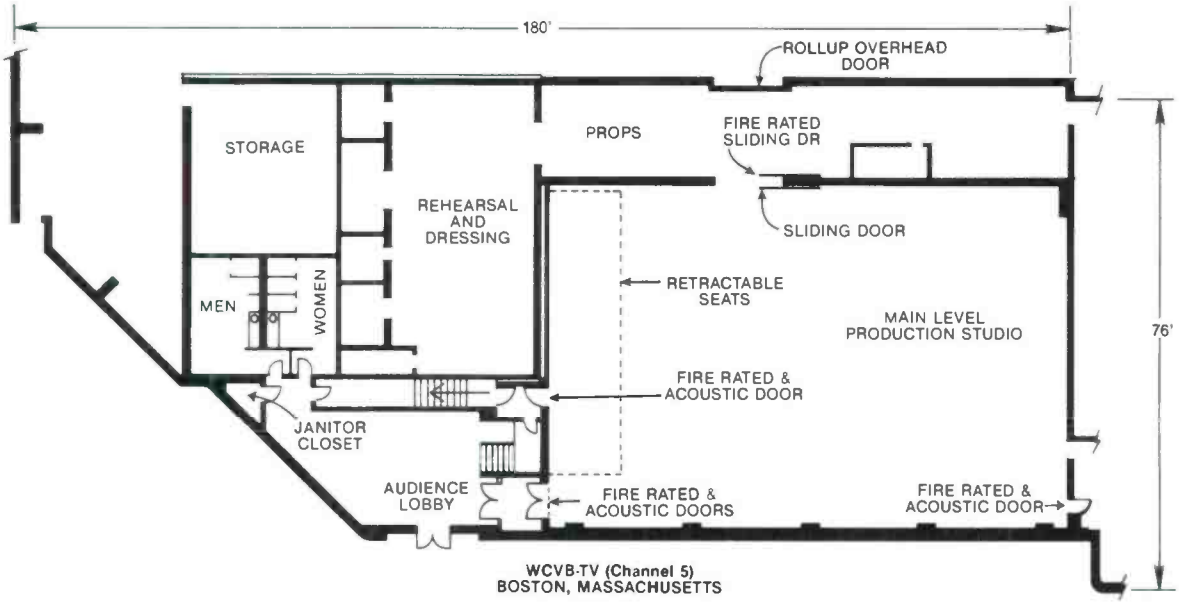


Fig. 3. Production studio addition.

Fig. 4.

EXAMPLE B

HOUSTON:

In relocating the Houston transmitter, we set the following goals:

1. Relocate from downtown site which was being surrounded by buildings taller than our transmitting antenna.
2. Locate in same general area as the existing Houston TV stations.
3. Ideal was to have an antenna height of 2000 feet AMSL.
4. Provide a Principal City Coverage over the same area as the old transmitter site.

We found a site and did get FAA approval for a 2000 foot AMSL antenna height. However, the site did present some problems as it was located on top a salt dome. The salt dome in itself created enough concern that it could require a chapter of its own. Suffice it to say after some lengthy research and a design by a well-known structural engineering firm we erected the tower or should I say towers as there were two towers 100 feet apart. The foundation design was such that the tower foundations as well as the transmitter buildings were all a part of one foundation.

The transmitter and antenna were selected on the basis of a practical consumption of primary power and with transmission line loss and antenna gain would give 5 Megawatts radiated power.

NOTE: See Fig. 5 & 6

EXAMPLE B (Cost)

New Building—Transmitter
2,300 sq. ft.

Gulf Coast Area (Houston)

Demolition & Site		
Structural	$ 29,000.	/$12.72
General Const.	77,000.	/$33.77
Decoration	6,000.	/$ 2.63
Heating & Ventilating	15,000.	/$ 6.59
Electrical	67,898.	/$29.78*
Plumbing	10,000.	/$ 4.39
Architect, Elect. & Mechanical Engrg.	14,730.	/$ 6.46
Special Woodwork & Built-ins	4,000.	/$ 1.75
Special Acoustical (incl. ceilings)		
		$98.09

NOTE: See Fig. 5 & 6

*Includes Auxiliary Generator, Pad and Roof

AM AND FM STUDIO FACILITIES

Building Planning

One of the prime requisites for a successful broadcast station is the careful layout of studio, production, and administrative areas to achieve maximum effectiveness of space and personnel. The following are four typical layouts depicting a small market minimum staff facility to an arrangement suitable for a large metropolitan operation employing a full complement of personnel. Each floor plan is handled differently according to the needs of different size stations.

Control room, studio, and production facilities for each station are in a centrally located CORE AREA. The suggested sizes of these areas should be considered as minimum from an operating standpoint with normal equipment complement. The layouts are presented as a guide for planning a modern, functional radio facility with considerations given to size of market, staff and programming requirements.

Plan One

With approximately 1,800 sq. ft., this floor plan provides adequate space for the small AM or FM station with a minimum staff. Since smaller staffs have several responsibilities, partitioned general office space is omitted in favor of a large news, transcription storage, and general-use area at the rear of the building.

The transmitter or workshop area is next to the control room, with a window recommended for a clear view of the transmitter meters. Alternate CORE AREA layouts are shown.

The building is of brick and plaster fascia, and includes a glass curtain wall. The building price will vary considerably depending on area construction costs; but a typical range is $60,000 to $75,000 (See Fig. 7).

Plan Two

In medium size stations, office space requirements for sales, promotion, and programming activities exceed the need for a substantially larger technical CORE AREA. This floor plan expands the "small station" layout to approximately 2,500 sq. ft., providing more room for the sales staff and clerical help, and an impressive office for the general manager. Studio and control room space is slightly larger in anticipation of more equipment and activities in these areas. The news director, transcription library, and chief engineer gain office space. Alternate CORE AREA layouts may be employed, and a few suggestions are indicated.

The building includes brick walls, weathering steel columns, and fascia, with dark glass entrance and glazing strips. Cost is approximately $65,000

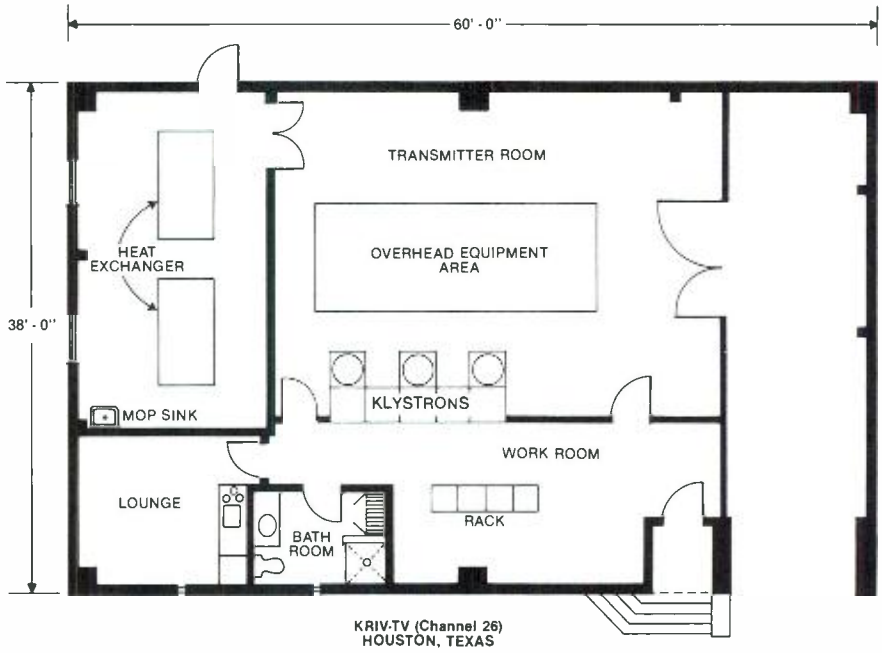


Fig. 5. Transmitter building.

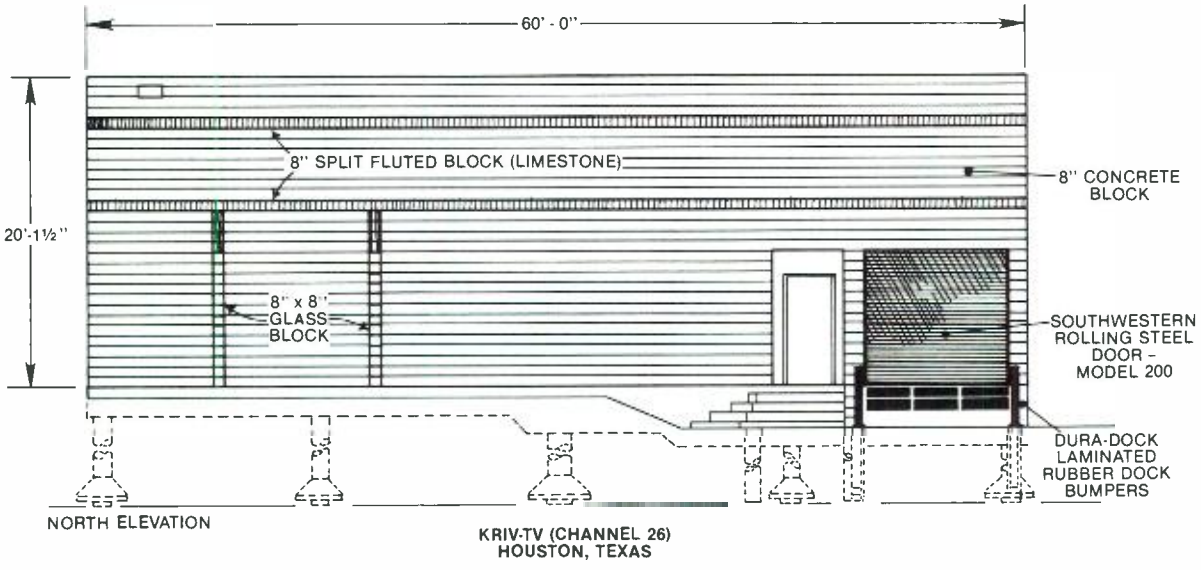


Fig. 6. Transmitter building.

to $90,000, but may vary considerably, depending on construction costs in your area. (See Fig. 8)

Plan Three

In Plan 3, the technical CORE AREA is adequate for two full-size control rooms, each with a large associated studio. Control rooms are separated by the transmitter, automation, or workshop area. This floor plan includes approximately 3,150 sq. ft. and is suggested for stations planning both AM and FM operations. Additional office space is also allocated for the larger staff in this station. See alternate CORE AREA floor plans for additional layout ideas. The mirror glass curtain wall building is set in a reflecting pool and costs approximately $90,000 to $135,000. Note: building cost may vary greatly, depending on the area in which it is built. (See Fig. 9)

Plan Four

This 4,300 sq. ft. studio/office complex is an impressive broadcast center. Of primary importance is the location of all control room and studio space in the center of the building, eliminating the problem of outside traffic noise in a metropolitan area.

Operating personnel are assigned to the rear office areas, and the news room is strategically located near the control rooms and an outside exit to the newsmobiles.

The building is of exposed concrete, with a dark glass curtain wall. Building price is approximately $100,000 to $150,000, but may vary greatly from area to area, depending on material and labor costs. (See Fig. 10)

CONTROL ROOM ANNOUNCE BOOTH DESIGN

Many present-day radio control rooms are not only used for this purpose but also act as announce booths where most of a station's announcing is carried on. In many cases the control room may be the only studio area in a station, and it will contain all the audio equipment of the station. Frequently, a transmitter and record library will also be located in the control room. This makes the problem of acoustics more complex but since radio sells with sound, good acoustics are a must when the best sound possible is desired.

Design Factors of combination control rooms are at best a compromise of the several design factors. In the design of this control room, consideration must be given to the following:

1. Location of the control room within the studio building;
2. Isolation: elimination of unwanted sound and noise, both internal and external;
3. Construction: dual wall, floating wall, single wall;
4. Reverberation control, elimination of unwanted reflections, and floor treatment;
5. Ventilation and air conditioning;
6. Size and arrangement of equipment;

Note: See section on ACOUSTICS in this chapter for more detail.

RADIO STUDIOS ON A LOW BUDGET

Considerations Involved in Building an AM or FM Station with Less Than an Optimum Budget

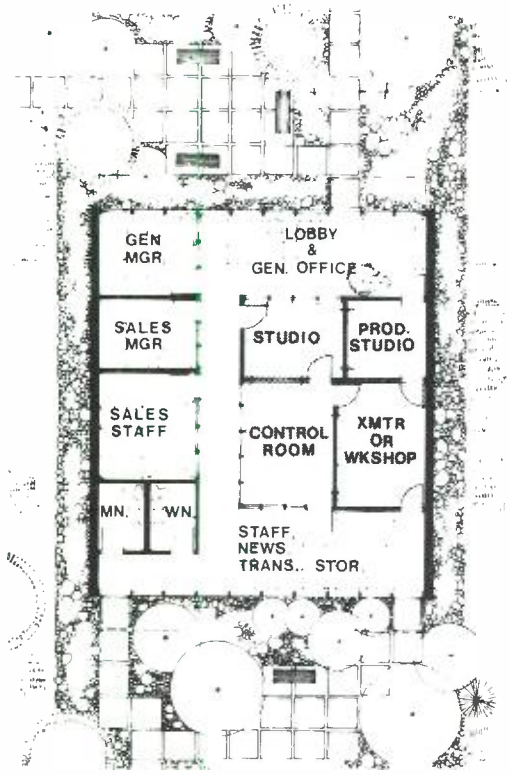
It would be easy to apply one set of standards for the construction of radio station facilities everywhere in the country. Unfortunately, the difference in cashflow of a 50,000-watt clear channel in a major market and a 250-watt daytime or Class A FM in a rural area dictate that the small market station is going to be quite different than its big city counterpart. In most cases, the selection of a studio site in a small market is dictated by what it costs to get the space. It is not unusual for space to be traded out in part or in full for advertising.

In many cases, the chief engineer will be presented with an existing suite of offices, a store front or even an older house that must be converted to a studio. The first thing to do in this situation is call a meeting of management, sales, and programming to see what they expect of the facility. If it is a typical small market station, it will fall within the following requirements:

1. Record shows: combination operation. Announcer playing records, taped commercials.
2. Direct airplay or recording beeper reports for later use in newscasts, farm reports, high school news.
3. Facility for picking up remotes from high school or college athletic events, church remotes.
4. Capacity of recording and dubbing commercials for later airplay.
5. Capacity for originating a live music program from your studio. (Quite often a church will use a studio to do a small service rather than invest in phone lines and remote equipment!)
6. Delayed programming such as a telephone talk, call in forum or swap shop show.
7. Remote off-air pickup of other AM and FM stations for rebroadcasting regional networks.

SMALL MARKET MINIMUM STAFF

Fig. 7. Small size AM station equipment list (Plan One).



Studio equipment (monophonic):

1	8-Mixer Console, mono
2	12" Turntable
2	Integrated Circuit Equalized Preamplifier, mono
2	12" Tone Arm
2	Stereo Cartridges (Outputs connect in parallel for monaural operation)
3	8'' Loudspeaker
3	Speaker Matching Transformer
3	Wall cabinets for Speaker
1	Cardioid Microphone
2	Dynamic Omnidirectional Microphones
1	Boom Stand
1	Desk Stand
1	Clamp-on Mike Stand
4	Wall Receptacles for Microphone
4	Microphone Plugs
4	Connectors
100′	2-Conductor #20 Microphone Cable, jacketed
500′	Shielded Miniature Audio Cable
1	Headphone
1	Phone Plug for Headphone
2	Studio Clocks

Studio equipment options (stereophonic)

1	Stereo Console
2	Stereo Equalized Preamplifier

Remote Broadcast Equipment:

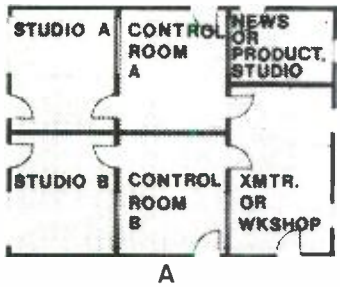
1	4-mixer Transistor Amplifier, Less Batteries
1	Battery Kit
1	Headphone
1	Plug for Headphone
1	Dynamic Microphone with 18 Ft. Cable
1	Plug for Microphone

Tape Recording Equipment:

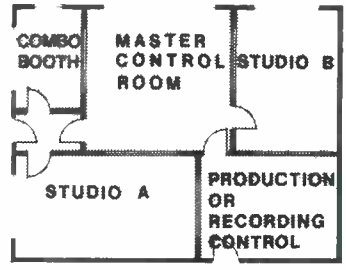
1	Half-Track Portable Tape Recorder, 7½'' per sec.
2	Cartridge Playback, mono
1	Recording Amplifier for above, mono
24	Cartridges, 40 Sec.
24	Cartridges, 70 Sec.

Remote Control Equipment for Unattended Operation:

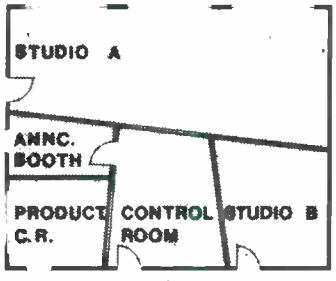
1	Remote Control System for unattended operation
1	RF Amplifier with Antenna
1	Rack Cabinet



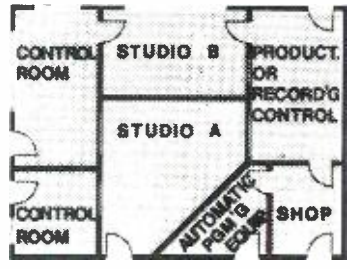
A



B



C



D

alternate "core area" plans

MEDIUM MARKET NORMAL STAFF

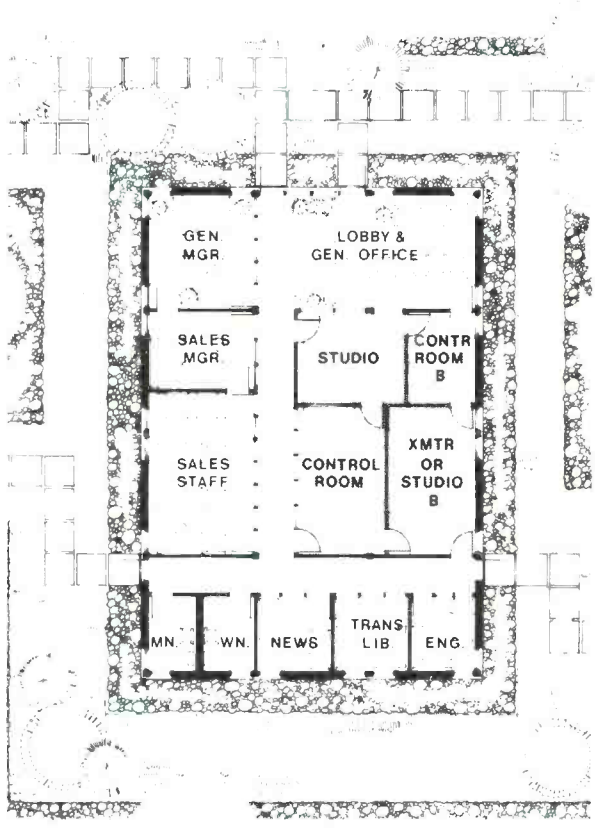


Fig. 8. Medium size AM station equipment list (Plan Two).

Studio Equipment:

1	8-Mixer Console, Monaural
2	12'' Turntables
2	Integrated Circuit Turntable Preamplifier
2	12'' Tone Arm
2	Stereo Cartridge (Outputs connected in parallel for monaural operation)
3	8'' PM Type Loudspeaker
3	Speaker Matching Transformers
3	Wall Cabinets for Speakers
1	Cardioid Microphone
2	Dynamic Omnidirectional Microphones
1	Boom Stand
1	Desk Stand
1	Clamp-on Mike Stand
4	Wall Receptacles for Microphone
4	Microphone Plugs
4	Connectors
100′	2-Conductor #20 Microphone Cable, Jacketed
500′	Shielded Miniature Audio Cable
1	Headphone
1	Phone Plug for Headphone
2	Studio Clocks.

Remote Broadcast Equipment:

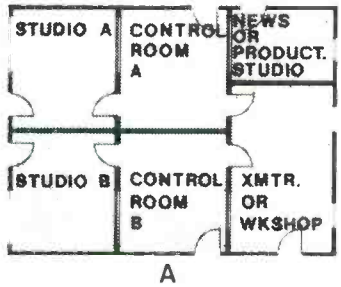
1	4-Mixer Transistor Amplifier, less batteries
1	Headphones
1	Phone plug
1	Omnidirectional Microphone

Tape Recording Equipment:

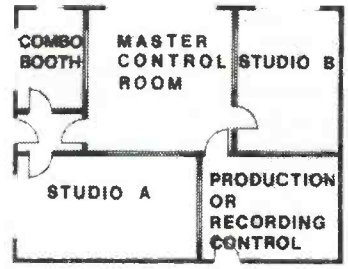
1	Half-track Portable Tape Recorder, 7½ in. per sec.
1	Cartridge Playback Unit and Recording Amplifier, one tone, desk mount
1	Cartridge Playback Unit, Desk Mount
24	40 Sec. Cartridges
24	70 Sec. Cartridges

Remote Control Equipment for Unattended Operation:

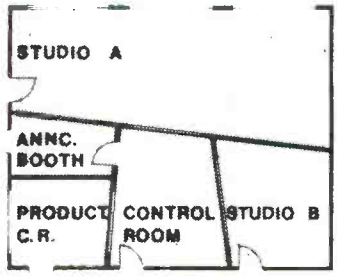
1	Remote Control System for unattended operation of transmitter
1	RF Amplifier with antenna
1	Rack Cabinet.



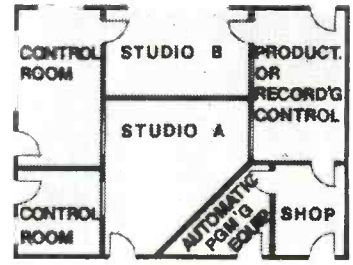
A



B

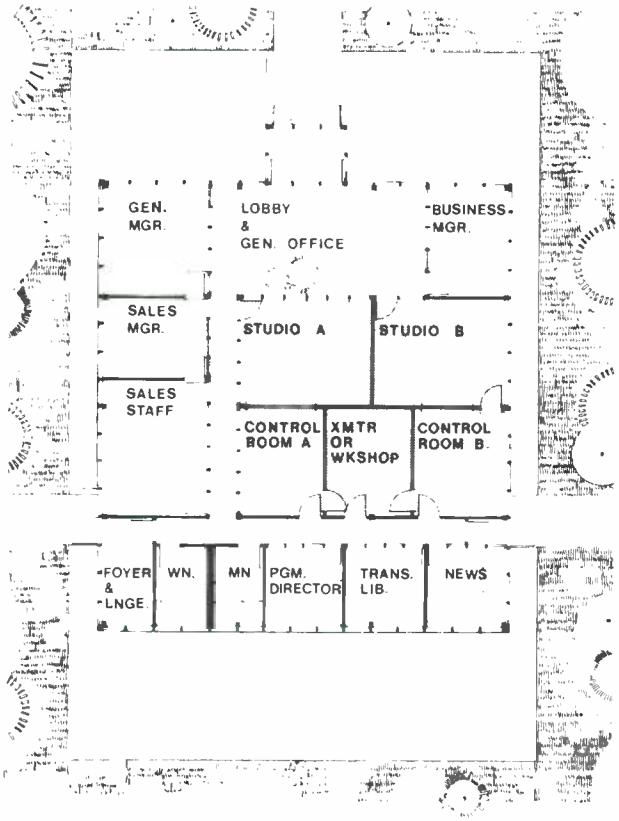


C



D

alternate "core area" plans



AM-FM OR DUAL CONTROL ROOM OPERATIONS

Fig. 9. AM/FM dual control room equipment list (Plan Three).

Transmitter Audio Equipment:
- 1 Rack Cabinet
- 1 AM Solid State Limiting Amplifier
- 1 FM Solid State Limiting Amplifier

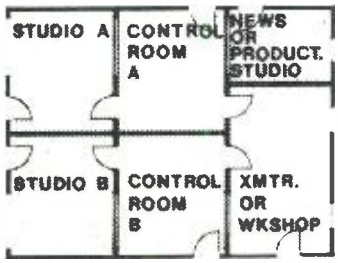
Monitors:
- 1 AM Modulation Monitor, Solid State
- 1 EBS Monitor
- 1 FM Modulation Monitor

Studio Equipment
- 1 8-Mixer Console, Monaural
- 2 12'' Turntables
- 2 Integrated Circuit Turntable Preamplifier
- 2 12'' Tone Arm
- 2 Stereo Cartridge (Outputs connected in parallel for monaural operation)
- 3 8'' PM Type Loudspeaker
- 3 Speaker Matching Transformer
- 3 Wall Cabinets for Speakers
- 1 Cardioid Microphone
- 2 Dynamic Omnidirectional Microphones
- 1 Boom Stand
- 1 Desk Stand
- 1 Clamp-on Mike Stand
- 4 Wall Receptacles for Microphone
- 4 Microphone Plugs
- 4 Connectors
- 100' 2-Conductor #20 Microphone Cable, jacketed
- 500' Shielded Miniature Audio Cable
- 1 Headphone
- 1 Headphone Plug
- 2 Studio Clocks.

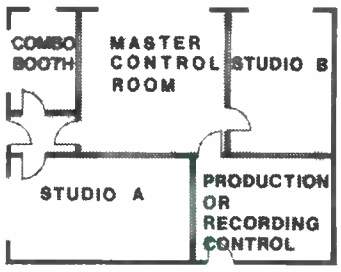
Remote Broadcast Equipment
- 1 4-Mixer Transistor Amplifier, less batteries
- 1 Headphones
- 1 Phone Plug
- 1 Dynamic Omnidirectional Microphone

Tape Recording Equipment
- 1 Half-track Portable Tape Recorder, 7½ in. per sec.
- 1 Cartridge Playback Unit and Recording Amplifier, one tone, desk mount
- 1 80 Cartridge Playback Unit, Desk Mount
- 24 40 Sec. Cartridges
- 24 70 Sec. Cartridges

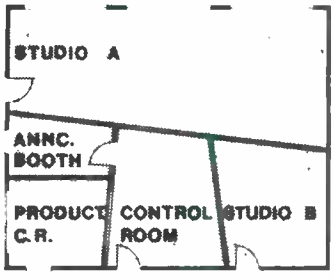
Remote Control Equipment for Unattended Operation
- 1 Remote Control System for unattended operation of transmitter.



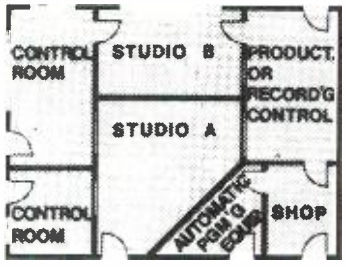
A



B



C

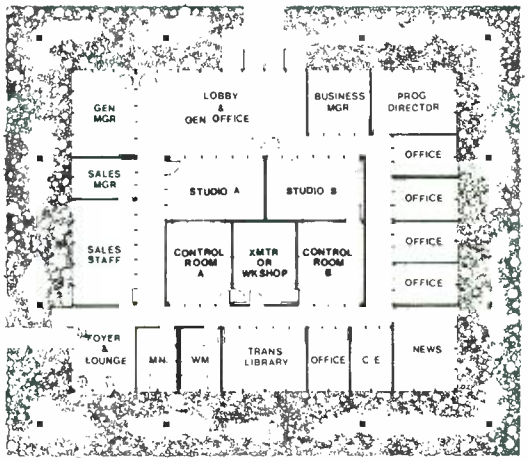


D

alternate "core area" plans

METROPOLITAN MARKET FULL STAFF

Fig. 10. Metropolitan market full staff (Plan Four).



Transmitter Audio Equipment (monophonic)
- 1 Rack Cabinet
- 1 FM Solid State Limiter

Monitors
- 1 FM Frequency Measuring Unit
- 1 FM Modulation Monitor
- 1 EBS Monitor

Stereo Options
- 1 Stereo Generator
- 2 FM Solid State Limiters, matched
- 1 Stereo Modulation Monitor
- 1 19 kHz Pilot Frequency Comparator

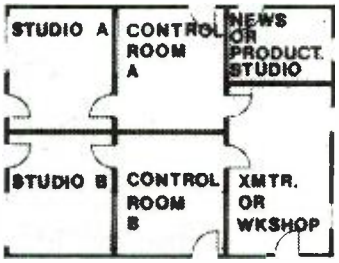
Studio Equipment (monophonic)
- 1 8-Mixer Console, mono
- 2 12'' Turntable
- 2 Equalized Preamplifier
- 2 12'' Tone Arm
- 2 Stereo Cartridge (Outputs connect in parallel for monaural operation)
- 3 8'' Loudspeaker
- 3 Speaker Matching Transformer
- 3 Wall Cabinets for Speaker
- 1 Cardioid Microphone
- 2 Dynamic Omnidirectional Microphones
- 1 Boom Stand
- 1 Desk Stand
- 1 Clamp-on Mike Stand
- 4 Wall Receptacle for Microphones
- 4 Microphone Plugs
- 4 Connectors
- 100′ 2-Conductor #20 Microphone Cable, jacketed
- 500′ Shielded Miniature Audio Cable
- 1 Headphone
- 1 Phone Plug for Headphone
- 2 Studio Clock

Studio Equipment Stereo Options
- 1 Stereo Console
- 2 Stereo I.C. Equalized Preamplifier

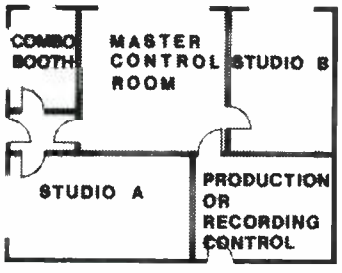
Remote Broadcast Equipment
- 1 4-mixer Transistor Amplifier, Less Batteries
- 1 Battery Kit
- 1 Headphone
- 1 Plug for Headphone
- 1 Dynamic Microphone with 18 Ft. Cable
- 1 Plug for Microphone

Tape Recording Equipment
- 1 Half-Track Portable Tape Recorder, 7½'' per sec.
- 2 Cartridge Playback, mono
- 1 Recording Amplifier for above, mono
- 24 Cartridges, 40 Sec.
- 24 Cartridges, 70 Sec.

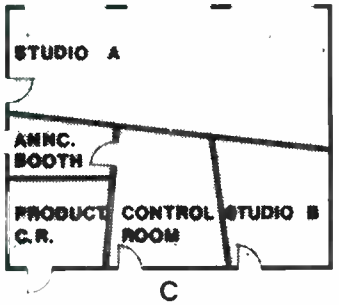
Remote Control Equipment for Unattended Operation
- 1 Remote Control System for unattended operation
- 1 RF Amplifier with Antenna
- 1 7 Rack Cabinet



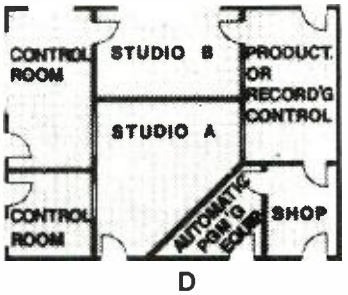
A



B



C



D

alternate "core area" plans

8. Remote pickup of mobile units and portable transmitters for news actualities and other events.

If the station is a new or growing operation and cannot afford the equipment to do all of the above, at least consider what functions may be required at a future date. For this reason plan now for what might be needed in two years.

Physical Layout

This will depend largely on what is available. The bare bones minimum control room known to be used was 6 ft. wide by 7 ft. deep. There was barely enough room for an operator, two turntables, cartridge machines, and a console. It worked.

The operation was well constructed, well maintained and well utilized. The technical quality of the programming was as good as many large operations in major markets, so it can be accomplished with small space.

When laying out studio location, do the following:

1. Draw a sketch of the available floor space and existing walls.
2. Make a number of copies of this floor plan and start drawing in studios, offices, reception areas and the like. Make three or four.
3. The first items you want to place are the main studio and control room. In smaller operations these are one and the same. Naturally they must be quiet, so keep them away from noisy areas such as underneath heavily traveled stairways, air conditioners, and front windows opening on busy streets. The control room floor should be very solid. The most desirable material to use if you are building a studio is reinforced concrete. If you are stuck with a wooden floor try and select a location that does not bounce. People walking on such a floor will cause the floor to move. This motion is transmitted to the turntable cabinet to the tone arm where it is picked up and sent over the air. In extreme cases, a heavy person can cause the needle to jump out of the groove. Sandbags or bricks in the base of the turntable cabinet will sometimes improve a bad situation.

   Another item that will determine placement of the control room is visibility of the meters on the transmitter and its associated monitoring equipment. FCC rules and regulations have recently changed regarding this requirement and undoubtedly will change in the future. Check the rules before you build. If you are fortunate enough to be putting in your own walls, stay away from designing perfectly square rooms. A room that is 8 by 8 by 8 ft. is going to have a very definite resonance. Strive for 6 by 8 by 10 ft. or dimensions in this proportion. Sound locks while desirable are not essential. Doors of solid construction with weatherstripping can be used effectively.
4. Measure some typical office furniture and cut out cardboard desks, file cabinets, counter tops and record cabinets to scale. Put in your furniture and see how it fits. Is there room for people to move around? Did you leave room for doors to open and close? Remember not to have doors open out into busy hallways where people will walk into them as they pass by. Doors come in all sizes. The average door in most stations is 3 ft. wide. If you get into a space problem this can be reduced by 6 inches or even a foot. But remember that you will be moving furniture and equipment in and out of that door and you should provide room for it to go in and out and be turned once it's in the room. The narrowest hallways should be no less than 3 ft. 6 in., preferably 4 ft. Also be aware that hallways take up space. For every square foot of hallway you eliminate you get an equal amount of space that can be used for something productive.

Equipment

In a low-budget situation remember this rule of thumb, "Is what I am about to buy going to pay for itself and make the station money?"

The purchase of a $200 directional microphone to do a one time remote broadcast when being paid only $100 for the whole job is poor business.

Use this logic when equipping the station. As mentioned earlier, create a list of those functions you will have to perform, spend only what is needed to get on the air and function. However, do plan for the future. Design around a console with enough inputs to accommodate these anticipated needs. A four potentiometer board is not enough for most operations. Even the smallest stations should have six or eight pots. A four pot board will be satisfactory today but two years later it will not. If the station is a one studio operation, how will the console be replaced while on the air? It makes good sense to purchase the proper console in the beginning.

Do not forget the patch panel. There is a growing tendency among engineers today to eliminate this important switching center. All high level inputs and outputs should appear here. Even console inputs should show up. This also applies to all recorders, tuners, and other audio sources. This practice makes for a very versatile operation and can save the embarrassment of dead air time if the console should fail. If this happens,

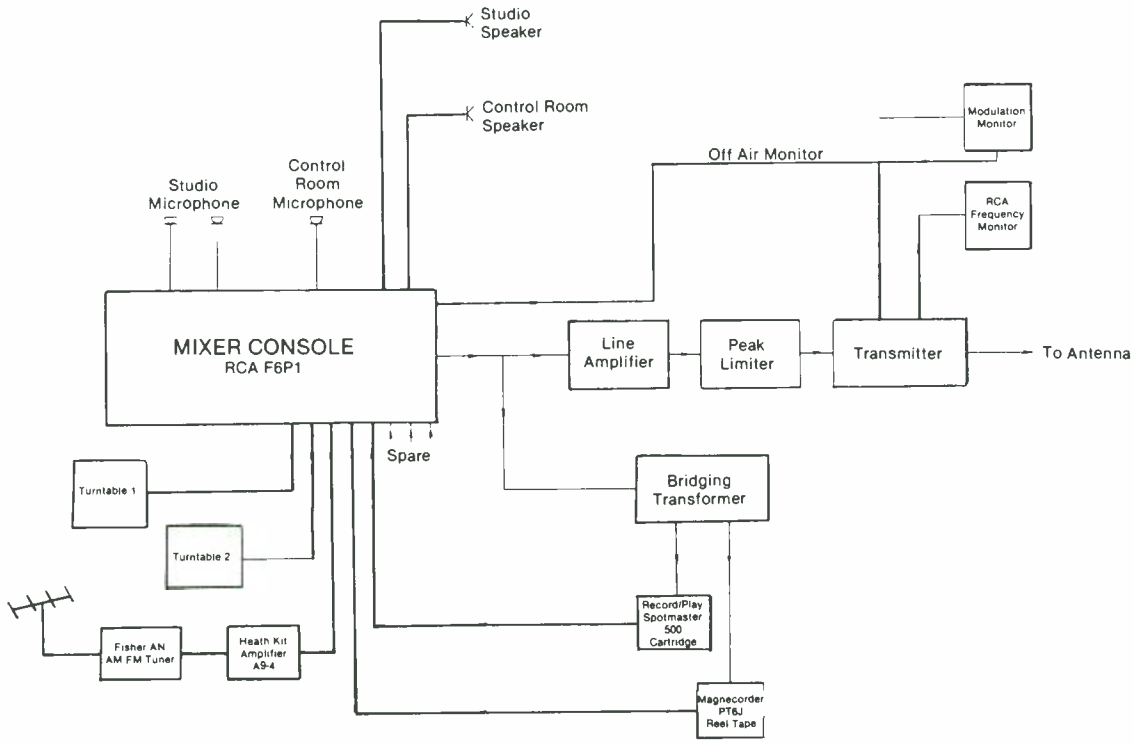


Fig. 11. Audio flow diagram from station WBME-AM.

the recorder can be patched directly to the transmitter, bypassing the defective elements in the system.

Fig. 11 shows the audio flow in a typical small market radio station with the bare essentials. This was installed at WBME-AM in Belfast, Maine. It should be considered a minimum installation. One cartridge tape machine, one reel tape, audio processing equipment and a transmitter. This system can be expanded to include other program sources as the station's needs grow.

Figs. 12 and 13 show the audio flow and physical layout of a Class C FM station in Topeka, Kansas. Note the versatility here. The studio can be operated through the automation system as a source. In the event of an emergency, the announcer can remotely connect the output of the console to the STL, bypassing the automation system. In the event of an STL failure, the audio can be patched directly to the transmitter via the remote control system line.

In selecting equipment for a small station, one may consider used equipment. U.S. made broadcast equipment is built to last. It is not unusual to see transmitters in regular use after 30 years. The same can apply for consoles, amplifiers, and some other audio equipment. However, if you purchase something this old, the chances are that the manufacturer will no longer be able to supply spare parts. Most equipment suppliers will maintain spares for 20 to 25 years. Do not get the impression that spare parts are no longer made, they just are not stocked by the equipment manufacturer. In many cases, it will be necessary to seek out the item wanted from the original component manufacturer.

Special items such as modulation and plate transformers can be rebuilt or fabricated; it can be costly but it can be done.

When buying a piece of used equipment, try and get the previous owner to throw in his spare tubes and other parts. Also obtain a history of the unit and where parts can be obtained. It is also advisable to find other owners of the same type of unit.

As mentioned previously in some instances, the licensee either has an available structure or wishes to take advantage of an existing structure to use as the nucleus of his broadcase facility. In such cases, the existing structure is usually a house or a desirable piece of property that can be easily expanded or converted into the studio/ transmitter building.

An excellent example of this concept is station WNHV, White River Junction, Vermont, that expanded upon an existing building to develop a very efficient and workable broadcast facility. Fig. 14 depicts the changes which were made to the existing building with the resulting added floor space.

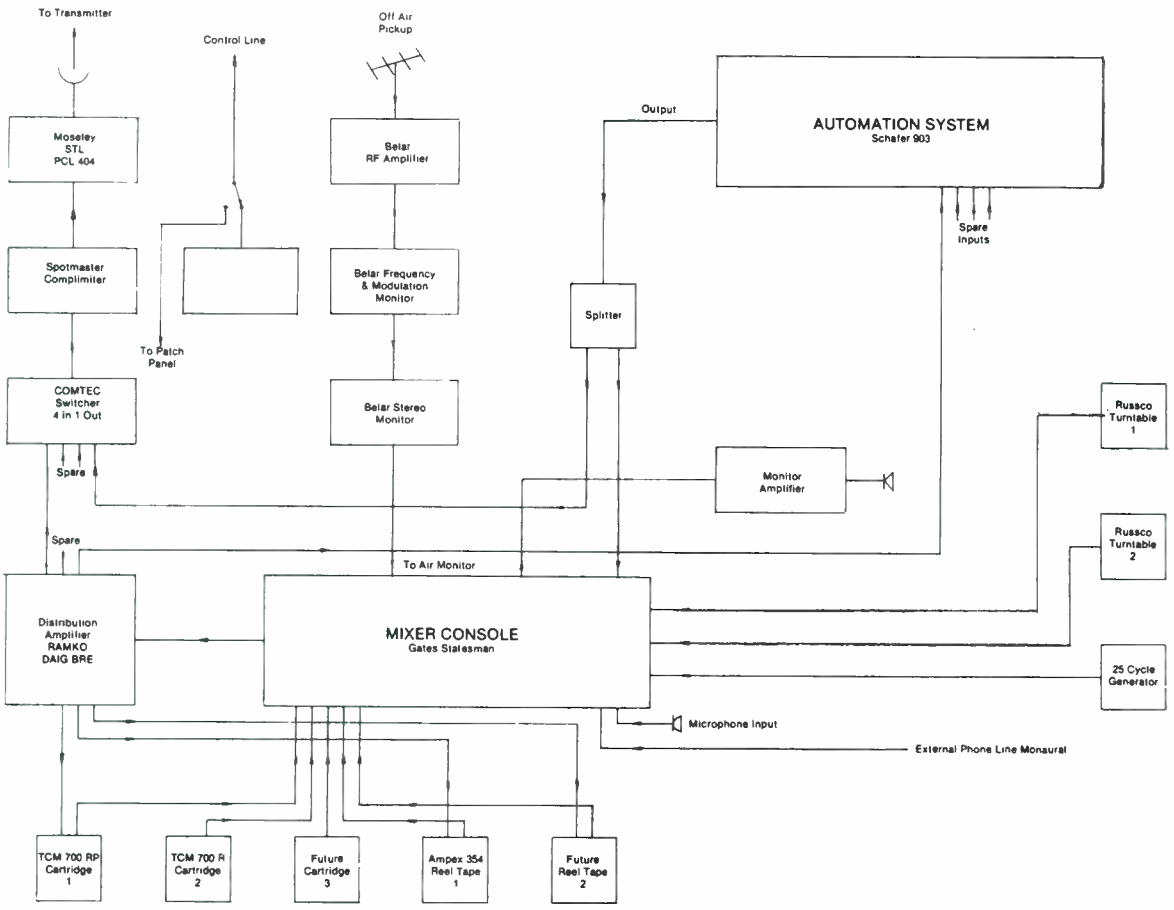


Fig. 12. Audio flow diagram from station KTPK-FM.

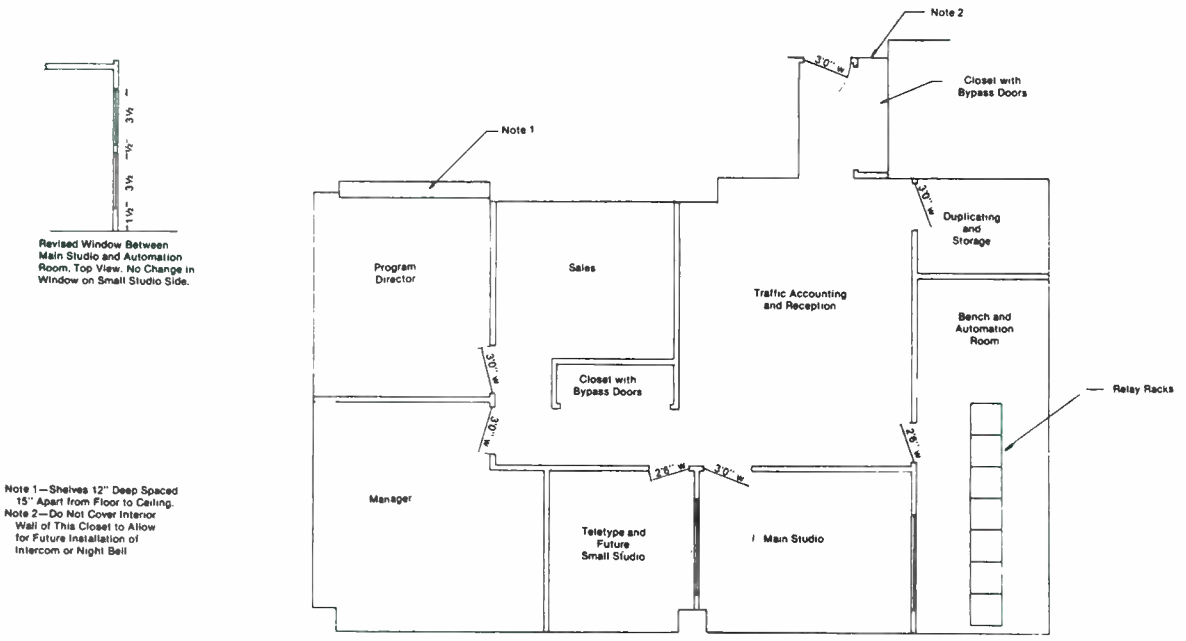


Fig. 13. Studio layout for station KTPK-FM, Topeka, Kansas.

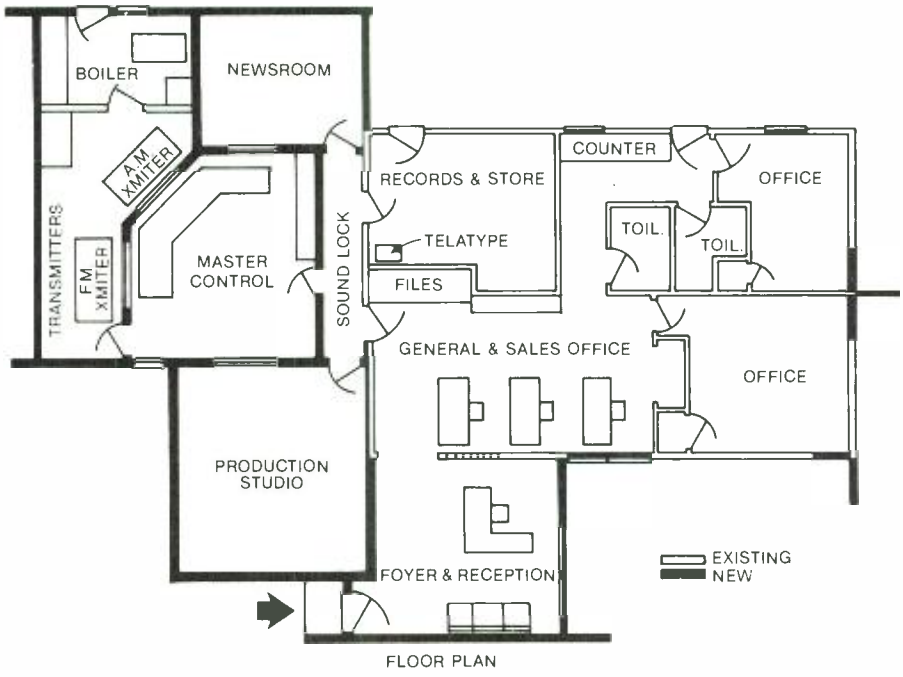


Fig. 14. Additions and alterations to WNHV radio station, White River Junction, Vermont.

The nucleus of this building was a nondescript, small house which was ultimately camouflaged behind additions and beneath new materials. Much attention was given to sound conduction, natural and artificial lighting, and controlled ventilation. Aluminum was used extensively throughout in conformance to the licensees needs. The modification added a total of 1,120 sq. ft., compared to 864 sq. ft. in the existing structure. Cost in 1984 would be between $20,000 and $35,000.

TABLE 2. Industrial and commercial division* — hourly labor costs.

The hourly labor costs shown in the column headed "Hourly Cost Including Subcontractor's 30% Markup" have been used to compute estimates in the "Labor" column on pages 212 to 457 of this book. All figures are in U.S. dollars per hour.

"Hourly Wage and Benefits" includes the wage, welfare, pension, vacation, apprentice and other mandatory contributions. The "Employer's Burden" is the cost to the contractor for Unemployment Insurance (F.U.T.A.), Social Security and Medicare (F.I.C.A.), state unemployment insurance, worker's compensation insurance and liability insurance. Tax and insurance expense included in these labor-hour costs are itemized in the sections beginning on pages 103 and 191.

These hourly labor costs will apply within a few percent on many jobs. But wages may be much higher or lower on the job you are estimating. If the hourly cost on this page is not accurate, divide your known or estimated cost per hour into the listed cost per hour. The result is your adjustment for any figure in the "Labor" column for that trade.

For example, the hourly cost (including 30% subcontractor's markup) for a carpenter is given as $32.08. Assume your carpentry subcontractor can be expected to charge 10% more, $35.29 per hour. Your adjustment is plus 10%. On page 285 the cost of laying 3/8" CD plywood roof sheathing is listed at $278. Your cost would be 10% more, $305.80

If you don't know what wage rates will apply on the job being estimated, use the table that begins on the following page. It shows estimated union wages in over 100 U.S. cities in percent of the wage listed below.

Trade	Hourly Wage and Benefits	Typical Employer's Burden (%)	Employer's Burden ($) Per Hour	Hourly Cost	Hourly Cost Including Subcontractor's 30% Markup
Air Tool Operator	16.64	25.8	4.29	20.93	27.21
Asbestos Worker	20.05	27.4	5.49	25.54	33.20
Boilermaker	21.98	20.9	4.59	26.57	34.54
Bricklayer	19.32	22.6	4.37	23.69	30.80
Bricklayer's Tender	14.61	22.6	3.30	17.91	23.28
Building Laborers	15.57	23.2	3.61	19.18	24.93
Carpenters	19.56	26.2	5.12	24.68	32.08
Cement Masons	19.11	20.2	3.86	22.97	29.86
Crane Operators	19.99	25.2	5.04	25.03	32.54
Drywall Installers	20.25	21.2	4.29	24.54	31.90
Drywall Tapers	17.14	21.2	3.63	20.77	27.00
Electricians	22.43	18.7	4.19	26.62	34.61
Elevator Constructors	21.24	18.2	3.87	25.11	32.64
Floor Layers	22.26	20.0	4.45	26.71	34.72
Glaziers	19.52	24.9	4.86	24.38	31.69
Iron Workers (Structural)	20.89	36.8	7.69	28.58	37.15
Lathers	19.42	20.6	4.00	23.42	30.45
Marble Setters	23.30	22.6	5.27	28.57	37.14
Millwrights	20.10	26.2	5.27	25.37	32.98
Mosaic & Terrazo Workers	17.73	20.0	3.55	21.28	27.66
Painters	19.08	23.0	4.39	23.47	30.51
Pile Drivers	18.73	31.6	5.92	24.65	32.05
Pipefitters	22.11	19.9	4.40	26.51	34.46
Plasterers	18.97	25.8	4.89	23.86	31.02
Plasterer's Helper	14.28	25.8	3.68	17.96	23.35
Plumbers	21.64	19.9	4.31	25.95	33.74
Reinforcing Ironworkers	20.53	21.5	4.41	24.94	32.42
Roofers, (Composition)	18.12	39.0	7.07	25.19	32.75
Sheet Metal Workers	21.93	21.0	4.60	26.53	34.49
Sprinkler Fitters	21.70	19.9	4.32	26.02	33.83
Tractor Operators	19.87	20.0	3.97	23.84	30.99
Truck Drivers	15.98	26.2	4.19	20.17	26.22

* © 1984 Craftsman Book Co., reprinted with permission.

TABLE 3.

LONG MEASURE

12 inches . . . . . 1 foot
3 feet . . . . . 1 yard
5-1/2 yards . . . . . 1 rod
40 rods . . . . . 1 furlong
8 furlongs . . . . . 1 sta. mile
3 miles . . . . . 1 leogue

SQUARE MEASURE

1 sq. centimeter . . . 0.1550 sq. in.
1 sq. decimeter. .0.1076 square feet
1 sq. meter . . . . . 1.196 sq. yd.
1 acre . . . . . 3.954 sq. rods
1 hectare . . . . . 2.47 acres
1 sq. kilometer . . . 0.386 sq. mile
1 sq. inch . . . 6.452 sq. centimeters
1 sq. foot . . 9.2903 sq. decimeters
1 sq. yard . . 0.8361 square meter
1 square rod . . . . . 0.259 acre
1 acre . . . . . 0.4047 hectare
1 sq. mile . . . . 2.59 sq. kilometers
144 sq. inches . . . . . 1 sq. foot
9 square feet . . . . . 1 square yard
30-1/4 sq. yds. . . . . 1 square rod
40 sq. rods . . . . . 1 rood
4 roods . . . . . 1 acre
640 acres . . . . . 1 square mile

SURVEYOR'S MEASURE

7.92 inches . . . . . 1 link
25 links . . . . . 1 rod
4 rods . . . . . 1 chain
10 sq. choins or 160 sq. rods . 1 ocre
640 acres . . . . . 1 square mile
36 sq. mi. or 6mi. square 1 township

CUBIC MEASURE

1.728 cubic inches . . . 1 cubic foot
128 cubic feet . . . . 1 cord wood
27 cubic feet . . . . . 1 cubic yard
40 cubic feet . . . . . 1 ton shpg.
2,150.42 cu. in. 1 standard bushel
268.8 cu. in.. 1 standard gallon dry
231 cu. in. 1 standard gallon liquid
1 cubic foot about 4/5 of a bushel
1 Perch . . . . . A mass 16-1/2 ft. long, 1 ft. high and 1-1/2 ft. wide, containing 24-2/3 cu.ft.

APPROXIMATE METRIC EQUIVALENT

1 decimeter . . . . . 4 inches
1 meter . . . . . 1.1 yards
1 kilometer . . . . . 5/8 of mile
1 hectare . . . . . 2-1/2 acres
1 stere, or cu. meter . 1/4 of a cord
1 liter 1.06 qt. liquid or 0.9 qt. dry
1 hektoliter . . . . . 2.8 bushels
1 kilogram . . . . . 2.2 pounds
1 metric ton . . . . . 2,200 pounds

METRIC EQUIVALENTS — LINEAR MEASURE

1 centimeter . . . . . 0.3937 in.
1 decimeter 3.937 in. or 0.328 ft.
1 meter . .39.37 in. or 1.0936 yards
1 dekameter . . . . . 1.9884 rods
1 kilometer . . . . . 0.62137 mile
1 inch . . . . . 2.54 centimeters
1 foot . . . . . 3.048 decimeters
1 yard . . . . . 0.9144 meter
1 rod . . . . . 0.5028 dekameter
1 mile . . . . . 1.6093 kilometers

DECIMAL EQUIVALENTS OF FRACTIONS

1/64	.0156	33/64	.5156
1/32	.0312	17/32	.5312
3/64	.0468	35/64	.5468
1/16	.0625	9/16	.5625
5/64	.0781	37/64	.5781
3/32	.0937	19/32	.5937
7/64	.1093	39/64	.6093
1/8	.125	5/8	.625
9/64	.1406	41/64	.6406
5/32	.1562	21/32	.6562
11/64	.1718	43/64	.6718
3/16	.1875	11/16	.6875
13/64	.2031	45/64	.7031
7/32	.2187	23/32	.7187
15/64	.2343	47/64	.7343
1/4	.250	3/4	.750
17/64	.2656	49/64	.7656
9/32	.2812	25/32	.7812
19/64	.2968	51/64	.7968
5/16	.3125	13/16	.8125
21/64	.3281	53/64	.8281
11/32	.3437	27/32	.8437
23/64	.3593	55/64	.8593
3/8	.375	7/8	.875
25/64	.3906	57/64	.8906
13/32	.4062	29/32	.9062
27/64	.4218	59/64	.9218
7/16	.4375	15/16	.9375
29/64	.4531	61/64	.9531
15/32	.4687	31/32	.9687
31/64	.4843	63/64	.9843
1/2	.500	1	1.00

CONVERSION FACTORS

(°C × 9/5) + 32 = °F.
(°F − 32) × 5/9 = °C.
Liter × 1 05671 = U S quarts
Quarts × .946333 = liters
Liters × 61 025 = cu in
Gallons × 231 = cu in
Kilograms × 2 2046 = lbs
Lbs × 453 59 = grams
Ounces (avdp) × 28 35 = grams
Kilowatts × 1 341 = horsepower
Horsepower × 746 = watts
1 atmosphere = 33 899 ft of water at 39 1°F
1 atmosphere = 760 mm of mercury
1 atmosphere = 14 7 lbs per sq in
1 cu ft. water = 62 37 lbs @ 60°F
1 cu in water = 0 036 lbs @ 60°F
Cu meters × 35 314 = cu ft
Cu ft × 0 02832 = cu meters
Centistokes × density = Centipoises
Pounds/gal at 20°C = Specific gravity at 20/20°C × 8 3216
1 cm = 0 3937 in
1 in = 2 540 cm

BUILDING MATERIAL WEIGHTS

ASBESTOS — 110-120 lbs. per cu. ft.
BRICK (Common) — 2-1/2"x4"x8-1/4", 5.4 lbs. each; 2.7 tons — M.
BRICK (Fire) (Standard) — 9"x4-1/2"x2-1/2", 7.0 lbs. each; 3.5 tons — M.
BRICK (Hord) — 2-1/4"x4-1/4"x8-1/2", 6.48 lbs. each; 3.24 tons — M.
BRICK (Paving) — 2-1/4"x4"x8-1/2", 6.75 lbs. each; 3.37 tons — M.
BRICK (Paving Block) — 3-1/4"x4"x8-1/2", 8.75 lbs. each; 4.37 tons — M.
BRICK (Soft) — 2-1/4"x4"x8-1/4", 4.32 lbs. each; 2.6 tons — M.
CEMENT — Bag — 94 lbs. eoch; bbl. weighs 376 lbs.
CLAY (Dry) — 63-95 lbs. — cu. ft.; 1700-2295 lbs. — cu. yard
CLAY (Fire) — 130 lbs. — cu. ft.; 3510 lbs. — cu. yard.
CLAY (Wet) — 120-140 lbs. — cu. ft.; 2970-3200 lbs. — cu. yord.
CONCRETE — 138 lbs. — cu. ft.; 3726 lbs. cu. yard.
CONCRETE: Cinder concrete — 112 lbs. per cu. ft.
Gravel and limestone concrete — 150 lbs. per cu. ft.
Trap-rock concrete — 155 lbs. per cu. ft.
CRUSHED STONE — 100 lbs. cu. ft.; 2700 lbs. — cu. yord.
GRAVEL — 95 lbs. — cu. ft.; 2565 lbs. — cu. yard.
HYDRATED LIME — Abt. 40 lbs. per cu. ft.
LIME — 75 lbs. — bu.; 320 lbs. — bbl. large; 220 lbs. small.
MORTAR — 103 lbs. per cu. ft.
PLASTER OF PARIS — 98 lbs. per cu. ft.
REINFORCED CONCRETE — 150 lbs. per cu. ft.
SAND (Dry) — 97-117 lbs. — cu. ft.; 2619-3159 lbs. — cu. yard.
SAND (Wet) — 120-140 lbs. — cu. ft.; 3240-3780 lbs. — cu. yard.
SHINGLES — Bundles 24" long, 20" wide, 10" high — weighs 50 lbs. Approx. 250 per bl.
SLAG — 1755-1890 lbs. per cu. yd.; 65-70 lbs. per cu. ft.
SLAG CONCRETE — 135 lbs. per cu. ft.
STONE RIPRAP — 65 lbs. — cu. ft.; 1775 lbs. — cu. yard.

ACREAGE AND AREAS

SQUARE TRACTS OF LAND

Acres	One Side Square Tract	Area
1/10	66.0 lin. ft.	4,356 sq. ft.
1/8	73.8 lin. ft.	5,445 sq. ft.
1/6	85.2 lin. ft.	7,260 sq. ft.
1/4	104.4 lin. ft.	10,890 sq. ft.
1/3	120.5 lin. ft.	14,520 sq. ft.
1/2	147.6 lin. ft.	21,780 sq. ft.
3/4	180.8 lin. ft.	32,670 sq. ft.
1	208.7 lin. ft.	43,560 sq. ft.
1-1/2	255.6 lin. ft.	65,340 sq. ft.
2	295.2 lin. ft.	87,120 sq. ft.
2-1/2	330.0 lin. ft.	108,900 sq. ft.
3	361.5 lin. ft.	130,680 sq. ft.
5	466.7 lin. ft.	217,800 sq. ft.

* ©1984 Craftsman Book Company, P.O. Box 6500, Carlsbad, CA 92008-0992. Reprinted with permission.

5.2

Planning and Design of Studio Lighting Equipment

Bill Marshall
Vice President
Facilities Design
Imero Fiorentino Associates
New York, New York

Visually nothing more fully characterizes a television studio than the vast array of lighting equipment suspended overhead. What may seem to be a random array of pipes, fixtures and cables is actually several carefully planned systems which allow a lighting director to accommodate virtually any lighting requirement (Fig. 1). The careful design and planning of the studio lighting systems is the key to achieving the primary function of a studio—a technically ideal environment for television production.

The modern television studio naturally evolved from the combined input of both film and theatre techniques. Like a film stage, television production required an acoustically treated, large open space, with the capability for overhead suspension of both lighting and scenic materials. The theatrical influence on television studios and their lighting systems came as result of early television broadcasting requirements. To meet the continuous production requirements of live television and the high illumination levels required by early cameras, television borrowed methods of theatrical efficiency such as C-clamps, pipe grids, and dimming, which are now standard features of a fully equipped studio.

In designing a television studio, the lighting system is a major consideration as it is so closely inter-related to the physical size and shape of the room. While the television industry has seen tremendous technological improvements throughout its evolution, the basic physics of light, and its ability to describe three dimensional form, cannot change. Consequently, many older studios have upgraded virtually every piece of broadcast equipment while the basic components of an older, well designed lighting system still function extremely well.

Various developments in broadcast equipment have progressively lowered the footcandle requirements for studio lighting. Parallel to these improvements, lighting control systems have also grown more sophisticated and have actually become less expensive. These factors combine to

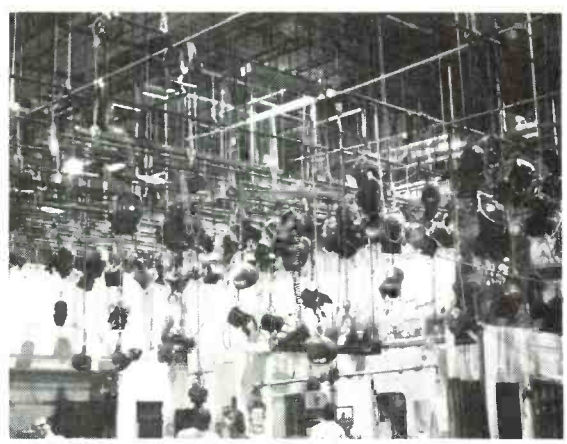


Fig. 1. This large fixed grid studio illustrates the relationship of the various aspects of the studio lighting system. (WPBT)

give the lighting director even greater control of the televised image.

STUDIO SIZE

Ideally, a studio provides the optimum environment for any type of production. In practice however, studios of various sizes tend to function best for particular types of production. The typical broadcast plant requires several sizes of studios to most effectively service its programming schedule. Typically, a small studio (1,200 sq. ft.) is dedicated to news, interviews, and public affairs, while 2,400 sq. ft. is the most common size of a small production studio. For general production, a studio of 5,000 sq. ft. or more will offer fewer limitations. The size of your studio must be carefully determined by your existing and future programming requirements, keeping in mind that the larger the studio, the fewer limitations you will build in. These are important decisions, since the lighting system must be planned relative to the size and specific requirements of the studio.

Studio Height

When determining the height of a new studio, the lighting suspension system must be given careful consideration. The grid height for small and medium size studios is a function of the current fixed TV aspect ratio 4:3 and the normal wide angle zoom lens. Most zoom lenses can cover approximately a ±45° field. By calculating the actual width of this maximum horizontal dimension, the height of the grid can be determined by applying the aspect ratio. You must also keep in mind that the studio lighting fixtures will hang approximately two feet below the suspension structure. In addition, a normal studio pedestal and cameraman will keep the lens approximately five feet in front of a wall or any other obstruction, further reducing the maximum coverage of the lens (Fig. 2). This method describes the theoretical maximum picture possible and the height the fixtures need to be mounted to stay out of the picture. However, television is primarily a close-up medium, and limitations in grid height can be overcome by various camera angles and special fixture mounting systems. Current experiments in high-resolution television may bring about a new, more rectangular aspect ratio in the near future, which will actually reduce the studio height requirement.

SUSPENSION SYSTEMS

The suspension system for the studio lighting is also a critical factor in determining studio height. All types of lighting suspension systems are commonly referred to as the "grid". In its simplest form the system consists of a series of pipes suspended below the studio ceiling, in a regular pattern (Fig. 3). A grid must allow lighting fixtures to be hung anywhere over the entire studio. Actually the grid can consist of several different types or combination suspension system.

Fixed Grid

A fixed grid is the most common and least expensive system of suspending lighting fixtures. The pipes are generally laid out on a perpendicular 4′ × 4′ spacing, which provides adequate flexibility in hanging positions (Fig. 4A). The most common fixed grid height is 14 feet. This height offers a good compromise between easy

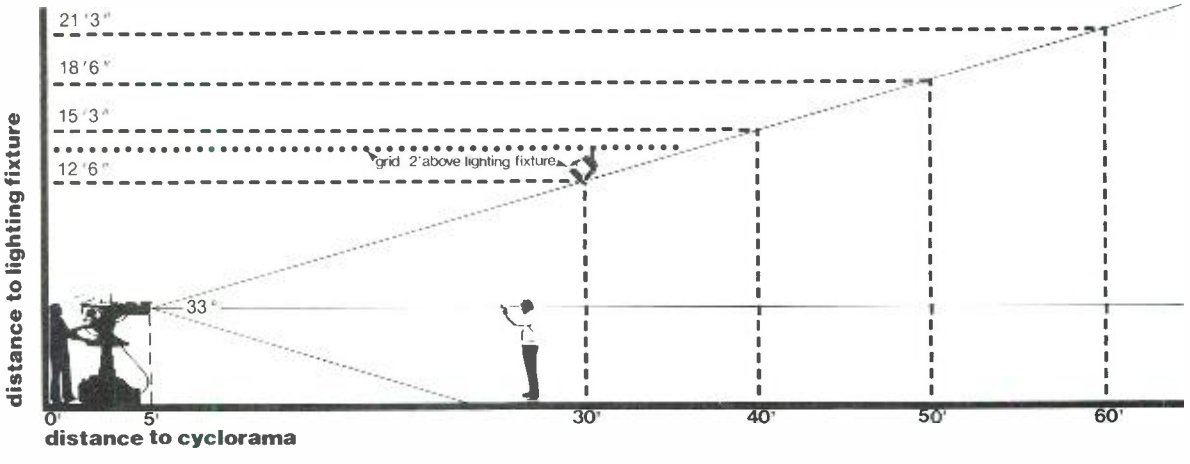


Fig. 2. This drawing illustrates how the vertical aspect of a camera lens at eye level determines the height of a studio grid.

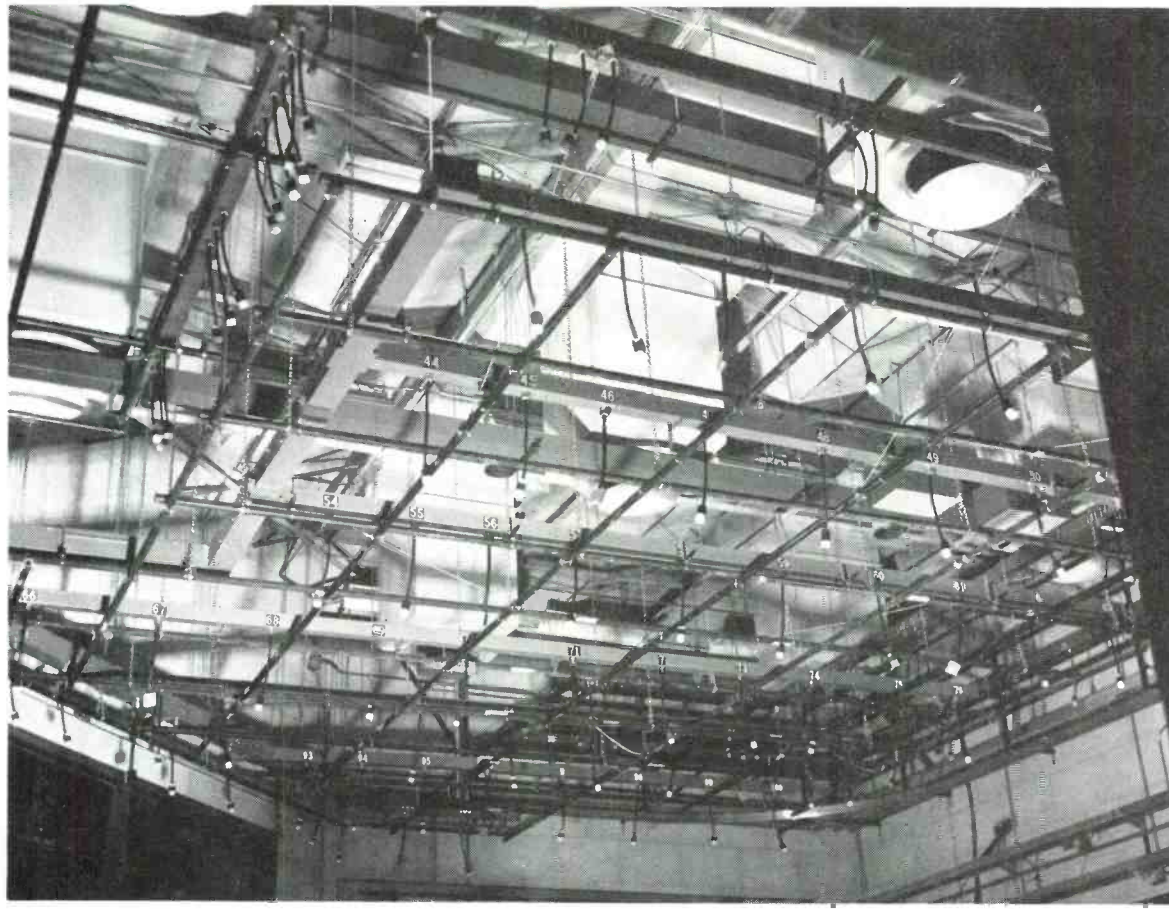


Fig. 3. This fixed grid studio employs two levels to create a higher apparent background, multiple pigtail outlets are positioned for cyc lighting units. (WFAA-Dallas)

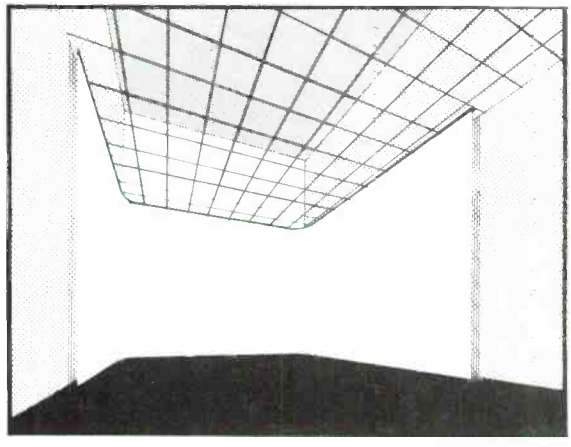


Fig. 4A. Fixed grid plan.

ladder reach and adequate clearance for wide shots. A fixed grid that is much higher than 14 feet greatly increases the amount of labor needed to install and adjust fixtures. For a large multipurpose studio, a fixed grid can be a serious limitation. Bi-level fixed grids have been utilized to create a higher apparent background without additional cost and to keep the major portion of the grid at a reasonable height. To solve this problem more efficiently, several other systems have been developed.

Catwalks

Catwalks are generally also hung at a fixed level. Catwalks provide a measure of increased efficiency over a fixed grid. Although they are somewhat more expensive, catwalks allow studio electricians to work on lighting at the same time carpenters are handling the scenery. This can be an important time savings on a tight production schedule. Catwalks are usually arranged to create a fixed grid utilizing their handrails in conjunction with an extension rod on each fixture (Fig. 4B). Catwalks when hung too low create the same height limitation as a fixed grid, but generally catwalks are higher than a fixed grid, with extension rods lowering the fixtures to a more efficient height. Unfortunately, catwalks do not eliminate actually getting on a ladder to adjust the fine focus of each fixture. Catwalks primari-

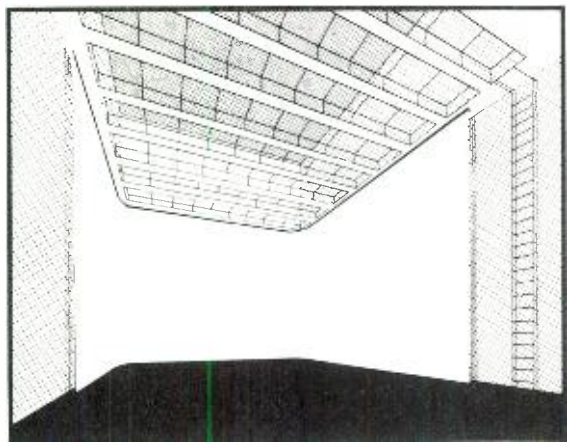


Fig. 4B. Catwalk grid plan.

ly save time in set up and strike and offer the crews a safe work platform above the studio (Fig. 5).

Recently, most fixture manufacturers have developed pole-operated yokes for their units (Fig. 6). Each fixture has a socket, which can be reached by a pole/crank to adjust each of the basic functions, pan, tilt, and spot/flood. There is a reasonable limit to how long a pole can be easily manipulated, but this feature considerably enhances fixed, high level grid systems. It is not possible to focus studio fixtures by this method as quickly or efficiently as by hand, but this system does provide a means of focusing otherwise unreachable units blocked by scenery and is seriously worth considering for any type of grid system.

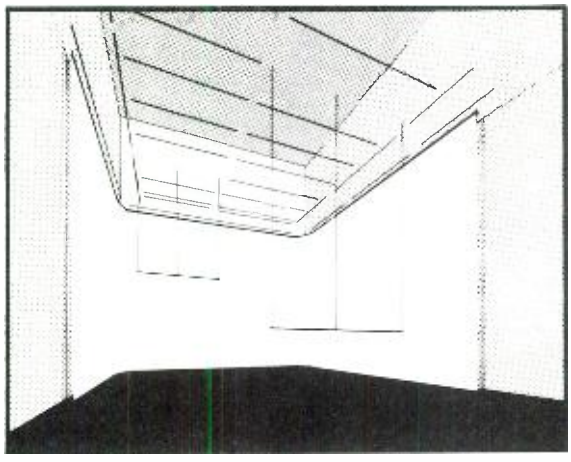


Fig. 4C. Batten plan.

Battens

The larger and therefore higher a studio that is required, the more complex the studio lighting suspension system becomes. In very large studios, a basic theatrical staging factor, in addition to the aspect ratio, determines the ultimate grid height. That is the "flyout clearance". Just as in a theatre stagehouse, flying scenery is a common requirement in larger-scale TV production. Flown scenery commonly requires a minimum grid height of 40 feet. To raise and lower the scenic units and the lighting fixtures, a regular pattern of long battens or pipes run across the width of the studio (Fig. 4C). These battens run up and down on steel cables and are manually balanced by cast iron weights. These counterweighted battens solve the height problems but add additional work in rebalancing the counterweight arbors everytime fixtures are added or removed from the batten. Counterweight rigging mounted along the studio wall encroaches on valuable floor space (Fig. 7).

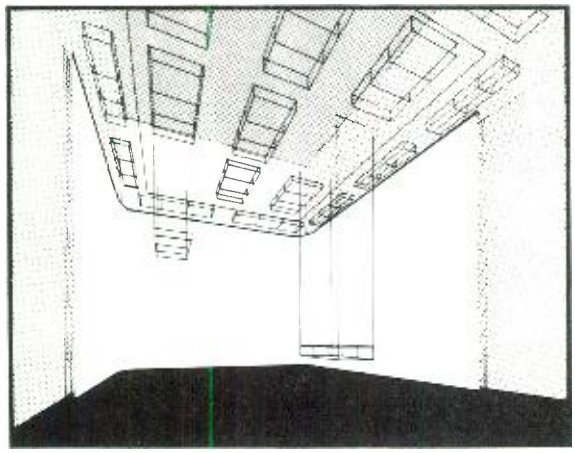


Fig. 4D. Modular grid plan.

Winches

To solve the negative aspects of counterweight systems, many installations use electric winches to raise and lower the battens. These winches can be operated by sophisticated control systems which will allow the batten to be lowered for service or adjustment and then returned to an exact preset trim or level (Fig. 8). The motors will easily lift any variable load within its designed capacity.

Many variations on the motorized batten system have been developed. In order to increase flexibility the battens have become shorter. This increases the number of motors required and the cost.

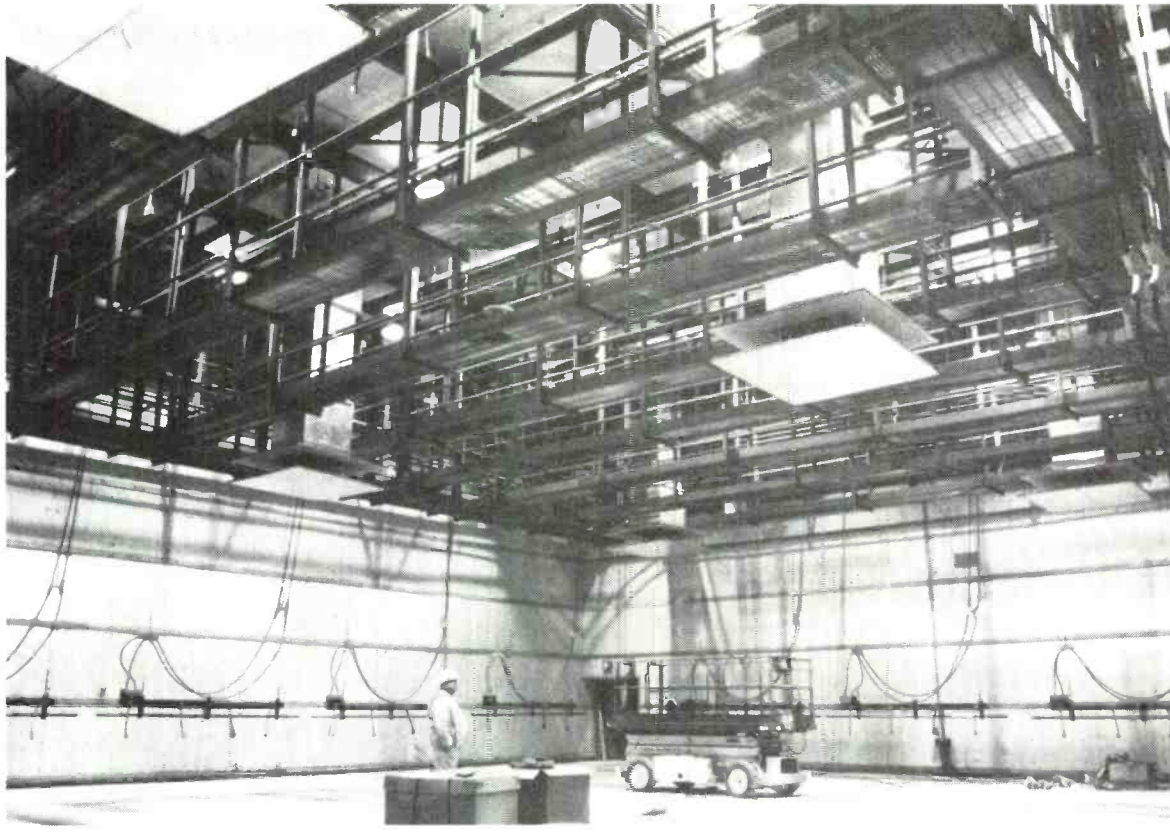


Fig. 5. In a catwalk studio lighting units are positioned in the open bays between catwalks. The motorized battens around the perimeter allow a higher backlight position where ceiling height is limited.

Fig. 6. By inserting a long crank into the adjustment cups, this pole operated fixture can be panned, tilted, or spot/flood focused from the floor. (Courtesy of Mole-Richardson)

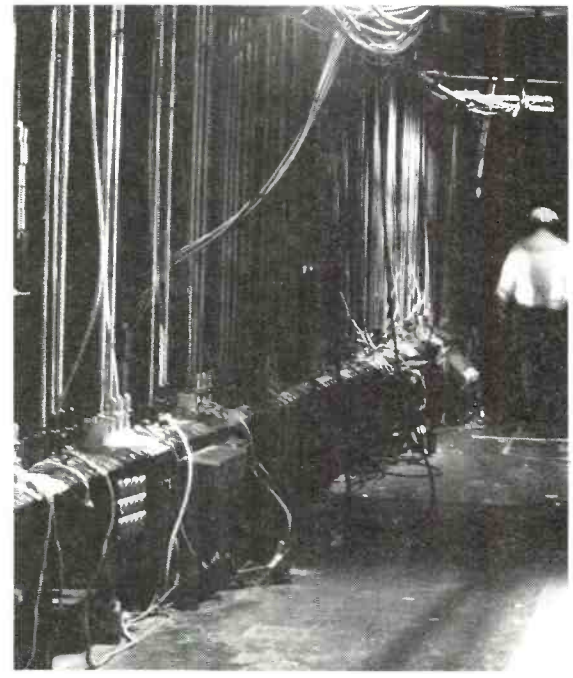


Fig. 7. A typical studio counterweight rigging system lockrail requires about 5 feet of floor space along one studio wall. (NBC-Brooklyn)

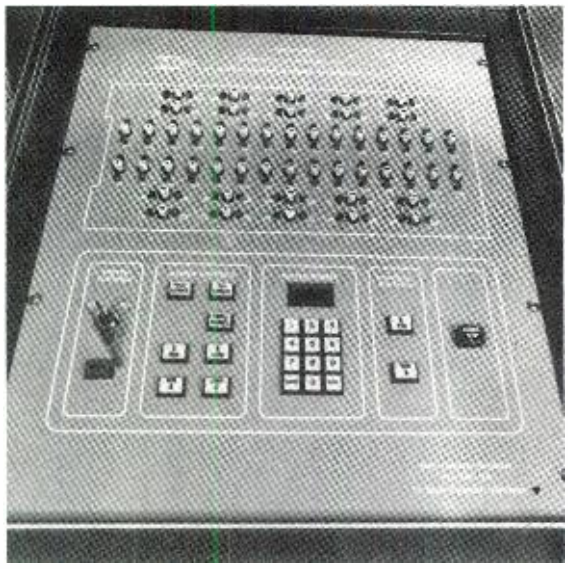


Fig. 8. Computerized control panel for the motorized batten system at WNET. The panel includes an illuminated display which mimics the actual batten layout. (Courtesy of Peter Albrecht Corporation)

Modular Grids—Self Hoisting

To take advantage of the convenience and power of electric winches without excessive cost, a number of modular grid systems have been installed. These modules are essentially small pipe grid sections, which can be raised and lowered. They offer a flexibility similar to short battens, but since they cover a larger area fewer motors are required (Fig. 4D). Because these modules are designed to be self-hoisting, the structural requirements of the studio structure are greatly simplified, and the grid remains clear for motors and steel hoisting cables (Fig. 9).

In studios which have either counterweighted or motorized battens a full walk-over grid should cover the entire studio. This grid-iron usually is made of steel grating or channels as in a theatre stagehouse and provides the support for the adjustable rigging. This walkover grid provides easy access for any overhead suspension task any production may require.

In developing a fully integrated grid system, it is essential to coordinate all the building's structural, electrical and mechanical systems, in relationship to each other and the grid. Whereas, in normal construction many of the mechanical elements in a ceiling are placed where convenient, it cannot be over-emphasized that improperly planned or installed ductwork and conduit runs can be a hindrance to production.

Cyclorama

Designing the cyclorama is integral in planning the studio lighting and grid systems. The grid or suspension system must provide a mounting position for the cyc lights located at the proper relationship to the cyc. Also, the total area of cyclorama will affect the calculation of the studio power service.

Hard Cyc

Small studios often incorporate "hard" cycloramas: smooth plastered surfaces which actually blend flush into the floor. These provide the ideal infinity effect which draperies cannot equally simulate (Fig. 10). Hard cycloramas can be easily painted any color as needed and are especially effective for certain chroma-key techniques that can be spoiled by even the most invisible seams. Hard cycloramas are generally limited to small studios since their hard surface area invariably creates acoustical problems (Fig. 10).

Cyc Pit

In very large studios a cyc pit (Fig. 10) is a compromise solution for creating this infinity effect. The pit contains and conceals the bottom cyclorama lighting, which is essential for a tall cyc and the bottom of the drapery. When it is shot from the proper angle, the pit will simulate a background without a horizon. (Fig. 11).

For most studios, a drapery cyclorama is the most convenient solution. This seamless drapery is hung on carriers which roll along a track and allow it to be positioned anywhere around the perimeter of the studio. Two parallel tracks permit another type of background to be pulled in front of the stretched cyc. Switches on the track system allow the draperies to be easily transferred to the front or rear tracks (Fig. 12). Leno or "filled scrim" is the most common drapery material, although seamless muslin is an inexpensive alternate material. Recently, a translucent plastic rear-projection screen type material has become a popular material because it can be lit from either the front or the rear.

In larger studios where experienced lighting directors are available, true white cycloramas are used to achieve greater color intensity on the cyc. However, in smaller studios, where the talent occasionally must work close to the background or where limited control equipment is available a 60% TV white cyc should be used for better control of contrast.

Drapery cycloramas are generally furnished with jack chain weights. Removable pipe weights bent to match the shape of the track should also be provided to create a wrinkle free background. One of the most common errors in cyclorama design is an insufficiently large radius at the corners of cyc. No matter what material the cyc is made of, the larger the radius the easier it is to light evenly and accomplish the desired effect.

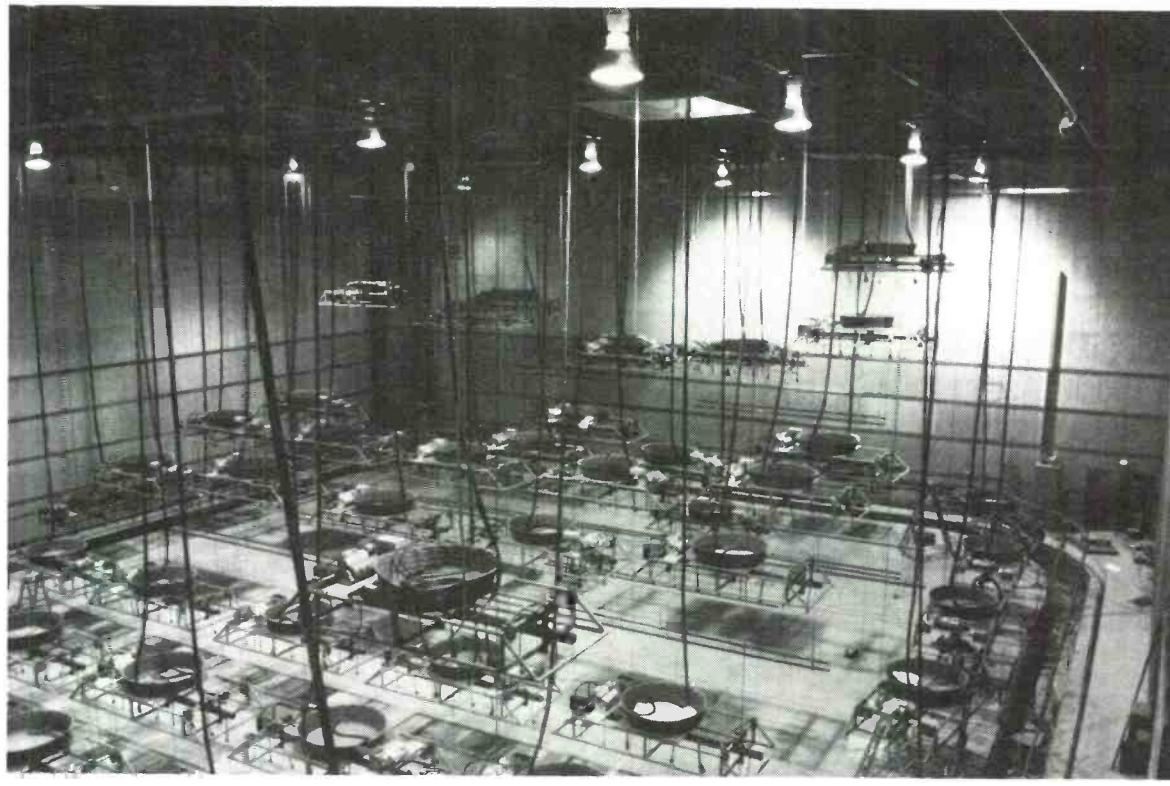


Fig. 9. Modular self-hoisting grids allow variable height suspension of fixtures in a regular pattern through the studio. The round tubs serve as cable collectors for lighting and winch power. (Dallas Communications Complex)

Fig. 10. Notice how well this hard cyc creates an infinity effect even with work lights and the floor partially finished. (American Express-NY)

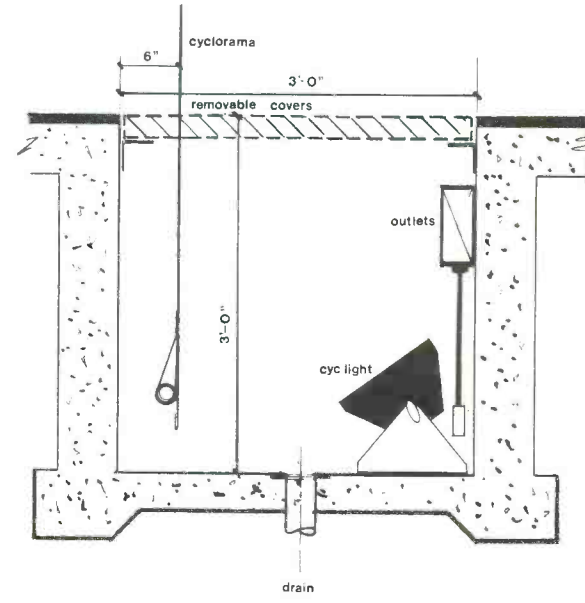


Fig. 11. Cyc Pit: Section view through a typical cyclorama pit.

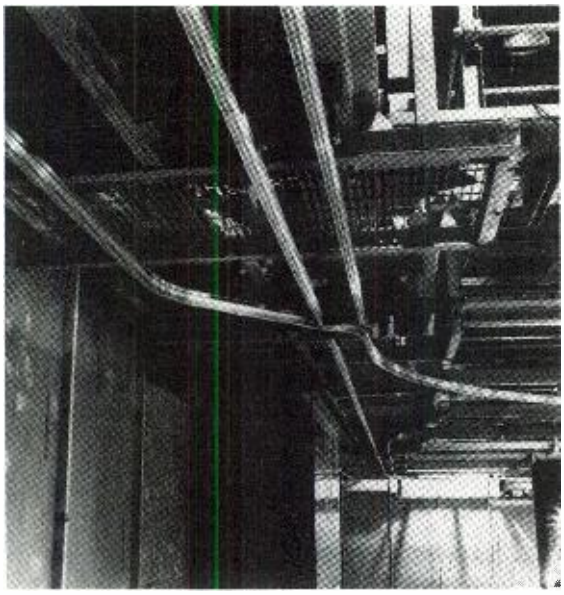


Fig. 12. Cycloramas and draperies can be shifted to various track configurations by utilizing transfer switches. (CBS-NY) (Courtesy of Peter Albrecht Corporation)

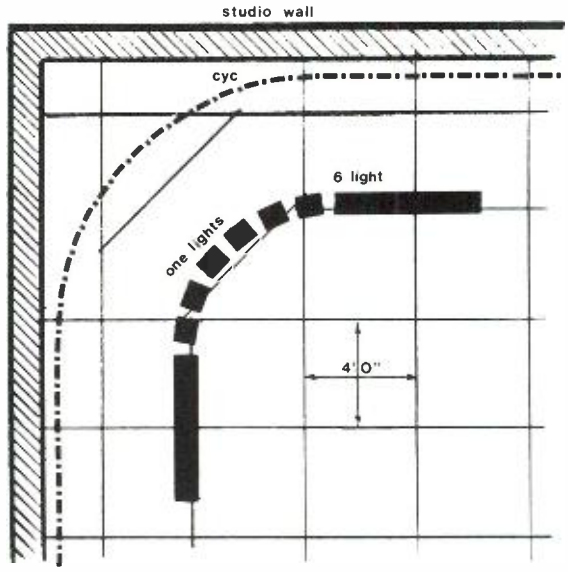


Fig. 13. Cyc Light Layout: Typical arrangement of strip cyc lights relative to the cyc curve.

Generally the arrangement of doors into the studio will define the most functional area for the cyc to be normally positioned. In the basic design of the grid or suspension system the type of cyc lighting system should be pre-determined, and the proper hanging system provided accordingly.

There are two basic types of cyclorama lighting fixtures. They are Striplights and a type of widespread fixture commonly known as "Far Cycs". Striplights are continuous rows of quartz halogen or Par lamps, which for an 18 foot high cyclorama should be mounted 5 to 6 feet from the cyc, while the "far cyc" units should be mounted 7 to 8 feet from the cyc (Fig. 13). The entire suspension system should be designed around these dimensions. Far cycs generally will light the cyc as evently, with less wattage than striplights. Because far cycs are mounted a greater distance from the cyc they force the talent further away from the background. Generally, striplights should be limited to three colors otherwise the separation between alternately colored lamps is too great to provide even coverage.

ARCHITECTURAL CRITERIA

Electrical

With the basic studio size determined and the "net production area" (NPA) defined by the cyclorama, it is possible to determine the power requirement for any given studio. The power requirements for studio lighting is a direct function of area and the required level of illumination. This power requirement remains consistent regardless of the grid height. For a lower grid, a greater quantity of smaller wattage fixtures are used, while a higher grid will require fewer fixtures of increased wattage. In either case, the total watts per square foot will remain roughly the same.

An average of 55 watts per square foot of NPA has been proven in production to provide sufficient power for any normal television lighting requirement. This method of calculating the studio load will provide sufficient power for virtually any situation. This is generally more power than is actually required for the average studio with today's state-of-the-art equipment, but it allows for overlighting by novices and higher levels necessary for special situations. It also provides sufficient power for an average cyclorama. Very tall cycloramas which may require double rows of fixtures at the top and/or the bottom cyc lights should be calculated as an additional power requirement based on the wattage per lineal foot of cyclorama according to the lighting system chosen.

This calculated power service describes a real maximum probable load, and the feeders must be able to supply this full amount of power (Fig. 14). Only certain limited productions will ever require this full amount. Also, note that for dimmer-per-circuit systems, the dimming capacity will be far greater than this calculated power service. The full dimming capacity need not be fully serviced, since the larger number of dimmers is a matter of convenience, and will never

be fully loaded beyond the maximum probable load.

Airconditioning (HVAC)

Because the maximum lighting loads seldom occurs, it is unnecessary to use that maximum load as the basis for the airconditioning capacity. Production practice has shown that a diversity of 60% can be applied to the maximum load and still provide sufficient capacity for full period shooting. Of course any other heat generating devices and the population of the studio should be included in the airconditioning calculations. A properly designed HVAC system will require very large ducts to meet stringent acoustical requirements. These large ducts can often interfere with a grid system and should be closely coordinated.

Determining Studio Power and HVAC Requirements

1. **Net Production Area (N.P.A.) =**

   N.P.A. = Actual Studio Area in Sq. Ft. minus area behind cyc and other areas unusable for production.

2. **Approximate Number of Studio Lighting Outlets Required:**

   $\frac{\text{N.P.A.}}{\text{15 Sq. Ft.}}$ = Number of outlets required (Patch Panel)

   $\frac{\text{N.P.A.}}{\text{18 Sq. Ft.}}$ = Number of outlets required (Dimmer-per-Circuit)

   Note: *Actual number of outlets determined by specific layout.

   *Breakdown of 20A. circuits and 50A. circuits varies by grid height.

3. **Studio Lighting Load:**

   N.P.A. Sq. Ft. × 55 Watts = Total _____ Watts.

4. **Studio Lighting Power Service:**

   $\frac{\text{Total Watts}}{\text{120V.}}$ = Total _____ Amps.

   $\frac{\text{Total Amps}}{3}$ = Power Service 3ϕ/4 Wire 120/208V.

   Note: Round off to the next larger standard panel size.

5. **Studio Lighting Heat Load for HVAC:**

   Studio lighting Load (KW) × 60% (Diversity) = Heat Load for HVAC Design (KW)

6. **Dimmer Room Heatload for HVAC:**

   HVAC Heat Load (Item 5 above) × 5% = Dimmer Room Heat Load

Fig. 14. Determining Studio Power Service—Table: the above describes the method of determining studio power.

Electrical Distribution

For a studio to be totally flexible, lighting equipment power must be distributed uniformly throughout the studio. At the grid level, power is commonly distributed through prewired plugging strips (Fig. 15). These strips are mounted directly to the grid, catwalks, or fly in and out on battens or moveable grid sections.

Each circuit terminates in the studio in a pigtail/outlet. There are two types of connectors in common use—stage pin connectors and twist lock. Stage pin connectors are less expensive and more common in rental equipment. If you envision renting additional fixtures on occasion, this may be an important consideration. In addition, the cost savings of stage pin connectors recur with fixture and cable purchase. Twist lock connectors have a positive locking feature. The final choice should be based on your specific requirements.

The number of circuits and their capacities is also related to studio size. The actual number of circuits is based initially on the square footage (approx. one outlet every 18 sq. ft. NPA) and then altered as necessary to conform to the particular grid system and the cyclorama layout. Dedicated circuits for the cyclorama are often overlooked. The cyc lights consume a large number of circuits and once they are hung in place they will seldom, if ever, be moved. Because of the rather wide spacing of the cyc units it is sometimes more efficient to feed these lights from individual grid mounted junction boxes rather

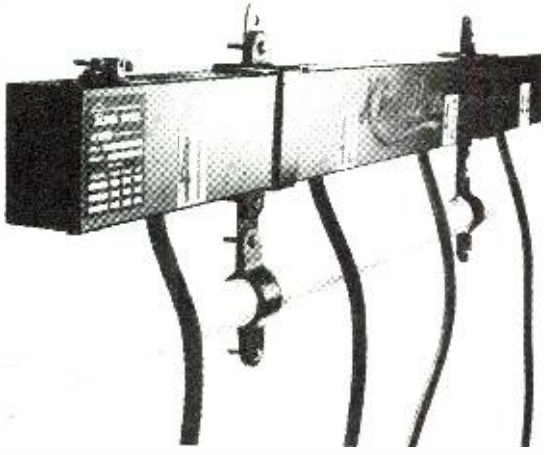


Fig. 15. Grid mounted connector strips provide a convenient means of distributing large quantities of circuits throughout the studio. (Courtesy of Kliegl Bros.)

than a plugging strip. Also, when using "far cyc" lights it is often convenient to double up the outlets to take full advantage of the 20A. capacity of the dimmers.

Additional circuits should be located around the perimeter of the studio at grid level. This is a natural backlight position for a set facing away from the wall. Properly located circuits save considerable time in running jumper cables.

At 30" above floor level, around the perimeter of the studio wall, mounted outlet boxes should be provided (Fig. 16). Generally, the governing factor for their placement is relative to a layout of floor mounted cyc strips. Otherwise these outlets are used for miscellaneous lights on floor stands and practical fixtures on the set.

For most studios the vast majority of circuits will be rated 20 amperes. The larger the studio, the greater the quantity of 50 ampere circuits. In a medium size studio (3,500-5,000 sq. ft.), 50A. circuits are generally located in a regular pattern throughout the center area of the grid and slightly more frequently around the perimeter backlight position. In larger and higher studios the density of 50A. circuits must be increased, although the overall outlet density should not be significantly decreased. On adjustable height grids, a full complement of both 20A. and 50A. outlets should be provided for using the appropriate fixtures for the varying heights. Large studios (10,000+ sq. ft.) with high grids must be furnished with 100A. circuits (Fig. 17).

Fig. 16. Wall mounted outlet boxes are generally located around the perimeter of the studio. (Courtesy of Kliegl Bros.)

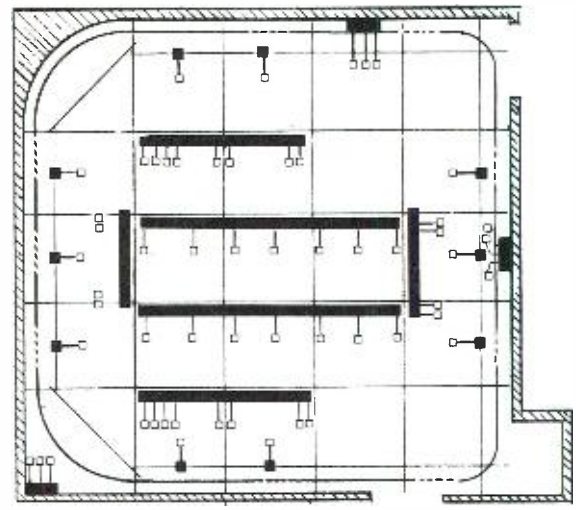


Fig. 17. Typical Studio Distribution Plan for a small industrial studio.

LIGHTING CONTROL

The importance of a dimming and control system cannot be underestimated. Dimmers allow easy control of numerous fixtures, balancing and recording of levels, and the blending of colors. A dimmer system frees the lighting director of the unnecessary burden of calculating and controlling the loads through more labor intensive mechanical methods. Electronic dimming and control allows the execution of complex lighting cues, which are a very effective production element.

Until recently, standard practice would have terminated all the circuits in a patch panel at which point they would be plugged into and powered by a limited number of large capacity dimmers. Because of the decreasing cost of mass produced electronic components, and the increased cost of hand fabricated equipment, patch panels are being phased out in favor of dimmer per circuit systems. The dimmer-per-circuit system offers greater flexibility at a comparable equipment cost and reduced installation labor. In this type of system every circuit terminates in its own dimmer, with the integral circuit breaker protecting both the dimmer and the circuit. The dimmer per circuit system gives the lighting director greater control through specific control of each individual fixture.

Dimmer Bank

The individual dimmer units generally plug into electronic equipment racks to form the dimmer bank (Fig. 18). This modular system also allows quick plug-in substitution of faulty dimmer

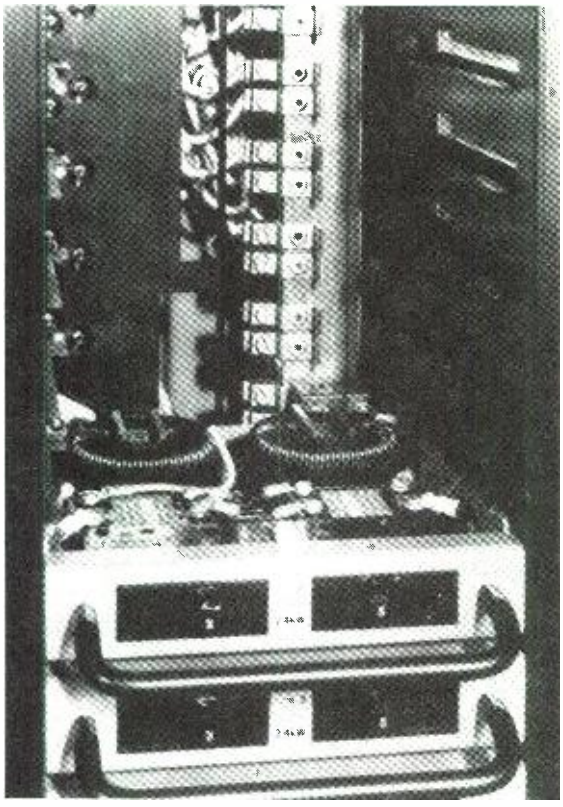


Fig. 18. Tray mounted dual dimmer modules allow high density and quick replacement. (Courtesy of Colortran)

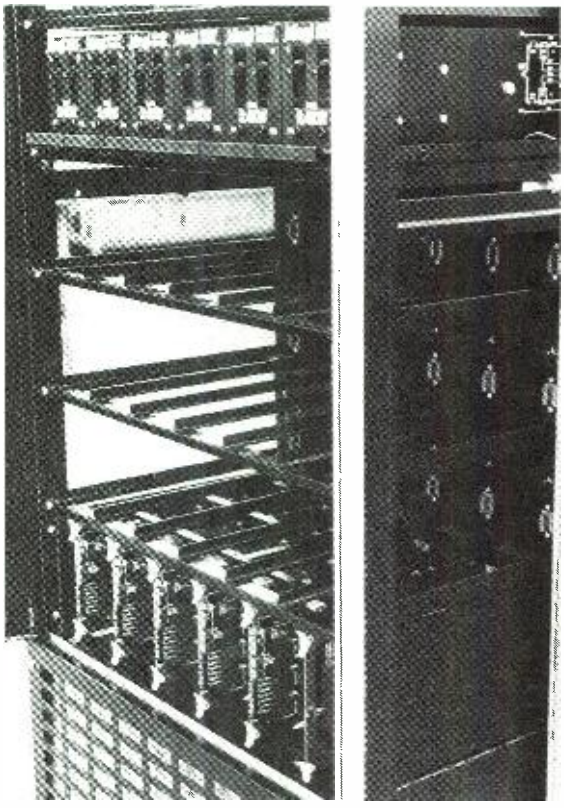


Fig. 19. Electronics common to multiple dimmer modules are located on cards in the bottom of each dimmer rack. (Courtesy of Kliegl Bros.)

modules (Fig. 16). Depending on the manufacturer, in excess of 96 individual 2.4 kW dimmer modules can fit into a single rack. All modern studio quality electronic dimmers utilize SCRs (silicon controlled rectifiers). These units are very reliable and are universally available in 2.4 kW, 6.0 kW, and 12.0 kW (20A., 50A., 100A. @120V) ratings. Only dimmers which have sufficient filtering to prevent unwanted RF interference and excessive filament vibration should be considered for use in television studios.

The location of the dimmer bank is an essential part of the initial studio space planning (Fig. 19). The dimmer room should be centrally located to minimize the length of all the circuit homeruns to avoid voltage drop and excessive installation cost. This room should be sized to allow sufficient space for required conduit radii, access to the feeder lugs, and adequate front clearance as specified by the local code.

Virtually all SCR dimmers are approximately 5% inefficient. Therefore, they could create heat equal to 5% of the energized lighting load. Since the maximum lighting load is an infrequent occurance the dimmer room cooling should more reasonably be based on 5% of the diversified load on which the studio HVAC is based.

Control Consoles

Along with the reduced cost of dimmers, the application of computer technology to lighting control systems have made today's dimmer per circuit system a financial reality.

In manual electronic dimming systems, an individual potentiometer or slider is required to operate each dimmer. To retain a particular dimmer setting, duplicate sets of sliders are necessary. Each preset group of these sliders is called a scene. While two scenes are sufficient for many productions, even a relatively simple production could require many more. The physical size of multi-scene control panels is cumbersome, and requires extensive paper work to record the setting for each preset.

Sophisticated control is possible through patching dimmers/circuits to a reasonable number of control channels. The simplest systems physically resemble the standard manual two scene preset system (Fig. 20). On these systems, each slider represents a channel rather than a hardwired individual dimmer. The specific number of control channels is a matter of convenience. Obviously, more channels afford greater control within a single scene.

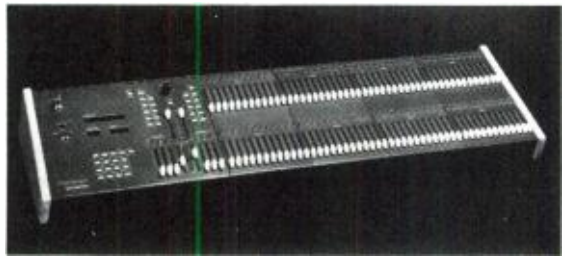


Fig. 20. Manual control panels with proportional patching can be programmed with a full scene in memory on each channel (Courtesy of Colortran)

Fig. 21. Midsize light computer with single display can program complex cues and can drive a convenient hand-held remote unit. Data cassettes provide library storage of all settings. (Courtesy of Kliegl Bros.)

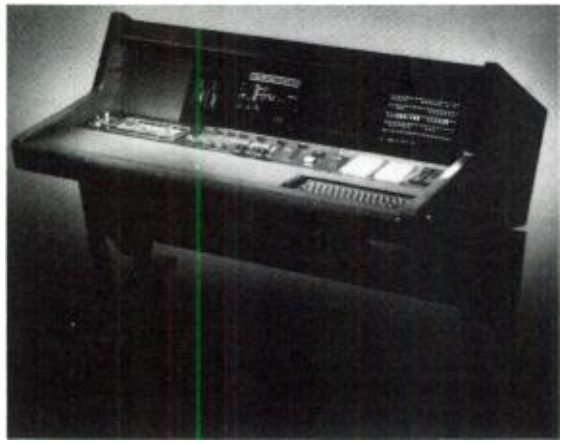


Fig. 22. The largest computer system utilizes two displays and floppy disks for storage. These systems can include complete backup systems. (Courtesy of Strand-Century)

In a dimmer per circuit system it is not unusual for a medium size studio to have in excess of 200 dimmers. To control this large quantity with only 24 channels it is necessary to patch the dimmers to channels utilizing only the dimmers required. The patching function allows any dimmer to be controlled by any channel. For example, the blue cyc lights load may require 12 separate dimmers. By patching them into the same channel they will operate together in perfect unison. All this patching occurs within the console and does not require any cord, plugs, or diode pins.

After patching the dimmers to channels and setting the desired levels, the entire preset can be stored in a memory by assigning a memory number. This preset can then be recalled by keying the appropriate number or operating the slider to which the preset has been assigned. This type of system is very economical and is suitable for most small and medium studio situations.

The greatest limitation with these simple systems is that once the levels are preset, there is no visual record of them unless you write them down or run a printout. In either case individual channels cannot be altered without reprogramming the entire scene.

This limitation is overcome in some systems with add on displays and functions available at extra cost. For studios which encounter more complex production requirements or too many dimmers for a small system, there are a number of systems with much greater capabilities. These control systems resemble a personal computer with specialized keypad and controls.

One type of system which is common to several manufacturers utilizes a single CRT to display various functions (Fig. 21). In operation, the screen displays the channel numbers and below each channel is a two digit number for the intensity. At the bottom of this field of numbers is the "cue sheet" which displays various operational functions such as cue numbers, fade times, etc.

The control panel on this type of computer control generally has a series of submaster sliders, X,Y faders, numerical keypad and a function keypad, and some tactile type of encoder for easily altering fade times and intensities.

The most complex systems employ dual CRT displays to actively display more information (Fig. 22). These systems offer so many esoteric features that most studios would never begin to tax their full potential.

Computerized lighting systems store their memory on either floppy disk or data cassettes for reuse. This permits a complete copy of all the settings in memory. In addition most larger systems are available with varying degrees of internal backup memory systems. The operational

software is permanently stored in ROM within the machine.

Most computer lighting systems were originally designed for the legitimate theater where the easy daily repetition of very complex multipart cues is the primary goal. Some manufacturers have modified their programming to be more sympathetic to television's somewhat unpredictable demands. In selecting a system with this caliber of sophistication, one must carefully determine which features are really necessary.

Computerized lighting systems have greatly simplified the installation of the control wiring (Fig. 23). While manual systems require at least one wire for every dimmer, these computrized systems can be run over a single coax or a few twisted pairs for the entire system. An advantage to this simplified cabling is that the console can be easily relocated to any of the plug-in stations. In addition, when the main computer console is located outside the studio, a small focus remote the size of a hand-held calculator can be used in the studio to activate fixtures as necessary for focusing or other simple operations (Fig. 24).

This allows the console to be located in the most convenient position for a particular phase of the production. It also allows several studios to share a more sophisticated system as required, since the largest systems can plug into the same control wiring as the smallest.

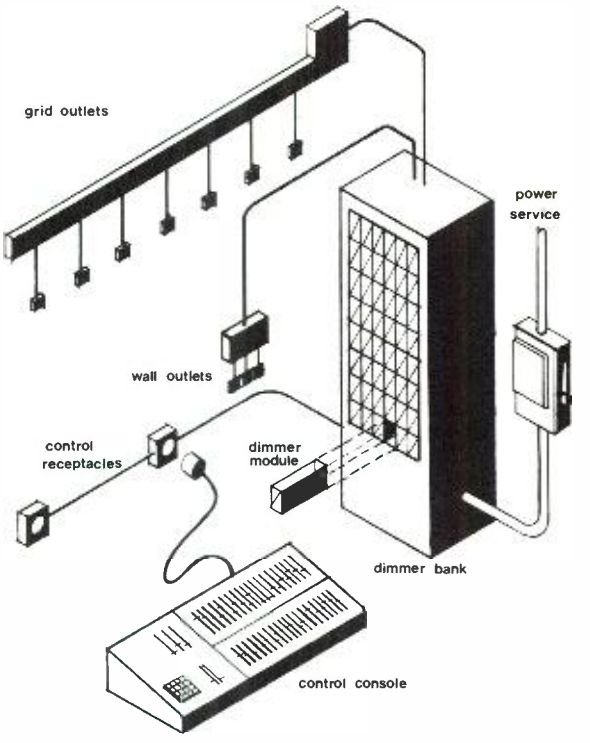


Fig. 23. Dimmer System Riser Diagram: indicating the basic components of the dimmer system.

LIGHTING FIXTURES

A television lighting director has quite a variety of lighting fixtures or luminaries available to accomplish the basic objectives of TV lighting: separation, modeling, accent, illumination, and directing viewer attention. This variety of fixtures and the various qualities of light which they produce have been developed to enhance the efficiency of studio operation. The luxury of utilizing a basic fixture and manipulating the quality of light by external diffusers, cutters, reflectors, etc. for each shot as in film is not normally possible in multi-camera television production. Therefore, a complement of fixtures with given characteristics provide a lighting director with a pallet of choices to design the lighting.

Reduced to its simplest form, television lighting design develops from a three point system including a key light, the principal source of illumination, base or fill light, a uniform diffuse illumination to establish sufficient levels for camera pickup and backlight, illumination from the rear, which highlights a form separating it from the background. There are a number of excellent texts specifically on lighting design techniques listed in the bibliography. These basic techniques are men-

Fig. 24. A complete line of "BABY" size units are available for tight locations and special applications. (Courtesy of Mole-Richardson)

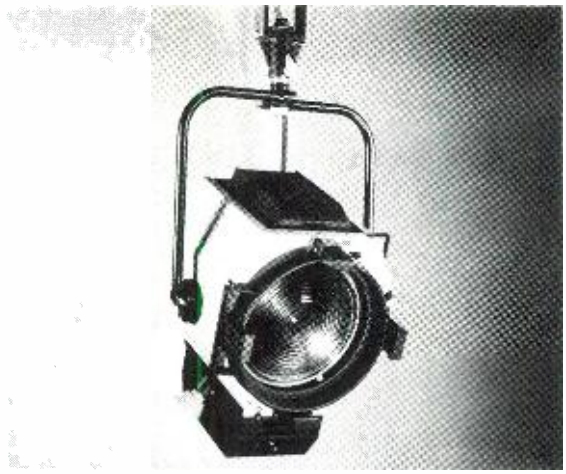


Fig. 25. Studio quality fresnel spotlights are much more durable and have superior optical systems compared to more inexpensive theatrical units. (Courtesy of Colortran)

Fig. 26. Studio fresnel spotlights must offer good quality long leaf barndoors as an essential accessory. (Courtesy of Strand-Century)

Fig. 27. A typical scoop unit. (Courtesy of Mole-Richardson)

Fig. 28. Softlights produce a very diffuse source and have switches to select as many lamps as necessary. (Courtesy of Mole-Richardson)

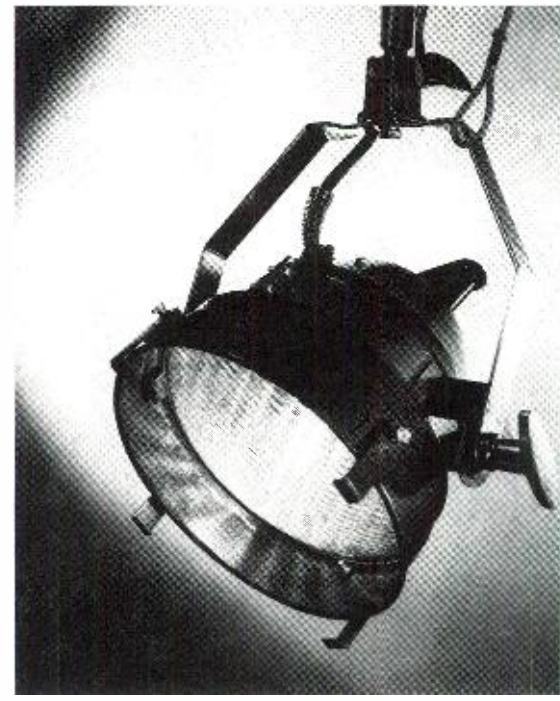


Fig. 29. Par head fixtures produce a tremendous amount of light in a very small package. (Courtesy of Colortran)

tioned only in reference to the following discussion of studio fixtures.

Fresnels

In a studio, the most common and useful fixture is the fresnel lens spotlight. The light from a fresnel is very controllable and has a smooth even field. By a simple adjustment of the position of the lamp, the fixture will produce either a narrow spot or wide flood beam of light. Equipped with barndoors this beam can be further shaped to virtually any pattern. Slots in front of the lens allow color, diffusion media or screens for intensity control to be slipped in place. A complement of single and double thickness, and half and full frame screens should be provided for all fresnels even when dimmers are available.

For most 14′ high grid studios the 6″, 8″ and 10″ in wattages from 500 to 2,000 are the most common units (Fig. 24, 25, 26). In smaller studios or tight applications "baby size" fixtures are often employed. These units enclose the same wattage lamps in small housings. A number of people prefer these smaller size units for their easier handling and somewhat different optical characteristics. As noted previously, the higher the grid, the higher the wattage fixtures are required. Therefore, in higher studios, the standard complement of fixtures might be 5,000 and 2,000 watt units or even up to 10,000 watts. Conversely, fresnel lens units are also available in sizes down to a 3″ lens with a 150 watt lamp.

In selecting a line of fresnels for your studio you must carefully weigh both the optical, and mechanical features. Poorly made fixtures will not focus properly once they are hot. Fixtures should also be well balanced, even with barndoors to remain in focus. The manufacturer should also provide a complete line of suitable accessories including barndoors, which are long enough, screen sets, diffusion frames and stand mounting hardware.

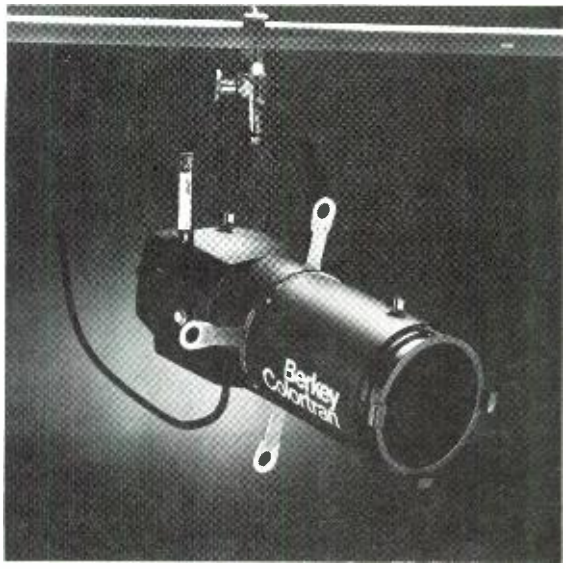


Fig. 30. Shutters on ellipsoidal spotlights allow the beam of light to be shaped into hard edge shapes or can project patterns. (Courtesy of Colortran)

Scoops

Scoop floodlights are used for a variety of soft diffuse requirements most commonly in groups to provide base light to a setting. These are very simple fixtures available in several sizes, where bigger is generally better (Fig. 27). Scoops are used invariably with diffusion media, so it is essential that a diffusion frame is ordered. This is the only fixture which should not use a Tungsten Halogen lamp. The large old fashioned PS shape incandescent lamp produces a much softer quality of light, because of its larger filament area. Some manufacturers make focusing scoops, which is generally a pointless additional cost, when used with diffusion material. While the majority of lighting can be done with fresnels and scoops, there are a vast variety of fixtures which each produce a different quality of light. For a harder rectangular field of fill light a broad can be used. It is very similar to a scoop in concept, except its housing/reflector creates a somewhat less diffuse light and also is always used with diffusion media.

The softlights are another type of diffuse base light fixture, in which the light sources are totally concealed and the light is reflected in an indirect manner. These units are not particularly efficient, but are unequalled in providing a shadow free light. They are available in a variety of sizes (Fig. 28). Large 4,000-8,000 watt units are pretty unwieldly for many applications, but the smaller units in the 1,000 to 2,000 watt range are becoming very popular as fill lights, because of the reduced levels required.

Probably, the most efficient incandescent fixture used in television lighting is the Par unit (Fig. 29). The lamp itself contains both the reflector and the lens, which is available in 5 different beam spreads. While limited to very large studios and remotes, the Par is a very inexpensive and powerful tool for the lighting director.

The ellipsoidal reflector spotlight is a unique effect light in a studio (Fig. 30). The optical system of this unit allows the beam of light to be hard or soft edged, or it can be cut-off by internal shutters. It is the most commonly used to project patterns on the cyclorama. Numerous photo-etched metal patterns are available, which drop into the pattern slot. Ellipsoidal reflector spotlights are available in a variety of optical systems, but the wide angle/short throw sizes are most useful in small and medium studios.

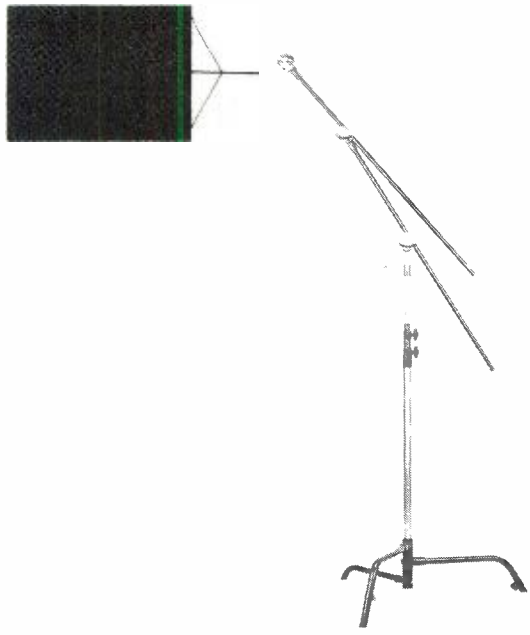


Fig. 31. The three level legs allow the stand to fold flat for storage. The head can grasp numerous flags, cutter, cookies, etc.

There are a number of accessories which make the lighting system work. Despite the expense and care expended on planning the grid system, it cannot satisfy every fixture mounting requirement; every studio must have some fixtures on rolling floor stands. In addition, many types of clamps and general grip equipment are available for special mounting situations.

One of the key accessories in the lighting system are extension rods. This device allow fixtures to be hung at a lower level than on the fixed grid. For example, a key light at a 30° angle to the talent could be much closer to the talent, and therefore brighter, than if it were hung lower. Counter-balanced devices such as pantographs and spring load telescoping hangers cannot be locked in place. Another drawback of these devices is that they must be precisely adjusted to the weight of a particular fixture and cannot be relied upon to stay in that position. Extension rods, which are nothing more than a pipe, which slides up and down are the cheapest and best choice.

The century stand (Fig. 31) has endless application around the studio. It can grasp all types of material such as flags, cutters, cookies, and support reflectors. Century stand use is limited only by your imagination. No matter how many are available, they will all be put to good use.

Ultimately, the proper quantity of fixtures, accessories, and other components of a lighting system for a studio of a given size can vary widely according to the requirements of a specific situation. For example, a studio with a fixed grid and a tight production schedule will function more efficiently with a heavy saturation of fixtures. With a large quantity of fixtures, major relocation of all the units is somewhat minimized. When sophisticated motorized grid systems are available, the ease of relocating fixtures will reduce the total quantity of fixtures for the same size studio. The choice of either of these two approaches is also dramatically affected by labor costs within a particular facility. Too often the expense of a few extra fixtures is not compared to the additional time and labor required to fully utilize a minimal complement of equipment or the cost of elaborate rigging. Final discussions on equipment purchase require a careful analysis of your specific production requirements in coordination with all the financial ramifications of various approaches.

The numerous technological improvements in reducing required lighting levels and improved control have allowed the television lighting director to become more of an artist and less of an illumination engineer. In planning a new studio, it is essential that the systems provided do not hinder this creative process.

All systems must be logical, and easily understood by the production personnel. The incorporation of specialized features tends to limit the flexibility of a studio. It should be possible to light a set equally well regardless of where it is placed within a studio.

Most television production people have the opportunity to be involved in planning a new studio maybe once or twice in their entire careers. Even years of experience in studio production are not necessarily the best preparation for coordinating studio requirements into a construction project. Often a new studio provides an opportunity to acquire a complement of equipment, which is more sophisticated than the existing staff's level of experience. In this situation, an experienced lighting director should be consulted in preparation of the equipment requirements and evaluating the quantities required. While manufacturers are sometimes helpful in this area, they are still primarily interested in selling you their product, and no single manufacturer offers a full line of suitable equipment in every area. By working with a consultant, you can share their experience in the planning and design of the lighting system for your studio.

5.3

The Broadcast Television Camera System

David H. Cooper
Executive Vice President
Fuji Optical Systems, Inc.
San Jose, California

OVERVIEW

The purpose of this chapter is to provide basic, practical information on broadcast camera systems, circuits and components. Major topics covered here are as follows:

- The Basic Camera System
- Camera Types
- The Optical System
- The Camera Tube
- Solid State Imagers
- Measurement and Performance of Imaging Devices
- Camera Performance
- Choosing a Camera

INTRODUCTION

The broadcast television camera system is a combination of many technologies. The zoom lens and beamsplitter are products of advanced optical design; the camera tube combines solid state and vacuum physics; solid state imagers reflect the state of the art in high density integrated circuit design; and the electronic control and processing circuitry is the result of sophisticated analog, digital and computer engineering.

It is not the purpose of this chapter to give a detailed insight into these technologies; such specialized information is better found elsewhere, but rather to provide the broadcast engineer with a practical understanding as to how these technologies work together and the various factors, which are important in the design and operation of a television camera system.

In the past all broadcast cameras were "tube-type", which means that they utilized camera tubes as imaging devices. However, recent advances in solid state imagers have resulted in improved resolution from these devices and they are being effectively used in portable cameras. Undoubtedly, as the imager technology further advances, these devices will begin to appear in the higher performance cameras.

THE BASIC CAMERA SYSTEM

All live television cameras are similar in principle, but differ in size and configuration according to their application. The basic elements of a live camera system are shown in Fig. 1, and described as follows:

The Optical System

Consists of a lens, filters, beamsplitter and, in the case of automatic cameras, some kind of pattern projector.

The Lens

Usually the lens is a "zoom" type, which means that the focal length can be varied and,

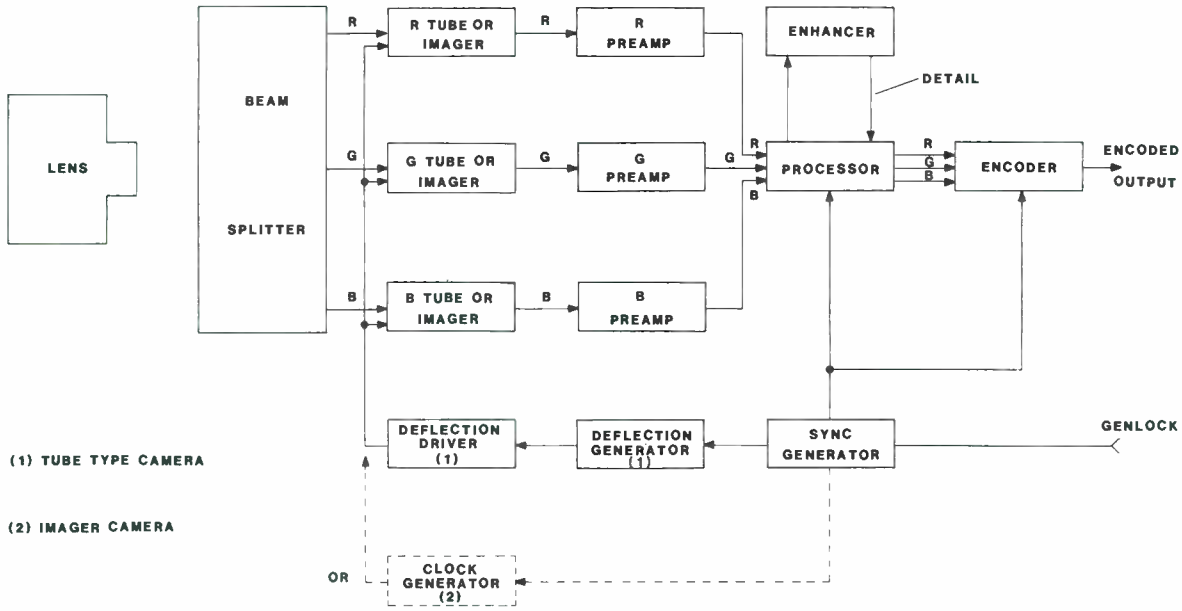
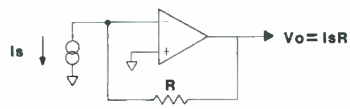
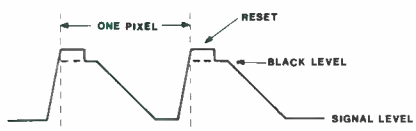


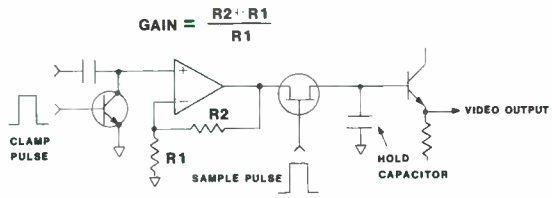
Fig. 1. Basic camera system.



(A) CAMERA TUBE PREAMPLIFIER



(B) CCD OUTPUT WAVEFORM



(C) IMAGER PREAMPLIFIER

Fig. 2.

therefore, is the magnification. The purpose of the lens is to focus the object of view into the camera head, through the beamsplitter and onto the light-sensitive surface of the imaging devices, which may be solid state imagers, or camera tubes.

The Beamsplitter

Beamsplitters are either of the "relay", or "prismatic" type, however broadcast cameras invariably use the latter. The purpose of the beamsplitter is to split the incoming light into its various color components, usually red, green and blue, and to provide the spectral response, or "taking characteristic" necessary for good colorimetry.

The Imaging Device

Usually a broadcast camera has three color channels; red, green and blue; and, therefore, utilizes three imaging devices, which may be camera tubes of the lead oxide, or Saticon (trademark Hitachi Ltd) type, or solid state imagers. At the present time the camera tube offers higher resolution and is used more often in broadcast cameras, particularly in the more critical applications, such as studio, or field production. However, the resolution of the solid state imager is continually increasing and we are certain to see more of these devices as technology progresses.

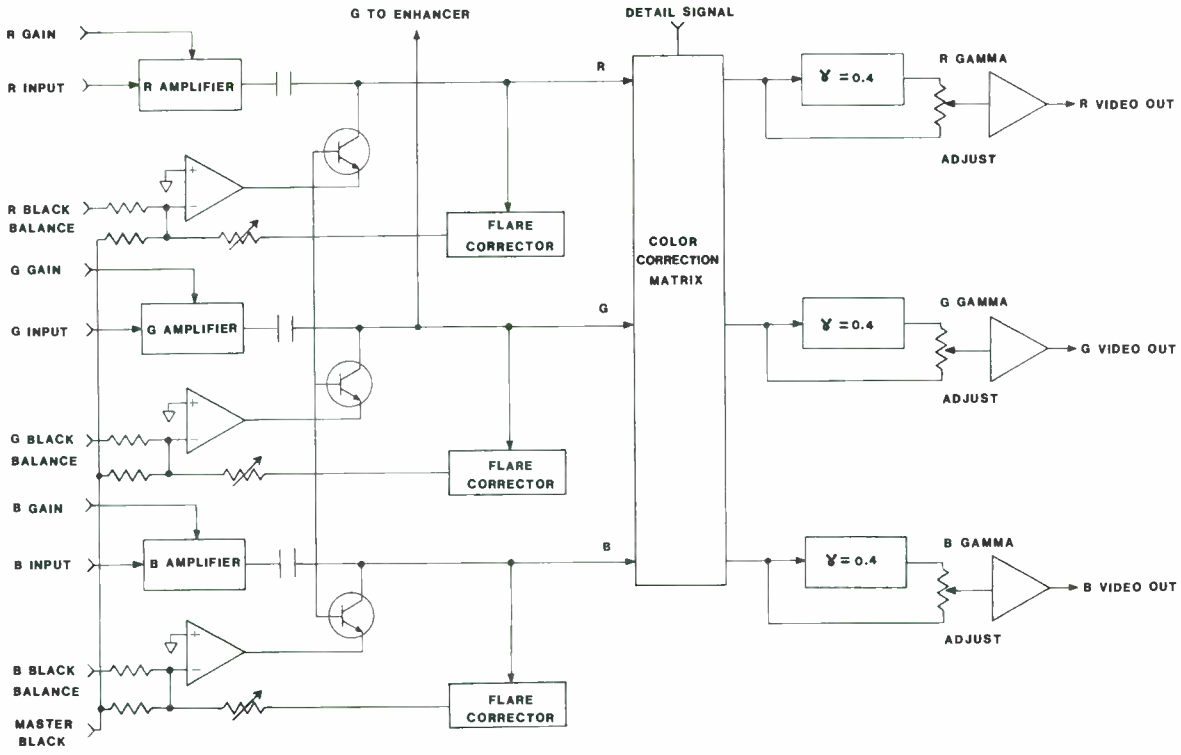


Fig. 3. Video procesor.

The Camera Tube Preamplifier

The purpose of the preamplifier is to amplify the relatively small signal current from the camera tube, which is usually in the range of 20 to 400 nanoamperes. The most common amplifier is the "constant transconductance" type, shown in Fig. 2A. Such an amplifier has a large loop gain, with current feedback through resistor, R, so that the output signal is given by:

$$V_{out} = I_{signal} \times R$$

The signal current is thereby predictably and accurately converted to a signal voltage.

The Image Preamplifier

The solid state imager usually includes circuits to integrate and amplify the transferred charge, so that the resulting output signal is in the form of a small modulation voltage riding on the tips of a rather large clock pulse, as shown in Fig. 2B. Therefore, the imager preamplifier must perform the dual function of further amplifying the imager output voltage and separating the signal from the clock pulse.

The block diagram of a typical imager preamplifier is shown in Fg. 2C, in which case the signal from the imager is first clamped and amplified. The signal is then removed from the clock pulses by means of a synchronous sample and hold technique. A low pass filter, designed to pass the reclaimed video signal, but to reject unwanted the sample pulse, should follow.

The Video Processor

A typical video processing system is shown in Fig. 3, with corresponding waveforms in Fig. 4. The function of the video processing system is described as follows:

Black Level Clamp This first clamp may be one of many, but is the most important, because it must establish the black level reference and identify the "capped" black level, which is the signal

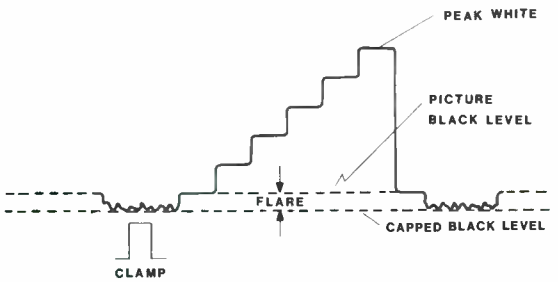


Fig. 4. Video waveform.

level present when there is no illumination entering the camera. It is indicated by the dotted line in Fig. 4. In the example shown, a switching type clamp is used, with the clamp pulse timed to coincide with either the horizontal blanking interval, in the case of a camera tube, or the overclocked horizontal period for an imager.

Black Level Control is necessary to provide master black level adjustment and to match the red and blue black levels to that of the green channel, by using the "black balance" controls.

Gain Equalisation is required to compensate for the varying spectral sensitivity of the imaging devices, and the gain is adjusted to obtain equal signal levels from the three color channels. Usually, the green imaging device is operated at a predetermined signal level and the video processor is designed to provide 100% output under this condition.

Adjustable gain is then provided in the red and blue channels so that these signals may be matched to that of the green channel, to achieve "white balance".

Flare Correction This phenomenon is caused by scattered light in the optical system, which gives rise to an elevated "picture" black level, as shown in Fig. 4. If flare was non-existent, a perfect black in the scene would produce a corresponding signal level equal to the "capped" black level. Because some degree of flare is always present, this scattered light will distribute over the entire picture area and raise the general level of the video signal, producing a black level error.

The spectral distribution of the scattered light depends on the reflectances in the optical system and, in particular, the reflectance characteristic of the imaging device photo-sensitive layer. For example, the brownish color of the lead oxide photosurface indicates that much of the red light is being reflected, a fair amount of green, but little blue light. Therefore, the amount of flare varies in each of the color channel and, in the case of the lead oxide camera tube, will be least in the blue channel.

To compensate for flare, the camera designer assumes that the total amount of scattered light is proportional to the total amount of light entering the optical system. For an imaging device, which has a linear transfer characteristic, the total illumination is proportional to the Average Picture Level (APL). The camera designer can determine the APL by integrating the video signal and producing a dc voltage which is proportional to the total incoming light. An adjustable percentage of this dc voltage is then applied as a flare correction to the black level control circuits in Fig. 3.

Gamma Correction is required to compensate for the non-linear characteristic of the monitor CRT. The typical CRT has the characteristic shown in Fig. 5C, which shows that the control grid voltage has progressively more effect on output brightness for high signals (white) than for low signals (black).

If the camera system, which includes the monitor, is to function as a linear transducer, the camera itself must have the complimentary, non-linear characteristic of Fig. 5B. These non-linear characteristics are known as the "gamma" characteristics of the device, which in the case of the CRT, is approximately 2.7. The general form of the CRT characteristic equation is therefore:

$$B = A(V_c - V_o)^{2.7}$$

Where:

B = the screen brightness.
V_c = the control grid voltage.
V_o = the control grid cut-off voltage.
A = a constant.

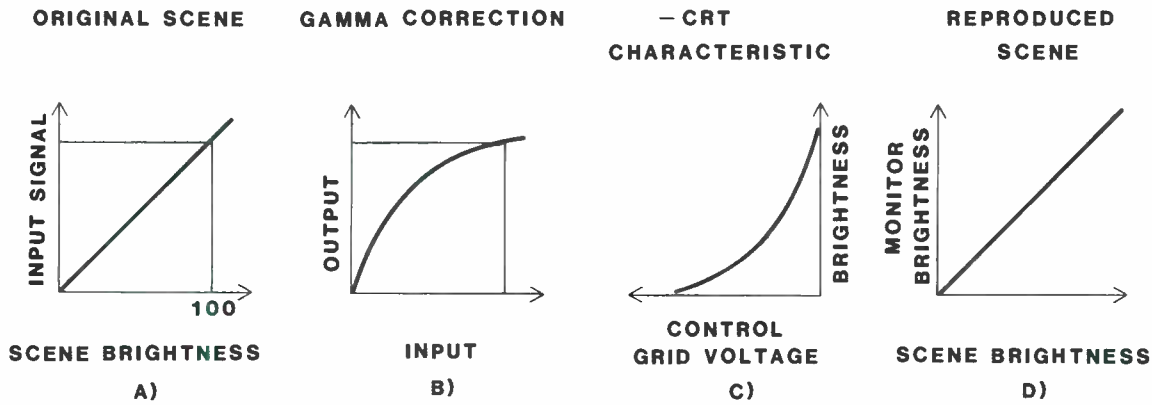


Fig. 5. Gamma correction.

The camera transfer characteristic must then be of the form:

$$V_c = KE^{\gamma}$$

Where:
K = a constant.
E = the scene illumination.
γ = the gamma of the camera.

For B to be proportional to E,

$$2.7 \times \gamma = 1$$

therefore, $$\gamma = 0.37$$

In practice, this degree of gamma correction would require a greatly amplified black signal, which would emphasize black noise. Also, it turns out that a system gamma slightly greater than unity gives a more dramatic quality to the picture, and is preferred by many broadcasters. Therefore, typical camera gamma correction usually falls in the range of 0.4 to 0.45, resulting in an overall system gamma between 1.08 and 1.22.

Aperture Correction The modulation depth of the camera tube as shown in Fig. 6, is limited by the diameter of the scanning beam spot size in conjunction with the lateral leakage of the photo conductor. In early types of camera tubes the spot size was the most significant factor and, because this dimension was controlled by the diameter of the electron gun limiting aperture, the resulting resolution characteristic became known as the "aperture response".

As explained in the section on solid state imagers, the modulation depth of the imager is limited by the size of its smallest picture element, the "pixel". For an imager with 403 horizontal pixels, the theoretical response is very similar to that of the camera tube, as shown in Fig. 6.

Good camera resolution requires that the MTF be corrected. The correction circuit must be of linear phase, such as the one shown in Fig. 7a, consisting of a pair of delay lines, with characteristic frequency, $f = 1/t$, Where t is the delay. The resulting correction characteristic is shown in Fig. 7b. "out of band" correction refers a characteristic frequency above subcarrier, and "in band" when the frequency is below subcarrier. The corrected response is shown in Fig. 7c.

Color Correction the color television camera and its monitor comprises a "tri-stimulus" system, which means that it employs an additive mixture of three primary colors to produce any other color within its range. The spectrum of colors that can be displayed on a television screen are limited by the coordinates of its phosphors. In 1953 the US

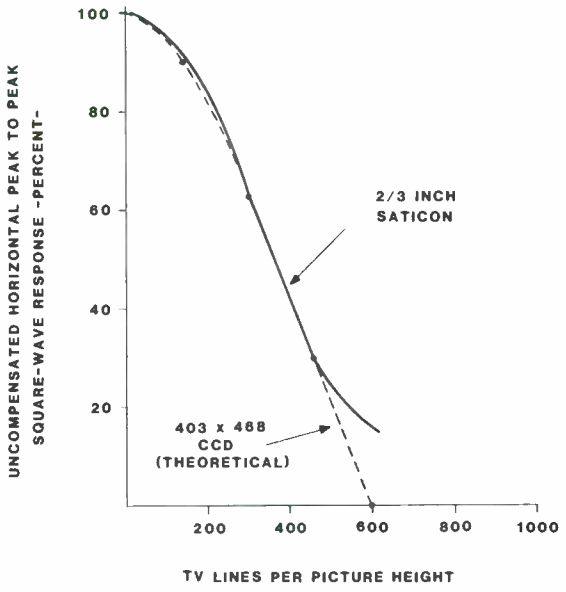


Fig. 6. Modulation depth.

National Television Standards Committee (NTSC) recommended the coordinates shown in the CIE diagram of Fig. 8, which were adopted by the Federal Communications Commission (FCC). The NTSC coordinates defines the range of colors which can be displayed by the television system.

In 1931, in an effort to standardize the interpretation of color, a set of "standard observer" tristimulus values were recommended by the Internation Commission on Illumination (CIE) as shown in Fig. 9. If we analyze the color camera channel responses required to obtain perfect colorimetry, in conjunction with an NTSC coordinate system, we obtain the characteristics shown in Fig. 10. Note the negative responses, or negative sensitivities required to obtain perfect colorimetry.

Fortunately in television, such negative sensitivities can be achieved to a close approximation by matrixing the three color signals, as shown in Fig. 11.

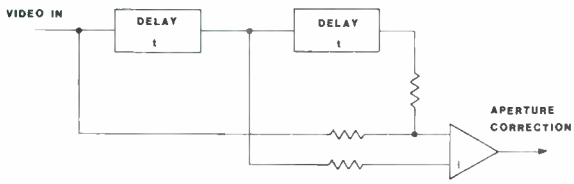
After matrixing, the corrected color signals have the form:

$$R' = a_{11}R + a_{12}G + a_{13}B$$
$$G' = a_{21}R + a_{22}G + a_{23}B$$
$$B' = a_{31}R + a_{32}G + a_{33}B$$

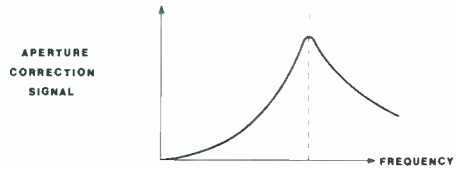
The sum of the coefficients:

$$a_{11} + a_{12} + a_{13} = a_{21} + a_{22} + a_{23} = a_{31} + a_{32} + a_{33} = 1$$

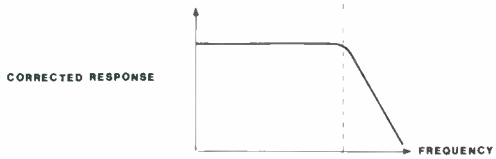
The values of the coefficients must be optimized for the corresponding taking characteristics of the beamsplitter.



(a) PHASE-LINEAR APERTURE CORRECTOR



(b) CORRECTION SIGNAL



(c) CORRECTED RESPONSE

Fig. 7.

However, certain camera manufacturers elect to utilize narrowed R,G,B taking characteristics to obtain increased color saturation, which achieves a result similar to that of the combination of broader responses and a subtractive matrix. While the latter method provides the most accurate color reproduction, narrowed response curves can provide good colorimetry and avoid the slight increase in noise arising from a subtractive matrix.

The Image Enhancer

Is also known as "contour correction", which, as the name implies, is a technique for emphasizing the horizontal and vertical edges, and greatly improves the subjective picture sharpness.

One form of image enhancer is shown in the simplified block diagram of Fig. 12. Usually the input signal is first passed through a "threshold" circuit, which clips out the black level signal and prevents it from entering the enhancer. There is no point in enhancing black level noise, which will later be further emphasized by gamma correction.

The principle of contour correction is illustrated in Fig. 13, which shows the process of enhancing the signal from a vertical white bar, Fig. 13a, which is passed through the two horizontal delay circuits of Fig. 12, resulting in undelayed (L), once delayed (M) and twice delayed (R) signals. The horizontal contour, or "detail" signal, D_h, is given by:

$$D_h = 2M - L - R$$

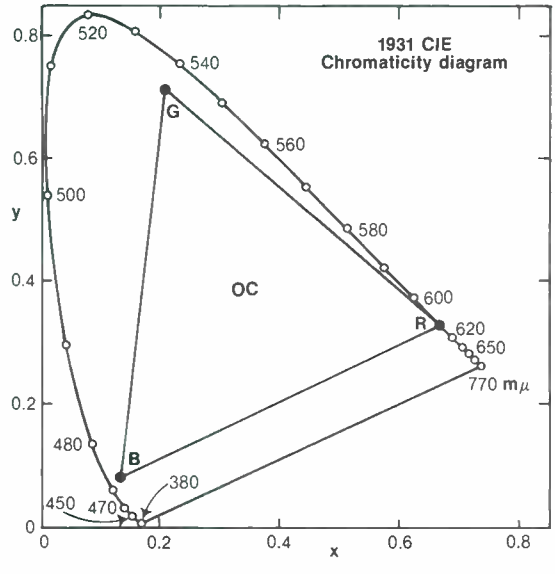


Fig. 8. CIE chromaticity diagram showing the NTSC color primaries.
(Courtesy of Wiley Publishing).

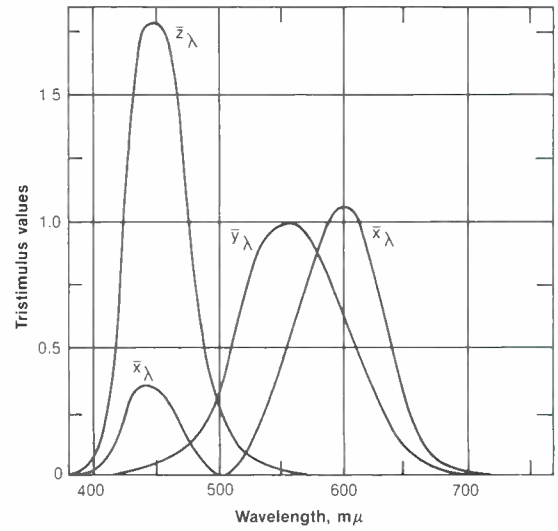


Fig. 9. The 1931 CIE standard observer curves.
(Courtesy of Wiley Publishing).

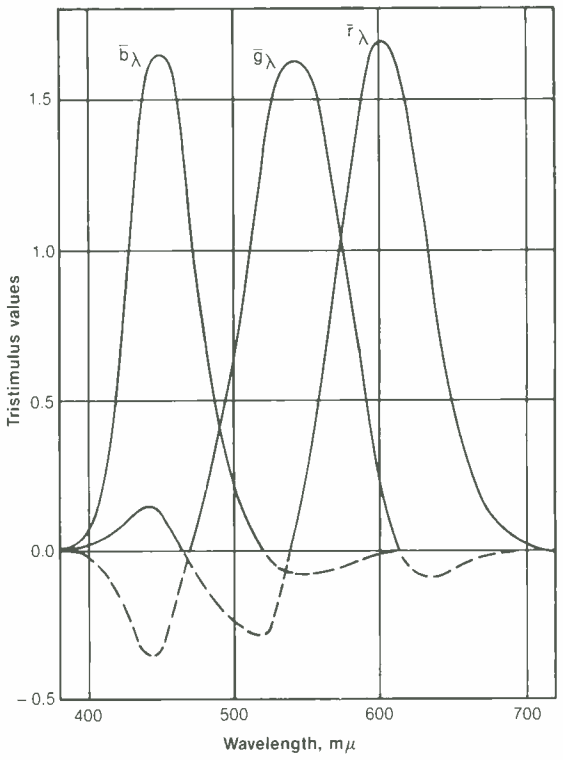


Fig. 10. Ideal taking characteristics.
(Courtesy of Wiley Publishing).

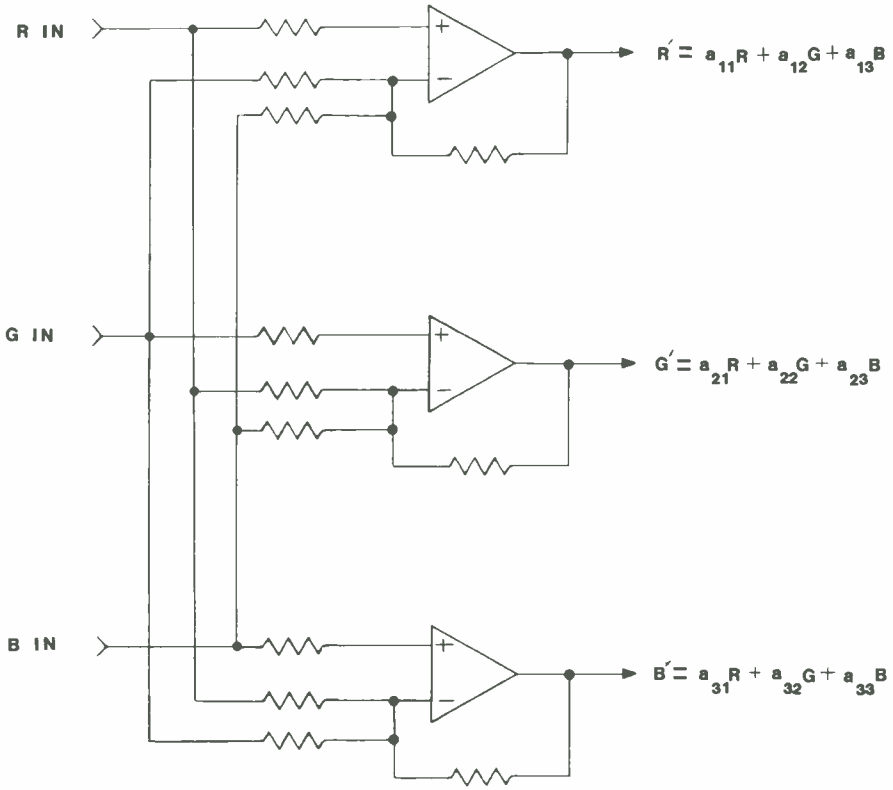


Fig. 11. Color correction.

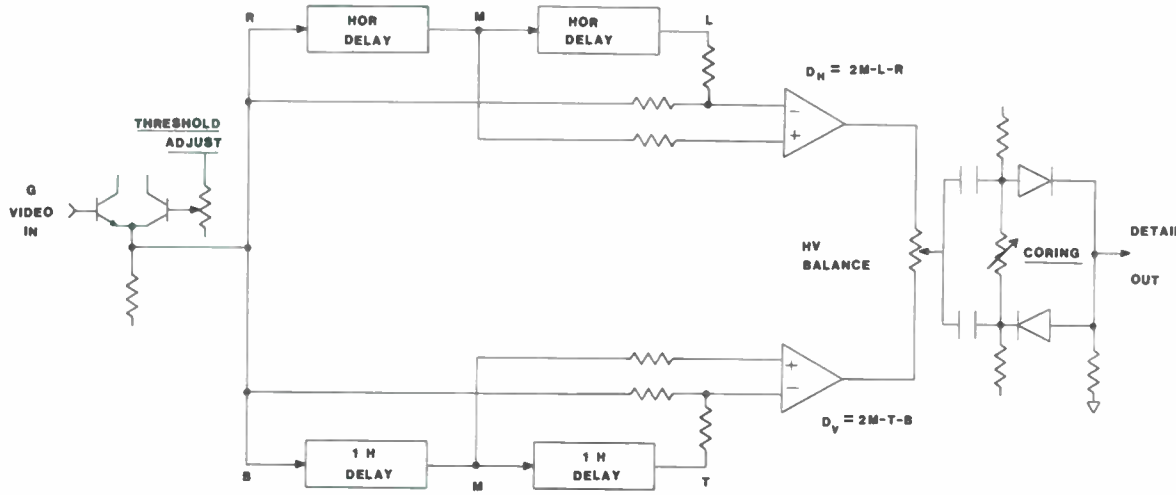
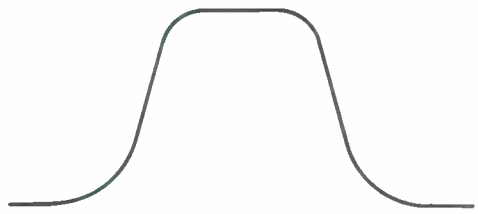
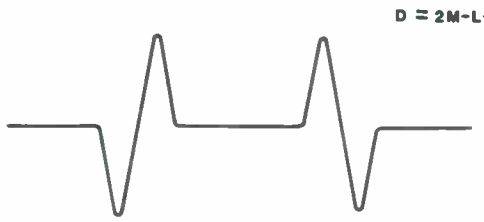


Fig. 12. Image enhancer.



a) UNCORRECTED SIGNAL FROM VERTICAL WHITE BAR



b) CORRECTION SIGNAL

c) CORRECTED SIGNAL

Fig. 13. Aperture correction.

and is shown in Fig. 13b. Adding this correction signal in the correct proportion to the uncorrected signal in Fig. 13a produces the corrected waveform of Fig. 13c. Increasing the amplitude of the detail signal causes the contour to become more exaggerated. Too much correction can over-exaggerate the edges with a rather unpleasant result.

The vertical enhancement signal is generated in the same way, using delay lines of one line duration, either of quartz, or CCD (Charge Coupled Device) type. In this case the undelayed (T), once line delayed (M) and twice delayed (B) signals produce the enhancement signal:

$$D_v = 2M - T - B$$

The Encoder

The purpose of the encoder is to combine the red, green and blue signals from the video processing system into a composite color signal, according to the color standard employed. In the USA the signal is encoded according to the NTSC standard, with the frequency characteristic shown in Fig. 14.

A simplified encoder block diagram is shown in Fig. 15. First, the red, green and blue input signals are combined in a matrix circuit to obtain the luminance signal (Y), and the in-phase (I) and quadrature (Q) components of the color signal. The matrix equations for these signals are:

$$Y = 0.30R + 0.59G + 0.11B$$
$$I = 0.60R - 0.28G - 0.32B$$
$$Q = 0.21R - 0.52G + 0.31B$$

The low pass filters limit the bandwidths of the I and Q signals to 1.3 MHz and 0.5 MHz respectively. Such bandpass circuits cause an inherent

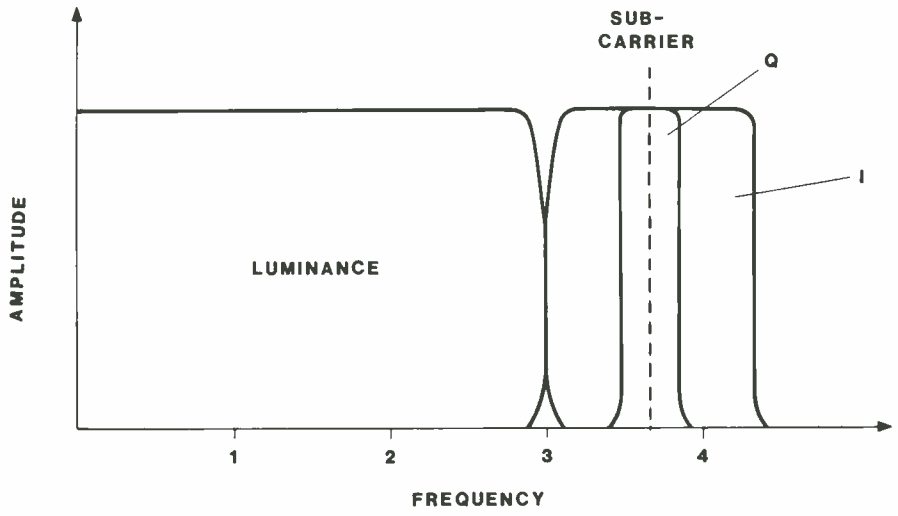


Fig. 14. NTSC frequency spectrum.

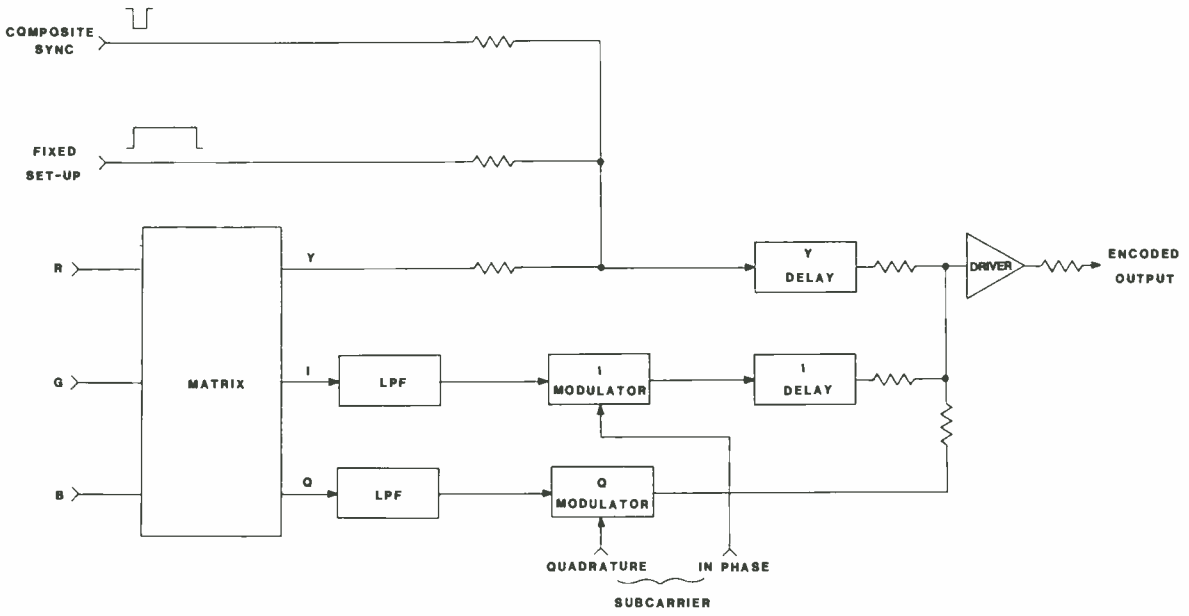


Fig. 15. Simplified encoder block diagram.

delay, the longest being the *Q* signal, with a delay of approximately 750 nanoseconds, depending on the actual network used. In order that the three signals remain in phase, it is necessary to provide a 750 nanosecond delay in the *Y* channel and approximately 400 nanoseconds delay in the *I* channel.

The two modulators receive in-phase and quadrature (90 degrees phase shifted) subcarrier components, as shown in Fig. 16. The in-phase component is modulated by the *I* signal, and the quadrature component by the *Q* signal. During horizontal blanking, correctly proportioned burst pulses are applied to both modulators, resulting in the subcarrier burst vector oriented at 180 degrees.

A fix set-up of 7.5 IRE units is added to the delayed luminance signal, together with the output of the subcarrier modulators, and a correctly shaped synchronizing pulse. The result is the composite waveform of Fig. 17, shown, in this case, with a color bar test signal.

Usually, the encoder includes a color bar generator, which provides a standard RGB signal to test the encoder set-up, and to provide an important aid for setting up the color monitor.

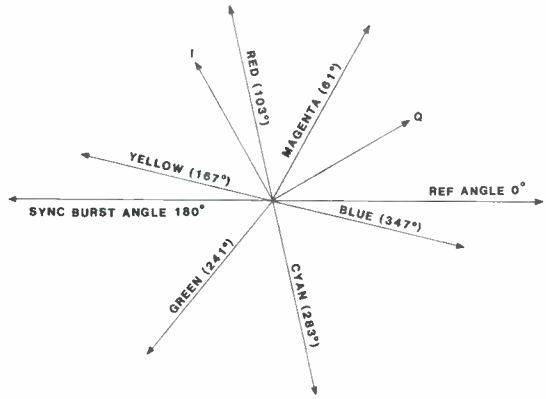


Fig. 16. Subcarrier phase relationship in the NTSC encoder.

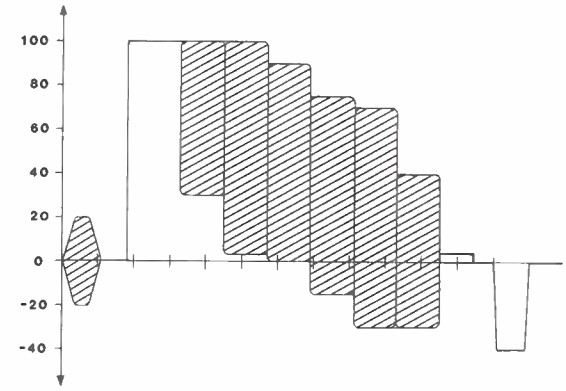


Fig. 17. Encoder output waveform.

The Synchronizing Generator

Is the master timing system, which provides all the pulses required by the camera, in accordance with the appropriate color standard? In the USA the output signal waveform must conform to EIA standard RS-170A (see Appendix A).

In event that the camera must be synchronized with another camera, or system, the synchronizing generator is provided with a "genlock" ability, whereby it can be phase-locked to an external composite color signal.

The Deflection System

The deflection system is employed in a tube type camera to provide the necessary scanning waveforms to the yoke scanning coils. Simplified deflection system is shown in Fig. 18.

In this case the vertical and horizontal master sawtooth generators produce the main scanning waveforms, dc voltage-controlled sawtooth generators provide the registration functions of size, skew and rotation and parabolic generators provide linearity adjustment.

Usually, the drivers function as current sources with sufficient feedback to ensure the scanning current through the deflection coil is a linear function of the input voltage waveform. In Fig. 18, the deflection current is given by:

$$I_{hor} = \frac{V_{master} + V_{size} + V_{linearity} + V_{skew}}{R}$$

$$I_{vert} = \frac{V_{master} + V_{size} + V_{linearity} + V_{rotation}}{R}$$

The Clock Driver

Usually, the imager contains three registers, as shown in Fig. 19, which represents a frame store CCD, the image, or "A" register, in which the image charge pattern is formed; the storage, or "B" register, into which the image is transferred from the "A" Register; and the horizontal shift register, which provides a line by line readout of the "B" register.

As illustrated in Fig. 19, the clock driver must generate the various pulses necessary to address the imager. The driver must produce a set of $V_{(A)}$ pulses during the vertical blanking interval to transfer the charge pattern from the "A" register to the "B" register. The $V_{(B)}$ pulses are required to subsequently move the data from the "B" register, line by line, to the horizontal shift register.

Once each line of charge has been transferred to the horizontal shift register, it is clocked out by the "H" pulses, pixel by pixel. Usually, the charge is shifted into a floating diffusion zone, which functions as a resettable capacitance, converting the charge pattern to a signal voltage. An additional horizontal reset pulse (*HR*) is required to reset the diffusion zone after each pixel is clocked out.

Power Supply

The power supply must produce the various dc voltages required by the entire camera system, including the relatively high voltages required by the camera tubes.

In the case of a portable camera, the power supply will be a dc to dc converter, which generates all the voltages required by the camera system from a portable rechargeable battery pack. Usually, the studio camera power supply operates from an ac input.

Automatic Set-up

The automatic set-up facility is only advantageous in tube type cameras, which require

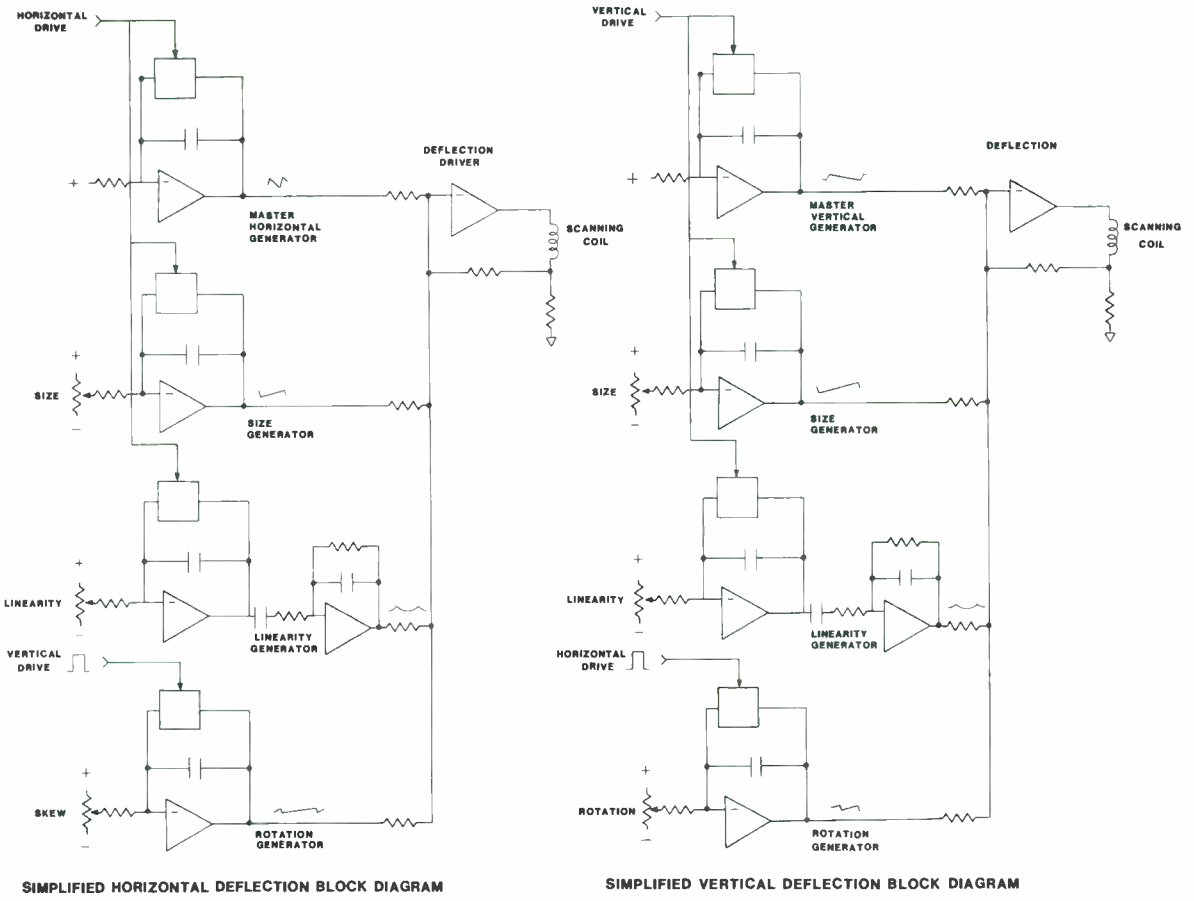


Fig. 18.

periodic adjustment, due to the inherent instability of the camera tube target and its thermionic electron gun.

The function of the automatic set-up system is to analyze the various video signals and registration errors and to generate either control voltages, or correction signals to accurately adjust the camera. Cameras with this feature require a pattern projector in the optical system (usually in the lens), which provides a test pattern compatible with type of automatic system employed.

CAMERA TYPES

The Studio Camera

This is a misnomer that previously referred to the relatively large cameras, which are most often used in the studio. Such cameras are neither restricted to studio use, nor the only cameras used in the studio. For example, many producers have discovered the advantage of having at least one portable camera in the studio; and many studios have found the smaller ⅔-inch (18mm) cameras to be a cost effective option.

The studio camera system usually consists of a camera head and CCU (Camera Control Unit). The camera head can be separated from the CCU by up to 1,500 feet of multiconductor cable, or as much as 6,000 of triaxial cable.

Studio cameras generally employ a 1¼-inch (30mm), 1-inch (25mm), or ⅔-inch (18mm) camera tubes. Due to its weight, the studio camera must be supported on a sturdy tripod, or pedestal, which also enables the use of a larger, higher performance lens. For this latter reason, primarily, the studio camera performance tends to be better than its "portable" counterpart.

Many cameramen favor the larger studio camera, even in OB (Outside Broadcast) applications, because they believe that a larger mass is necessary for a smooth, controlled pan. To a degree this is so, but a tripod with a fluid head can provide much of the same "feel," in fact, the movie industry has depended for many years on the smooth movement provided by the fluid head.

The Portable Camera

This camera must be small and light weight, so that it may be comfortably supported on the cameraman's shoulder for long periods of time. The portable camera can operate as a self-contained unit, or may be capable of modular adaptation to work with an RCU (Remote Control Unit). The RCU may be separated from the camera by up to 1,000 feet of multiconductor cable, or up to 6,000 of triaxial cable.

Due to the necessity for minimum size and weight, portable cameras utilize ⅔-inch (18mm), or ½-inch (12.5mm) camera tubes, or solid state imagers. Also, in the interest of size, the lens must be small and, therefore, its performance range is limited, compared to the studio camera lenses.

If the portable camera is used in an application where it can be supported by a tripod, a larger, so called, EFP (electronic field production) lens can be used. Such a lens greatly improves the portable camera's performance, which consequently can approach that of a studio camera.

The ENG Camera

The ENG (Electronic News Gathering) camera is a particular version of the portable camera, which design is optimized for televising the news.

The requirements of ENG puts severe constraints on the camera design, beyond the need to be small and light weight. The ENG camera must be extremely rugged, reliable and stable; the very nature of its use means some degree of physical abuse is unavoidable and there is no time to go through a lengthy camera set-up just as a news story is breaking. Because the ENG camera is used under a wide range of uncontrolled lighting conditions, it must also be very sensitive and able to handle spurious highlights without severe picture degradation from veiling glare, or other problems.

The EFP Camera

This is a special type of portable camera, which, as the name implies, is used for portable production. Fundamentally, the needs of portable

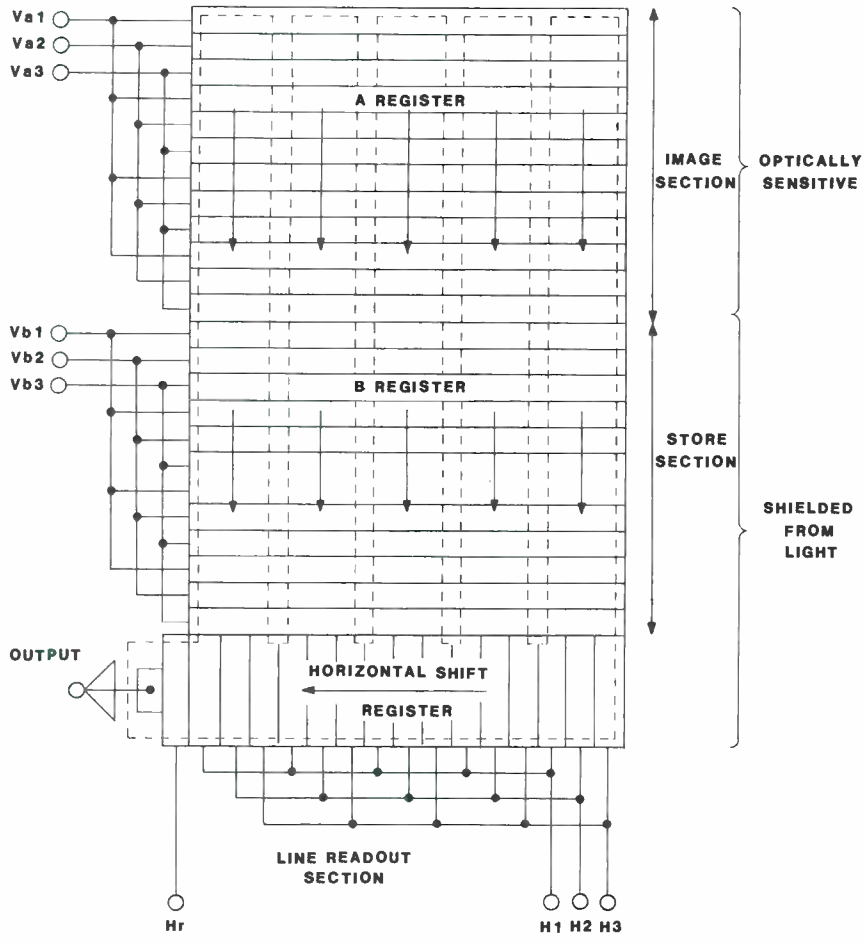


Fig. 19. CCD frame transfer array schematic.

production are similar to those of the studio, except that the camera system must also be easily transported and capable of both handheld, or tripod operation. The EFP camera, therefore, should have the performance of a studio camera, combined with the virtues of a good ENG camera.

Ideally, the EFP camera should be portable, but with the ability to adapt to large "EFP" lenses and to be remote controlled from considerable distances up to 6,000 feet. Such cameras provide great flexibility in both field production and sports applications.

The Sports Camera

This term that can be applied to any camera that is used in sports coverage. As discussed above, "studio" cameras are frequently used in this application, which is also ideal for the EFP camera.

Several factors are of prime importance in a camera used for sports coverage: The camera must accept a lens with a large zoom range if it is to cover a ball game effectively from high in the stadium, follow the action around a race track, or at a golf tournament. The sports camera must also be remote controllable from the great-distances encountered in these applications.

THE OPTICAL SYSTEM

Lens Parameters

Focal Length determines the angle of view of the lens, which relationship depends on the camera image format, as shown in Fig. 20. For example, a 9.0mm focal length in ⅔-inch format gives the same angle of view as 13.0mm in 1-inch format, or 18.0mm in 1¼-inch format.

Angle of View is related to focal length as shown in Fig. 20. Because of the 4:3 aspect ratio of our television standard, the angle of view is greater in the horizontal direction than in the vertical direction.

Field of view is related to the angle of view as follows:

$$\text{Field of View} = 2D\tan(\text{angle of view}/2)$$

Where D is the distance from the camera to the object of view. For example, if the object of view is 1,000 feet away and the lens has an angle of view of 2 degrees;

$$\begin{aligned}\text{Field of View} &= 2 \times 1{,}000 \times \tan(2°/2)\\ &= 2{,}000 \times 0.0175\\ &= 35 \text{ feet}\end{aligned}$$

This situation could represent a camera located 1,000 feet from the starting gate at a race track.

Relative aperture (F/Number) describes the speed, or light gathering power of the lens. The relative aperture is defined as:

$$\text{F/Number} = \frac{\text{Focal Length}}{\text{Effective Diameter}}$$

Because the light gathering power of a circular aperture is proportional to the square of its diameter, the light gathering power, or speed of a lens is inversely proportional to its relative aperture, or F/Number.

For example, the typical sensitivity of an ENG Camera is 200 foot candles at F/4.0. If the camera lens has an F/1.6 maximum relative aperture, the following illuminations are required

F/Number	Illumination
4.0	200 ft candles
2.8	100
2.0	50
1.6	32

Switching in 12 dB added gain (×4) would give such a camera a maximum sensitivity of 32/4 = 8 ft. candles.

Ramping is a term applied to the increased F/Number (reduced speed) of some lenses as the focal length is increased. In the example of Fig. 21, the lens has a relative aperture of F/1.6 through a zoom range of 12mm to 120mm, but may "Ramp" down to F/2.8 at its maximum focal length, 180mm. For an ENG camera with the sensitivity indicated in the above example, 32 ft. candles would be sufficient illumination at a focal length of 12mm to 120mm, but 100ft candles would be necessary at 180mm.

Ramping is an inevitable result of a small objective element at the front of the zoom lens. In ENG Camera lenses the objective element is deliberately small to minimize the overall weight and some ramping is not uncommon. Ramping is only a problem if there is insufficient illumination for the lens to be used at its maximum focal length.

Modulation Transfer Function (MTF) defines the resolving capability of the lens and is measured by looking at a 100% amplitude sine wave bar pattern and determining the depth of modulation obtained in the image. With few exceptions, the MTF is better in the center of the picture and decreases towards the corners. The difference between the center and corner modulation is less when the lens is stopped down than when the iris is wider open.

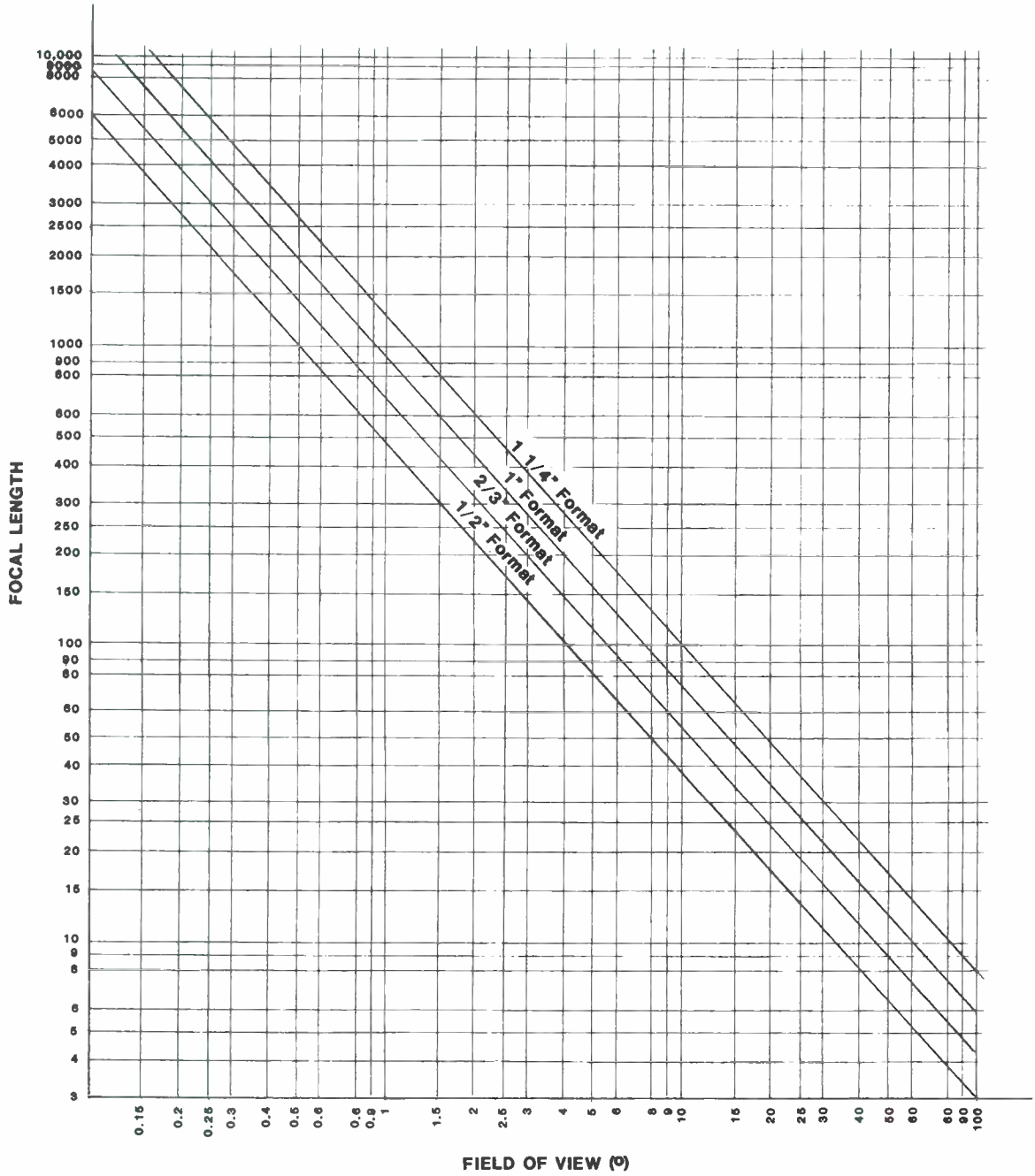


Fig. 20. Focal length vs. horizonatal field of view.

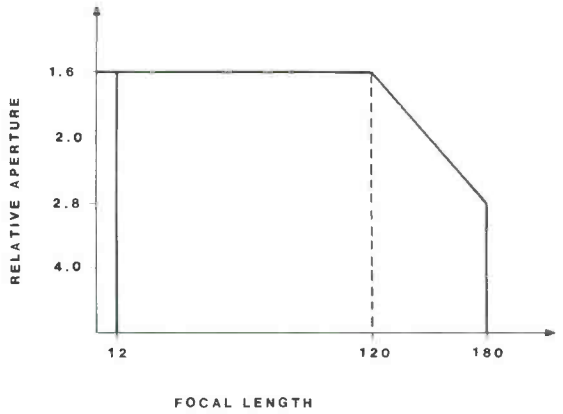


Fig. 21. Lens ramping.

Most lenses exhibit their best MTF when operated in the middle of their aperture range. For example, a lens with aperture range of F/1.6 to F/16 will probably give its best modulation at about F/4.0. If the lens is further stopped down towards F/16 some small reduction in modulation may result due to the light being defracted as it passes through such a small aperture. However, as the lens is opened towards its maximum aperture of F/1.6 a more severe loss of modulation depth is likely to occur as the spherical aberrations become more significant.

The MTF characteristic of a typical zoom lens is shown in Fig. 22. Note that the MTF becomes worse as iris is opened and that this difference is more exaggerated in the corners, which illustrates the importance of evaluating a lens at its maximum aperture.

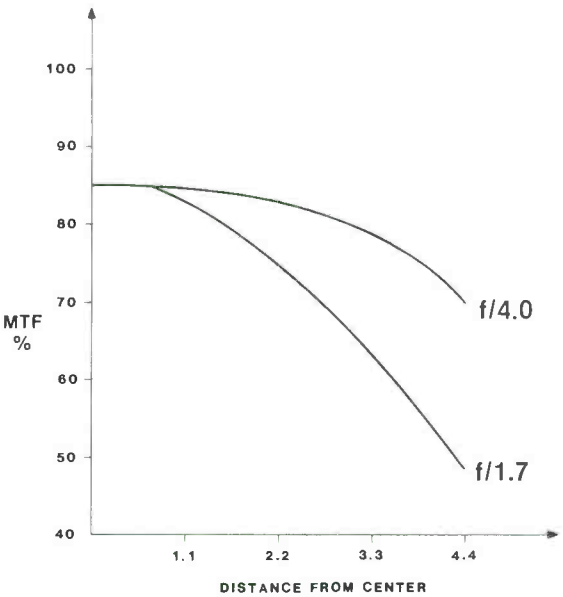


Fig. 22. Typical MTF characteristic for ⅔ inch lens. (average for all focal lengths)

Uniformity of field (vignetting) refers to the response to a white field over the full picture area. The typical uniformity of field characteristic of a zoom lens is shown in Fig. 23, which illustrates that the response is usually greatest in the center and least in the corners. The non-uniformity in the corners becomes more pronounced at wide aperture, and varies with focal length. Again, it is important to evaluate a lens at maximum aperture, when such characteristics are at their worst.

Longitudinal chromatic aberrations. Although the lens designer makes a great effort to achieve consistency, the focal length of a zoom lens tends to vary slightly with color throughout its zoom range. This means that there will be some small differences between the color channels, in both focus and image size, as the zoom is operated.

The spectral variation in focal length is called the longitudinal chromatic error and is, to some extent, inevitible with today's state of the art. In general, the more severe the constraints that are placed on the lens designer, such as the need for a smaller, faster lens for a portable camera, the more difficult it is to keep these aberrations small.

Usually, the lens designer can decide where the chromatic aberrations will be distributed. Often he will decide that most of the error will be in the blue, because this channel contributes less to the overall picture quality.

The longitudinal chromatic aberration for a typical zoom lens is shown in Fig. 24. Note that the red and blue channels tend to have a fixed focal length error with respect to green, plus some error that varies with focal length. The fixed component of error can be corrected using the focus tracking adjustments of the red and blue yokes, however the variable error will inevitably result in some degree of defocussing at certain focal lengths.

Similarly, the average value of the magnification error can be corrected in a tube type camera by adjusting the scanned raster sizes, however the variable error component that changes with zoom will result in some slight misregistration at certain focal lengths. It is best to set up the camera registration at some point in the middle of the focal length range, so that the variable errors are evenly distributed throughout the zoom range.

The CCD camera presents a special problem, because the image size is fixed. Lenses designed for CCD cameras must have minimum chromatic aberrations.

Geometric Distortion. All lenses exhibit some degree of geometric distortion, which is a symmetrical error, as shown in Fig. 25a, effecting the red, green and blue images equally. In the case

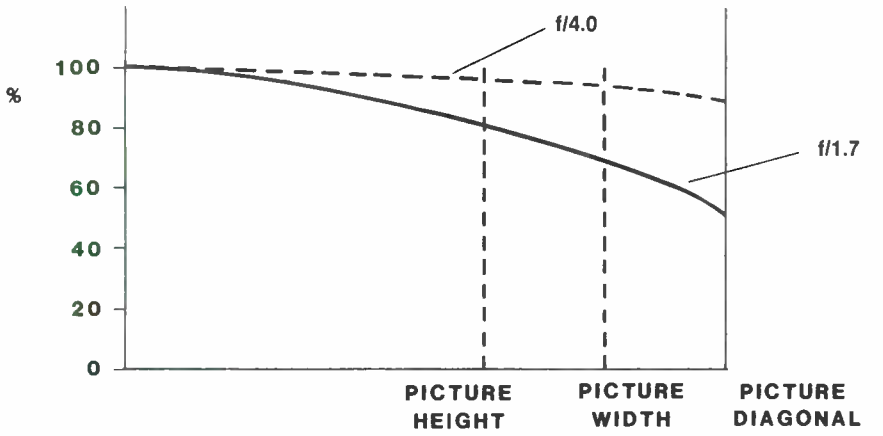


Fig. 23. Uniformity of field.

of the zoom lens, the distortion varies with focal length (Fig. 25b), such that the negative (barrel) distortion occurs at short focal lengths, and positive (pincushion) distortion occurs at long focal lengths. Again, it is advisable to set up the camera at some point in the middle of its zoom range, where the average value of distortion is present.

Minimum Object Distance (MOD) is the closest focussing distance of a lens. Wide angle lenses generally have the smallest MOD and telephoto lenses the longest. This is a most important factor in choosing a lens to ensure that the MOD is adequate for the particular application.

The Relay Type Beamsplitter

The relay type beamsplitter is shown in Fig. 26, in which the taking lens focusses the scene onto the field lens, which is an intermediate focal plane. The re-imaging lenses, in turn, focus the field lens image onto the imaging devices via the dichroic mirrors, which provide the beamsplitting function.

The first mirror is usually a red reflecting dichroic surface, with the transmission characteristic shown in Fig. 27a, which separates out the red component of the image by reflecting it back to the first surface mirror, from which it is focussed onto the imaging device, via the re-imaging lens and red trim filter. The transmission characteristic of the trim filter combines with that of the red dichroic mirror to produce the overall red response curve required in Fig. 27c.

The blue-green light passes through red dichroic filter and the blue component is reflected by the blue dichroic mirror, with the transmission characteristic shown in Fig. 27b. The blue image

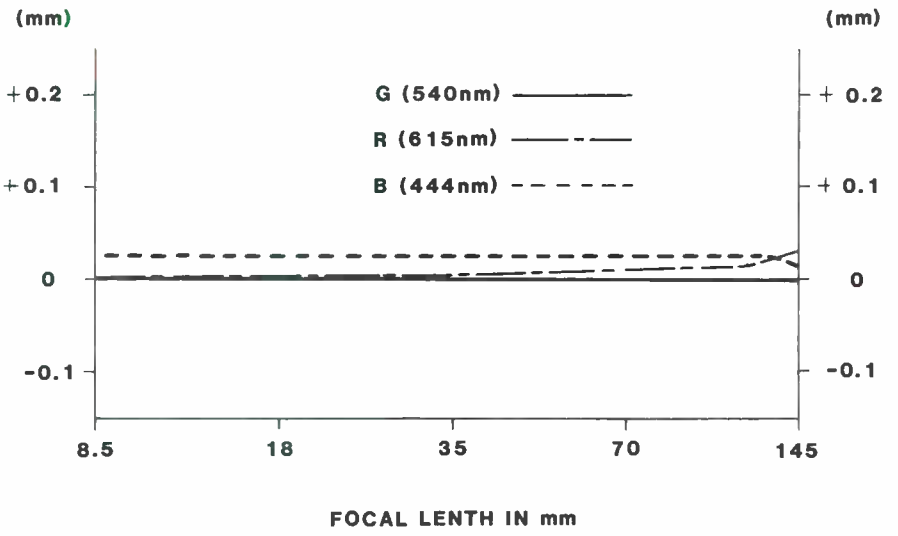
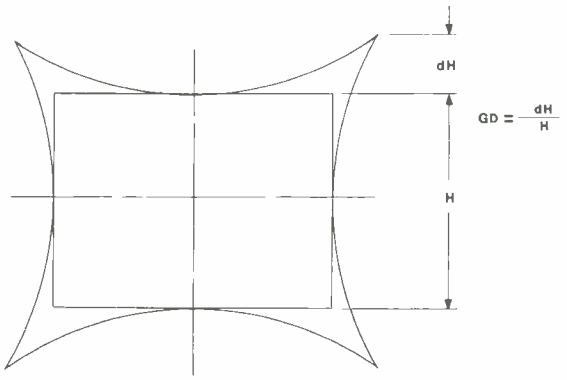
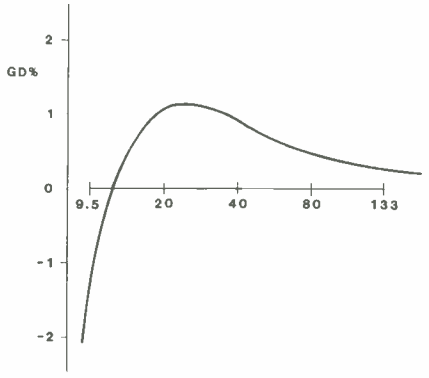


Fig. 24. Longitudinal chromatic aberration.



(a)



(b)

Fig. 25. Geometric distortion.

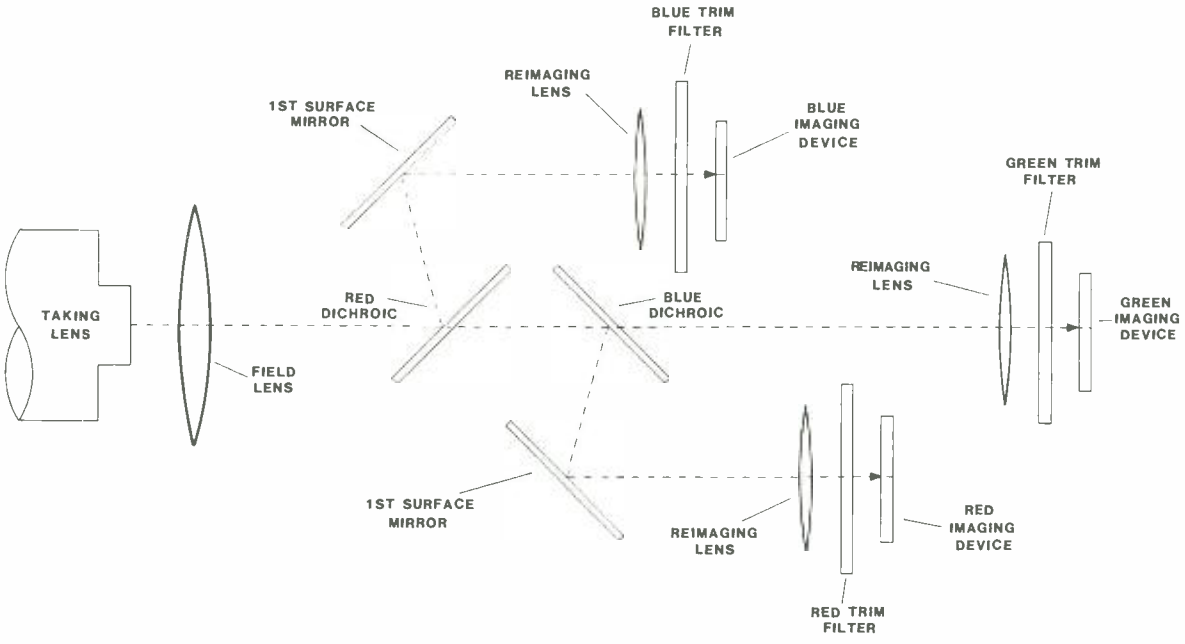


Fig. 26. Relay type beamsplitter.

is then focussed onto the blue channel imaging device, via the remaining first surface mirror and blue trim filter. The remaining green light passing through the blue dichroic mirror is focused onto the green channel Imaging Device via the green trim filter. The overall response is shown in Fig. 27c.

The purpose of the field lens is to ensure that the maximum amount of light from the taking lens is directed into the re-imaging lenses, otherwise extremely poor sensitivity and vignetting would result.

There are several disadvantages in the relay type beamsplitter for broadcast camera applications; it is relatively large and, unless fast and expensive re-imaging lenses are used, it has lower sensitivity, resolution and more vignetting than a prismatic system. It also requires more surfaces than its prismatic counter part, which results in increased transmission loss and flare.

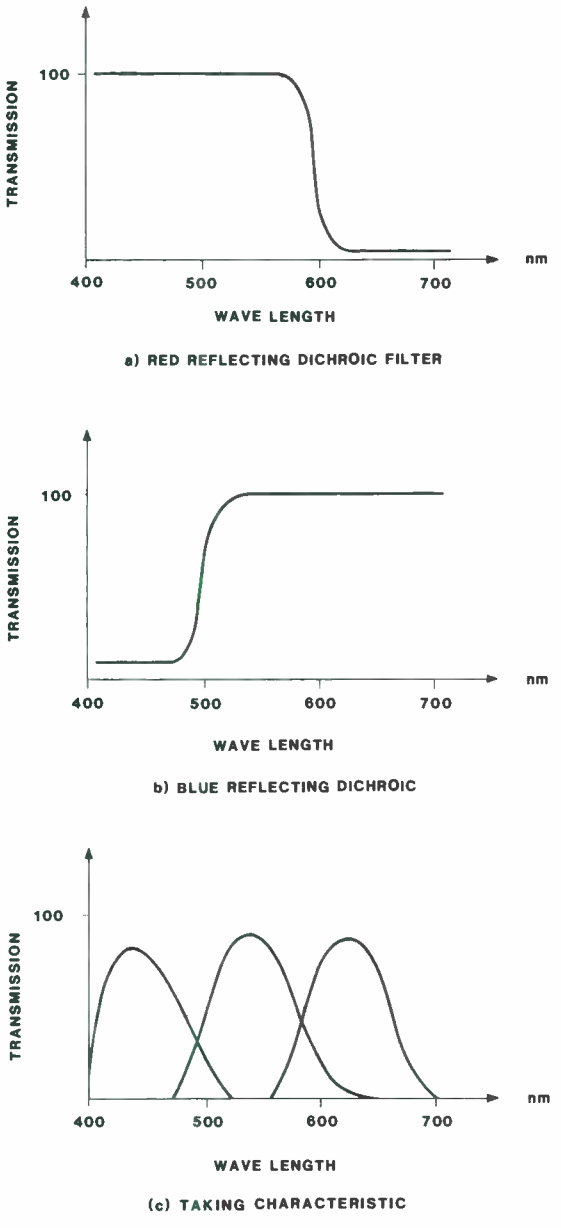


Fig. 27.

The Prismatic Beamsplitter

As shown in Fig. 28, the prismatic beamsplitter is usually constructed of three precision blocks of glass. The taking lens must have a long back focal distance, in order to focus the image through the prism onto the imaging devices.

Light from the taking lens enters prism block (a), the front surface of which is often coated with an infrared blocking dichroic filter to prevent this light reaching the imaging devices, which would otherwise impair the color fidelity. The red light is reflected by the dichroic mirror on the first surface of prism block (b), which has the characteristic shown in Fig. 27a, and, because of the acute angle it makes with inside of the first surface of block (a), it is totally reflected through the red trim filter onto the red imaging device.

The green-blue light passing through the red dichroic filter is similarly reflected by the blue reflecting dichroic mirror on the first surface of block (c) and totally reflected into the blue imaging device. The green light continues onto the green imaging device.

As with the relay system, the trim filters tailor the overall spectral response so to that required in Fig. 27c.

The principle advantage of the prismatic beamsplitter is that it is small and has good mechanical stability. Also the prism can be designed to pass a large cone of light, which means that it can accept a fast lens. Typical lens apertures for existing prismatic beamsplitters are as follows:

Format	Typical Aperture
1¼"	F/2.1
1"	F/1.5
⅔"	F/1.2
½"	F/1.2

Filters

Color filters are usually housed in a wheel between the taking lens and beamsplitter. The following filters are commonly used;

CLEAR	—Clear glass
WRATTEN 85B	—Converts daylight to studio color temperature, 3,200 degrees Kelvin.
0.6 ND	—Neutral density filter reduces camera sensitivity by 4 times.

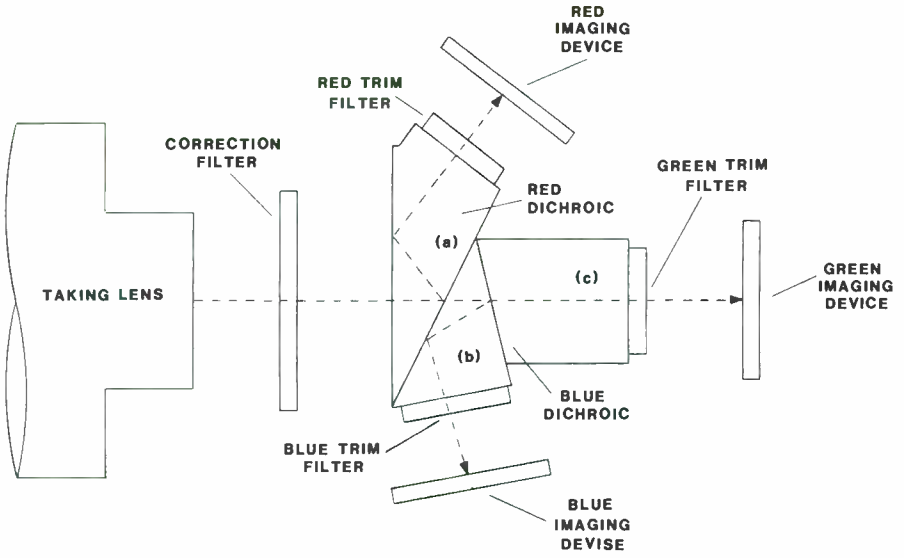


Fig. 28. The prismatic beamsplitter.

1.0 ND —Neutral density filter reduces camera sensitivity by 10 times.

1.0 ND + 85B —Reduces sensitivity by 10 times and converts daylight to 3,200 degrees Kelvin.

CAMERA TUBES

Two types of camera tubes are currently used in broadcast television cameras; those with a Lead-oxide photosurfaces, and the "Saticon" (trademark Hitachi Ltd), which uses a photosurface consisting of a selenium, arsenic and tellurium compound.

Lead-Oxide Camera Tubes

The Lead-oxide camera tubes are marketed under various trade names; the Plumbicon (trademark Philips ND), and the Leddicon (trademark English Electric Valve Co. Ltd). The lead-oxide camera tubes are fundamentally similar, consisting of a complex layer of lead monoxide formed by evaporation techniques. Because part of the layer is formed by evaporation in a partial pressure of inert gas, the lead-oxide surface has a fluffy texture, which results in a lower capacitance for reduced lag.

The standard lead-oxide layer has a spectral response, which peaks in the green-blue part of the spectrum and does not exhibit good red sensitivity. For the red channel an "extended red" version of the tube is used, which is formed by further doping the layer to enhance the red sensitivity.

The Saticon

The Saticon has a glass-like layer which is amorphous in structure and gives a more uniform spectral response than the standard lead-oxide surface, so that a special red channel tube is not necessary and flare is reduced.

Comparison Between Lead-Oxide and Saticon Tubes

Due to competitive pressures, these two camera tubes have advanced steadily and their performances are very similar. Because it is normal for there to be a significant tolerance in the various performance parameters of both tube types, it may not be possible to decide which tube type is best from a single comparison.

Camera Tube Set-Up

Before attempting to measure any camera tube characteristics, it is necessary that the device be set up in accordance with the manufacturers recommendations. In general, the following set-up adjustments are necessary:

X and Y Alignment. Incorrect beam alignment can significantly impair the camera tube performance. Usually a camera is equipped with a focus "rock" facility to aid in accurate alignment. If focus rock is not available, manually rock the focus control a little each side of true focus and adjust the X and Y alignment control until the focus rocking causes the center of the picture to rotate without horizontal, or vertical movement.

Signal Current. The correct signal current is necessary for best performance. If the signal current is too large, beam pulling can result and, together with the excessive beam current required, reduced resolution can result. If the signal current is too small, the signal to noise ratio will be impaired. The following signal currents are usually recommended;

Format	Signal Current
30 mm	300–400 nA
25 mm	220–300 nA
18 mm	180–200 nA
13 mm	150–200 nA

Beam Current misadjustment can also significantly impair performance. If the beam current is too small, obviously the target will not be adequately discharged, resulting in greyscale distortion and blooming.

The effect of too much beam, however, can be more subtle. As the beam current is increased the average energy of the electrons in the beam changes, in particular in the radial direction, and the cross-section of the focussed beam becomes larger. Excessive beam, therefore, results in reduced resolution, increased build-up lag and, in severe cases, can produce a distortion of the raster, which impairs registration.

The correct setting of the beam depends on whether the camera employs ABO (Automatic Beam Optimization), or not. A standard logarithmic greyscale (Fig. 29) is a convenient test pattern for this purpose.

Adjusting the Beam Without ABO—make sure that adequate beam is available and adjust the lens iris to obtain 100 IRE units of signal, then open one more f/stop. Reduce the beam and note that the when insufficient beam is available the signal level reduces and the white chip of the grey scale is not fully discharged, so that its edges bloom and become ill-defined. Increase the beam current until the white chip is visibly discharged, the blooming effect disappears and the edges "snap" into place.

Adjusting the Beam Current With ABO—Because the various ABO systems require different set up, refer to the manufacturer's instructions.

SOLID STATE IMAGERS

Imager Types

The solid state imagers that are currently used in broadcast cameras are of the CCD (Charge Coupled Device) type. These imagers are organized into horizontal rows and vertical columns of image elements, known as "Pixels". The greater the number of pixels, the higher the resolution of the device.

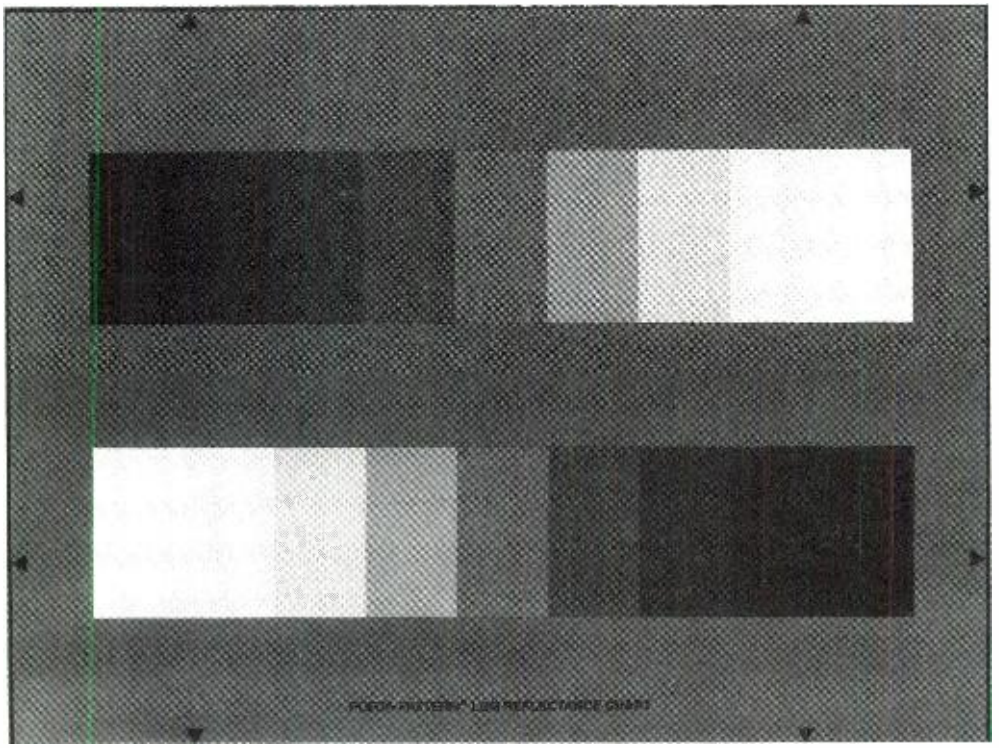


Fig. 29. 9-step log grey scale chart.

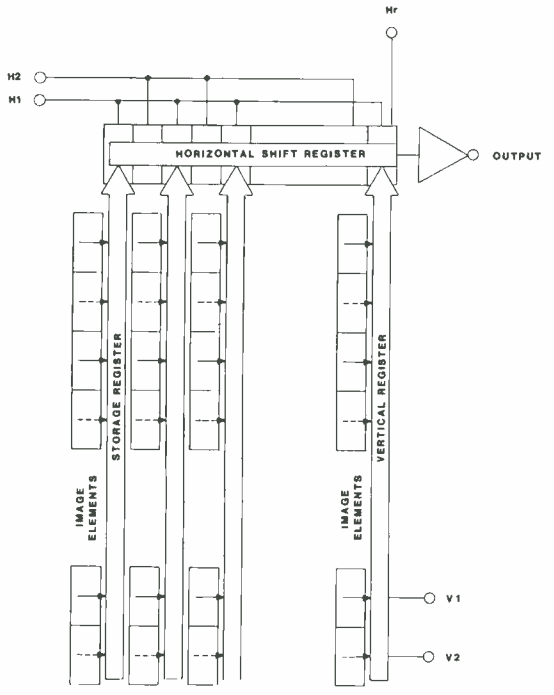


Fig. 30. Interline transfer CCD.

The charge pattern formed in the CCD pixels is allowed to integrate during the unblanked frame period, and is then transferred to a separate storage register during the vertical blanking interval. The stored image is then transferred row by row into a horizontal register, from which it is clocked out during the unblanked horizontal period. This transfer process passes the charge pattern from pixel to pixel, hence the term "Charge Coupled Device".

There are two basic kinds of CCDs; the "interline transfer" type uses a storage register, which is integrated with the image register, as shown in Fig. 30, the "frame transfer" type uses a separate storage register, as shown in Fig. 19. The interline transfer type of CCD has the disadvantage that almost half of the image area is used for the storage register, which reduces sensitivity and increases aliasing. However the completely separate storage register of the frame transfer device requires almost twice as many transfers, which means that the transfer efficiency must be very high to avoid resolution loss.

CCDs may be of the "front-lighted" type, in which case the illumination must pass through the address structure of the device, consisting of evaporated metal, or poly-silicon, resulting in a significant light loss, particularly in the blue.

In the case of the "back-lighted" CCD, an extremely thin silicon wafer is be mounted on a glass substrate and the light enters the device from the glass side, thereby avoiding losses through the address structure.

Imager Set-Up

Set-up requirements for the various imagers differ significantly and the user should refer to the manufacturers instructions for details. Basically, however, all imagers require certain drive pulse levels and voltages for efficient operation. Failure to make the correct adjustment can result in poor performance, such as low resolution, blooming, smear and poor signal to noise ratio.

Imager Resolution

The imager is a spatial sampling device with a characteristic Sin x/x response, Where $x = L_c F_s$. F_s is the spatial frequency and L_c is the pixel dimension. For a CCD with 403 horizontal elements, the spatial frequency of the pixels is 7.6 MHz and, according to Nyquist's Theorum, the maximum spatial frequency that can be resolved is 3.8 MHz (304 TV lines).

However, the theoretical response at the Nyquist limit is 64 percent and there is significant response above this limit due to "aliasing" or "moire" effects. It was earlier supposed that the frequencies above the Nyquist limit should be suppressed by the use of an optical low pass filter to prevent beat patterns. However, more recent studies indicate that there is some merit in allowing some aliasing to occur, which effect yields a better subjective sharpness than would be expected from consideration of the Nyquist limit alone.

Comparison Between Solid State Imagers and Camera Tubes.

Resolution

The response of the solid state imager is limited by the number of horizontal pixels, whereas the camera tube resolution is limited by its scanning beam spot size and the photosurface lateral leakage. The MTFs of a 2/3 inch format Saticon and a 403 horizontal pixel CCD are compared in Fig. 6. Using some aliasing can produce a desirable effect, the subjective sharpness of portable cameras using these devices can be similar.

Sensitivity

The back-lighted, frame store CCD, which avoids the light loss in the address structure, can provide approximately the same sensitivity as the camera tube. Front lighted imagers are about ½ to 1 f/stop less sensitive.

Signal To Noise Ratio

Primarily due to the very small capacitance of the floating diffusion zone in the CCD (approximately 0.07 pf) the imager is capable of an extremely high signal to noise ratio, 64 dB, or more. By comparison, the camera tube S/N ratio is limited by the total capacitance shunting the preamplifier, to approximately 57 dB.

Stability

The mechanical and thermal instability of the camera tube's electron gun prohibits long term registration stability, and the photoconductor characteristics slowly change, so that the color balance must be occassionally adjusted. The imager, however, has stable sensitivity and no mechanical parts to move.

Lag and After Image

As discussed later, the mobility of the charge carriers in the photoconductor, and the inability of the electron beam to discharge the target in a single field, give rise to significant lag and after image effects in camera tubes. On the other hand, these phenomenon are completely lacking in the solid state imager.

THE MEASUREMENT AND PERFORMANCE OF IMAGING DEVICES

Limiting Resolution

This is a somewhat arbitrary and not so accurate measurement of an imaging device's resolution, but is conveniently performed with the resolution chart shown in Fig. 31. To be meaningful, however, this measurement must be performed using a high resolution monitor and a video system with adequate bandwidth. A lens with known resolution should be used and the illumination adjusted so that the lens iris can be set at approximately three f/stops closed from its maximum aperture. For example, an f/1.6 lens should be set at about f/4.0. Cameras tubes should be aligned before making this measurement.

To measure the limiting resolution, the camera is adjusted to frame the resolution chart, such that the tips of the alignment triangles coincide with the raster edges. The camera is focussed so that best center resolution is obtained. The limiting resolution is determined from the resolu-

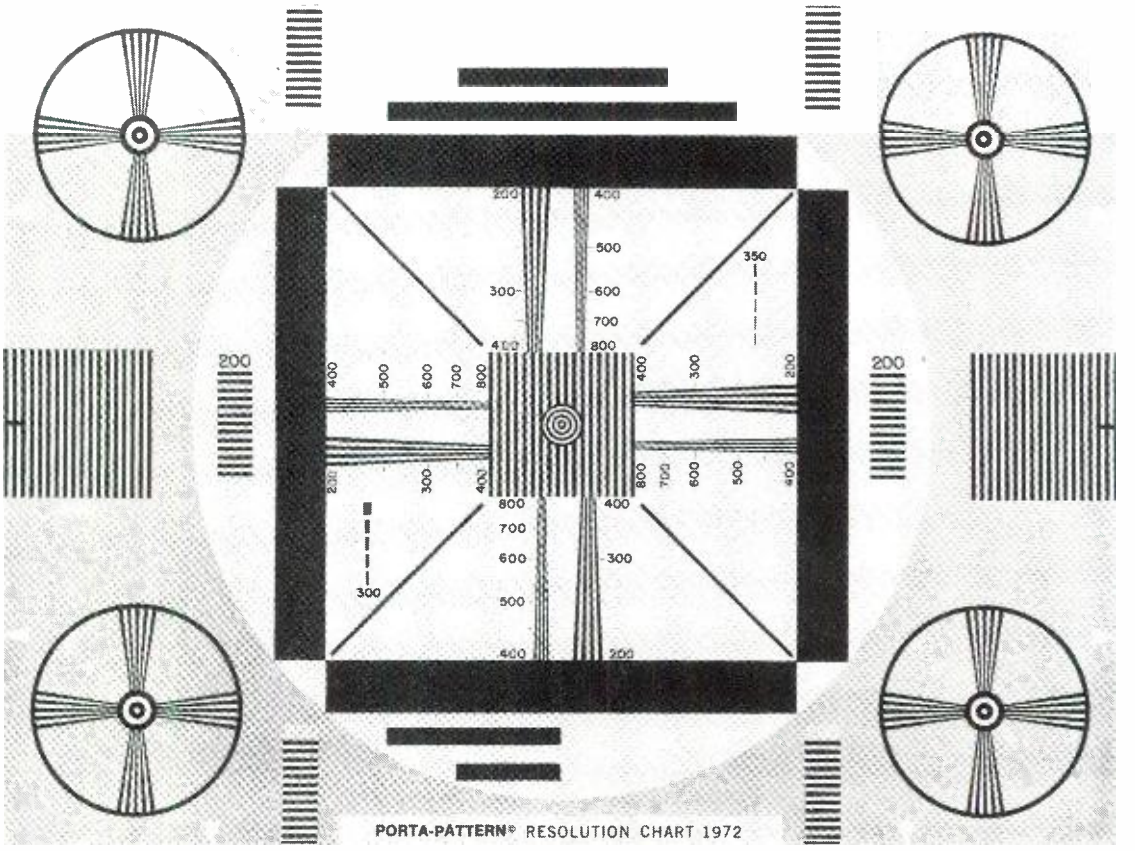


Fig. 31. Resolution chart.

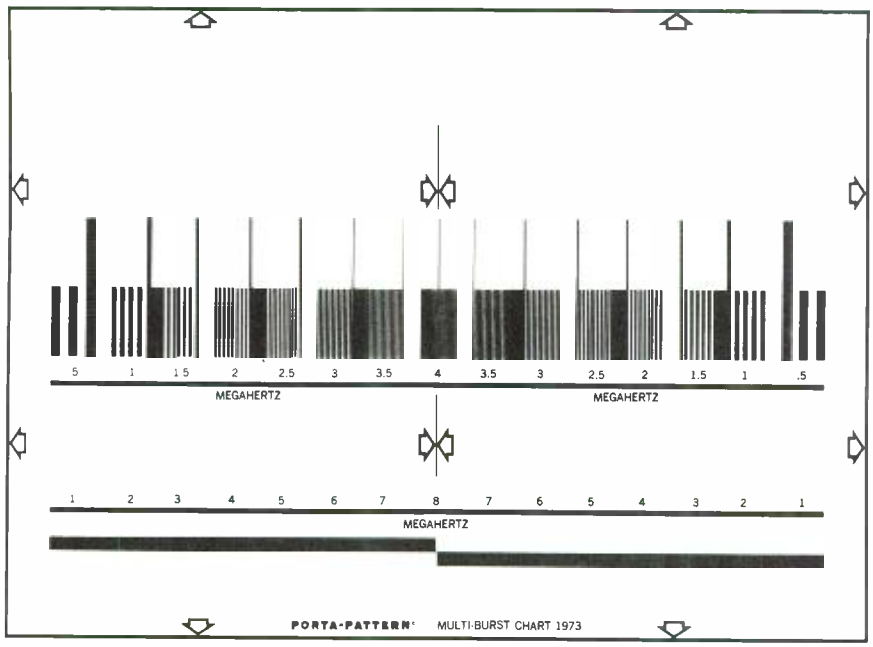


Fig. 32. Multi-burst chart.

tion wedges and defined as the point beyond which the black and white bars can no longer be resolved. Center resolution is determined from the center wedge, corner resolution from the corner wedges.

Amplitude Response

This is a more precise measurement of an imaging device's resolution using a standard burst pattern (Fig. 32) and a waveform monitor with line selection capability. The same lens and video system requirements apply as in the measurement of limiting resolution. The camera aperture corrector and gamma correction should be turned off.

Adjust the camera to accurately frame the burst pattern so that the tips of the alignment triangles coincide with the raster edges. Position the line selector so that the line passing through the center of the bursts is displayed and adjust the lens iris and master black level control so that the signal from the 0.5 MHz burst ranges from 0 to 100 IRE units.

The Amplitude response is determined from the peak to peak signal corresponding to each burst relative to the 0.5 MHz amplitude. Usually, the amplitude response of a studio camera is measured at 5.0 MHz, which corresponds to 400 TV lines, and a portable camera is measured at 4.0 MHz, which corresponds to 320 TV lines.

The burst pattern waveform also provides a simple method of checking the video amplifier response. If the amplifier has a flat response the waveform from the 0.5 MHz burst will have the symmetrical shape shown in Fig. 33a. If, however, the amplifier is over peaked, the waveform will exhibit an overshoot similar to that shown in Fig. 33b. An amplifier with poor high frequency response will give the waveform of Fig. 33c.

An accurate amplitude response measurement can only be made if the amplifier has a flat response. An over-peaked amplifier will not only give an unrealistically high response measurement, but will also result in ugly picture edges. An under-peaked amplifier will give poor response measurements and a "soft" picture.

Sensitivity

The imaging device manufacturer usually expresses sensitivity in microamps/lumen, but this measurement does little to inform the user what sensitivity he can expect from his camera.

The camera manufacturer's specification, however, is more useful to the broadcaster, because it tells what lens aperture is required to achieve full output (100 IRE units) from the green channel at a given illumination. For example, an ENG Camera's sensitivity is usually specified as 200 fc at f/4.0, for a 60% reflectance white, with 3,200 degrees Kelvin illumination.

Several factors affect camera sensitivity:

- *The taking characteristic, or spectral response of the beamsplitter.* As this parameter is fairly well defined for good colorimetry, most cameras are similar in this regard.

- *The choice of imaging device.* Tube type cameras, using lead oxide and Saticon type tubes, have similar sensitivity. The sensitivity of cameras with solid state imagers, however, depends greatly on the type of imager used, as explained in (6.1). In general, cameras, which use back-lighted frame-transfer type CCDs (Charge-coupled Devices), can provide a sensitivity similar to tube type cameras. Cameras using other types of front-lighted imagers tend to be a half of one f/stop less sensitive than tube type cameras.
- *The imaging device operating level,* which is the recommended signal current in the case of a camera tube, or a percentage of the saturation level in the case of a solid state imager. For example, a 25mm tube type camera operating at a green channel signal current of 300 nanoamps will require 36% more illumination than the same camer tube at 220 nanoamps.
- *The choice of lens.* The imaging device illumination for a given lens aperture is given by:

$$\text{Illumination} = \frac{TB}{4f^2(1+M)^2} \quad \text{footcandles}$$

Where:
T = lens transmission
B = scene brightness in footlamberts
f = relative aperture
M = magnification from scene to device

M is usually small enough to be neglected. Usually T has a value of approximately 0.8, which means that there is a 20% light loss through the lens. Larger and more complex lenses employ a larger number of optical elements, which means that the transmission losses are likely to be greater than those of a more simple lens.

Camera sensitivity is conveniently measured by using the logarithmic greyscale shown in Fig. 29 and a 3200 degree Kelvin source of illumination, such as standard studio quartz-halogen lighting.

If a reflectance chart is used, make sure the lighting is uniform, hold an accurate light meter against the white chip and set the illumination to the required level, say 200 footcandles. Adjust the lens iris to obtain 100 IRE units from the green channel and record the f/number as the measurement of sensitivity. Usually a new test pattern with a clean white chip has a 60% reflectance, so this measurement can be directly compared with the camera manufacturer's specification.

If back-lighted test pattern and light box is used the white chip brightness should be adjusted using a spot brightness meter. However, in order to compare with the cameras manufacturers reflectance chart specification, the brightness of the white chip should be set to 60% of the reflectance chart illumination. For example, a 120 footlambert transmission chart white chip provides the same brightness as a 60% reflectance chart with 200 footcandles illumination.

Fig. 33. Effect of frequency response on the reproduction of a white bar.

Lag

This term is the short term persistence characteristic of tube type cameras. "Build-up" lag refers to the delayed signal increase that occurs after illumination is suddenly applied. "Decay" lag is caused by the inability of the scanning beam to completely discharge the target each

field. The camera tube manufacturer uses relatively sophisticated instrumentation to measure lag, which is usually specified as the percentage of signal present three fields after the illumination has been changed. Usually, the broadcaster must use more simple methods to judge lag.

Lag is more pronounced at low signal currents and, because the blue channel signal current is relatively small, such cameras exhibit predominantly blue lag. This can be illustrated by slowly panning the camera backwards and forwards across a greyscale chart (Fig. 29). Note that, as the camera is panned to the left, the white chip exhibits a yellow build up at its leading edge and the black chip shows a magenta decay at its trailing edge.

The presence of build-up and decay lag limits the amplitude response in the case of moving objects, thereby giving rise to a "dynamic resolution", which is lower than that obtained in a static scene.

Because the pixels of the solid state imagers are completely emptied each field, lag is not a problem in these devices.

After Image

This is a long term persistence characteristic in camera tubes, but is usually not a problem unless the tube is defective, perhaps through old age. After image is usually expressed as the time taken for the residual signal from a prolonged 100% highlight to decay to 1%.

Highlight Sticking

This refers to a phenomenon in camera tubes, whereby a long term persistence follows an excess highlight, such as a specular. Usually, highlight sticking is not a problem with lead oxide tubes, but in the case of the Saticon, excess illumination can temporarily collapse the field across the target, so that the charge carrier mobility is reduced and the image decays more slowly, with the effect that a moving highlight leaves a trail across the picture. The occurrance of this problem is greatly reduced in cameras, which employ ABO.

Highlight Overload in Imagers

In conditions of excess illumination the pixel wells become filled and the excess charge can "spill" into adjacent pixels in the same column. If the imager design does not incorporate "drains" to carry the overflow to the substrate, excess highlights are characterised by vertical white lines passing through the highlight and usually extending the full picture height.

Smear in Imagers

A characteristic vertical smear effect occurs in frame transfer CCDs, if the device is not shuttered during the period when the image is being transferred from the "A" register to the "B" register. This is particularly noticable in highlight areas, and is caused by the illumination creating a charge pattern trail while the image is being moved between registers.

CAMERA PERFORMANCE

System Parameters

The overall performance of the camera system depends not only on the performance of its lens, optical system, or imaging device, but also on the effectiveness of its electrical and mechanical design. For example, the factors affecting picture quality depend as much on the performance of the camera electronics, as it does on the lens, beamsplitter and imaging device.

The performance contributions of the optical system and imaging device have already been considered and this section will deal with those independent camera parameters, which have an important influence on the overall system performance.

Basically, the important camera characteristics concern set-up accuracy and stability, overall picture quality, ruggedness and reliability.

Camera Set-Up and Evaluation

Because each camera differs in some way it should be set up precisely according to the camera manufacturers instructions before attempting to evaluate its performance. The following evaluation sequence is recommended:

1. *Color channel performance.* If possible, turn off the image enhancement, frame the resolution chart of Fig. 31, make sure the camera is focus tracked and observe the picture from each of the color channels in turn, both on the picture and waveform monitors.

Visually, the individual pictures should demonstrate good resolution, both in the center and corners. Providing a good lens and black and white monitor are used, the following limiting resolutions should be obtained in the center:

	RED	GREEN	BLUE
1¼ and 1 inch tubes	500	600	700
⅔ and ½ inch tubes	400	500	500
solid state imagers *	300	300	300

* For an imager with 400 horizontal pixels.

Observe the waveform from the burst chart of Fig. 32 and verify that good amplifier response is indicated by a symmetrical waveshape from the 0.5 MHz bar, as shown in Fig. 33a. Note the depth of modulation obtained from each channel. Results may vary considerably for different cameras and imaging devices, so the following is only a guide to level of response expected:

	RED	GREEN	BLUE	BURST FREQUENCY
1¼ and 1 inch tubes	50%	55%	60%	5 MHz
⅔ and ½ inch tubes	40%	45%	50%	5 MHz
solid state imagers	45%	45%	45%	3.8 MHz

Basically, the premise is; if the camera cannot produce good pictures from the individual color channels, then it is unlikely to make a good composite color picture.

2. *Registration.* Frame the registration chart of Fig. 34 and observe the registration accuracy. Registration is usually specified in three zones:

   Zone 1—A circle equal to 80% of picture height.
   Zone 2—A circle equal to picture width.
   Zone 3—The area outside Zone 3.

   One relatively simple way of judging the camera's registration performance is to remember that the width of the lines in the registration chart is 0.2%. Therefore, for example, in the case of a 0.2% error between two channels, the corresponding displayed lines would spread and touch. For a 0.4% error, the lines would be separated by a gap equal to the width of a line.

   It is also important to check a camera's registration stability, by remeasuring after it has been operating for some time. It is also a good idea to see how the registration holds up to shock and vibration, for example, after carrying the camera in the trunk of a car, or wheeling the tripod across a bumpy parking lot, particularly if it is a portable, or sports camera.

3. *Grey-scale tracking.* Using the pattern in Fig. 29, check to see if the camera is color balanced on all steps of the grey-scale. This may be conveniently done by observing the color monitor and switching the chroma on and off. If the grey-scale is perfectly balanced, there will be no change in color. Open the iris so that pattern is overexposed and the at least half the grey-scale goes into the white clipper. Observe that the black chips are still color balanced, which is a good test as to whether the flare correction circuits are correctly adjusted and operating well.

4. *Image enhancer performance.* Frame the grey-scale chart and adjust the iris to obtain a 100 IRE output signal from the white chip. Observe the color monitor and note whether the edges of each chip are equally enhanced, which confirms that the horizontal and vertical enhancement is balanced.

Note that as the chips become darker, the magnitude of the enhancement decreases in proportion, but remains balanced horizontally and vertically. At some level the threshold circuit will inhibit enhancement of the darker chips. It is important that this occur as close as possible to the black level, without permitting the enhancement of any noise that might be present in the blacks.

Next view a subject, which contains fine, subtle detail, such as hair, or a tennis ball. If the fine detail is clearly defined and the higher contrast edges are not overemphasized, the coring circuit is correctly adjusted and working well. If the depth of coring is excessive, the subtle detail will be lost and the picture will exhibit an imbalanced detail. Excessive coring should not be necessary, unless the camera tube has poor resolution, or for some other reason the camera is excessively noisy.

CHOOSING A CAMERA

Choosing a Studio Camera

In the studio, performance is of principle importance and small size and portability are rarely required. The broadcaster should, therefore, give his first consideration to the larger, tripod mounted cameras using 1¼, 1 inch, or ⅔ inch camera tubes.

Frequently, the studio is small and a wide angle zoom lens with a minimum object distance of three feet, or less, is advisable. However, a word of caution; if a studio audience is involved, it may well be necessary to position a camera 50 to 90 feet from the talent. Consider the case where the camera must be 50 feet away and a head and shoulders shot is required. This means a field of view of 2 feet, so the angle of view is:

$$\theta = 2 \text{ Tan}^{-1} 1/50 = 2.3 \text{ degrees}$$

which means, for example, that a 428 mm focal length is required in 1¼ inch format. If a 17mm lens is required for wide angle purposes (53.45 degrees field of view), then a 25.1 zoom lens is necessary.

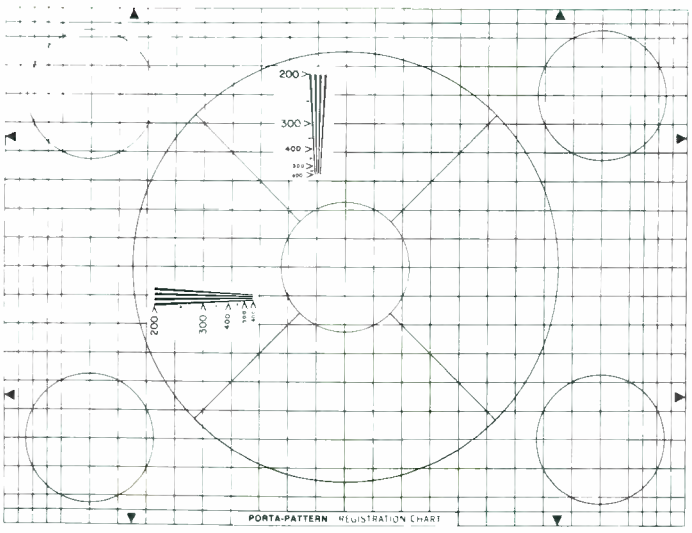


Fig. 34. Registration chart.

Choosing an ENG Camera

The ENG camera must be small, light weight and extremely rugged. The lens must have a reasonably wide angle, for example, 9 mm in ⅔ inch format, with a minimum object distance of 36 inches, or less, to permit use in confined spaces. Because lighting is often uncontrolled and frequently inadequate, high sensitivity is important. Probably, the broadcaster should look at a 14:1, F/1.7 zoom lens, with a minimum focal length of 9 mm in ⅔ inch format, which will give an MOD of about 32 inches. The usable sensitivity should be 5 foot candles, or less.

Choosing an EFP Camera

As previously discussed, the ideal EFP camera must combine the performance of a studio camera with the convenience of a portable camera. Therefore, the camera should be basically portable, but adaptable to the use of large lenses. The camera should be very stable and, if possible, have an automatic set-up feature. This is particularly desirable if the camera is to be used for field production, involving expensive talent and many extras. The producer will not be so happy if he has to wait 20 minutes for camera set-up before he can continue with take number 27!

The configuration will depend on the particular application. If the camera is to be frequently used in a portable application, a high quality ENG type lens is required. If true field production is the application and the camera can be tripod mounted, then a larger, higher quality EFP lens can be used. If the application is sports, then a lens that can zoom to a long focal length is a must, but, because the camera may also be used in close proximity to the commentator, a wider angle and close focussing distance may also be required. This is the ideal application for the new breed of lenses, which combine a wide angle with a large zoom range, for example 44:1.

The EFP camera may be used as a self-contained unit, or may be controlled from a Remote Control Unit (RCU). In certain cases, it may be necessary to control the camera from a great distance, such as sports, which favors the use of a triaxial interconnet.

Because base-band video is sent through the multi-conductor camera cable, the losses can become excessive at distances over 2,000 feet, with the result that there is a severe picture quality degradation after equalization. When long distances are involved, the single, triaxial cable is recommended, in which case the signals and controls are multiplexed onto a single conductor using an RF carrier. Both AM and FM systems are used. Performance is significantly improved and is acceptable to distances of 6,000 feet, or more.

Choosing A Sports Camera

As in the case of the ENG camera, the sports camera must be very rugged and stable and the camera crew will probably be happier if it is not so heavy. All things considered, this is an ideal application for the EFP camera.

However, the lens performance is a key factor. The coverage of many sports requires the use of a long telephoto lens, for example; golf, football and horse racing. Therefore, the sports camera should accept the larger zoom lenses with a zoom range 30:1, or more.

Usually, the camera is controlled from an OB vehicle, which in certain cases may be a long distance from the camera. For this reason, the use of a triaxial camera cable is popular, because it enables distances to 6,000 feet.

APPENDIX A

Please see Fig. 2. in Chapter 5.4.

APPENDIX B

Depth of Field and Focus Tracking

Depth of Field

When a lens is focussed on an object, there is a range of distance, which is also in focus, both in front and behind the object. This is known as the "depth of field" and depends on the angle of view and the relative aperture of the lens.

A wide angle lens (shorter focal length) has a greater depth of field than a telephoto lens. For a given lens, the depth of field is greater at f/4.0 than at f/1.6. However, this comparison does not necessarily hold for lenses with different formats. For example, f/4.0 in 1¼" format is equivalent to approximately f/2.8 in 1" format, f/2.0 in ⅔" format, and f/1.5 in ½" format. If these lenses are all adjusted to have the same angle of view, their depths of field will be equal.

For this reason, the smaller format cameras have no disadvantage compared to those with larger format, in either angle of view, or depth of field."

Focus Tracking

When the photosurfaces of the imaging devices are correctly located at the exit focal planes of the beamsplitter, the corresponding images will remain in focus as the lens focal length is varied. The optical system is then said to be "focus tracked". The procedure for focus tracking is as follows:

1. Adjust the illumination so that the lens aperture may be fully opened without the video signal clipping. A wide aperture is important, because the depth of field becomes small and the focus adjustment is, therefore, more sensitive.
2. Adjust the zoom to maximum focal length and focus the lens onto a detailed object or test pattern at least 20 feet away.
3. Adjust the lens to minimum focal length and adjust the position of the green channel imaging device to obtain sharp focus of the test pattern. Repeat 2) and 3) to ensure accurate green channel tracking.
4. Return the lens to minimum focal length and adjust the position of the red and blue channel imaging devices to obtain sharp focus of their corresponding images. The system is now focus tracked.

5.4

Video Signal Switching, Timing, and Distribution

Jay Kuca
Marketing Manager
Modular Products Division
The Grass Valley Group, Inc.
Grass Valley, California

INTRODUCTION

The video signal contains a large amount of information. In addition to basic picture parameters such as brightness, hue, and saturation, the video signal includes horizontal, vertical, and color timing information. And recently, more and more ancillary information has been added, primarily in the vertical blanking interval: vertical interval test signals (VITS), vertical interval reference signals (VIRS), teletext, closed captions, time of day and time code information, source identification data, etc.

Technological advances in the last thirty years have made it possible to pack all of this information into substantially the same bandwidth originally allocated for the monochrome television picture alone. But along with the increased information density has come a need to maintain a very high level of performance along the entire signal path. Therefore, careful attention must be paid to the design of any modern video system if optimum results are to be achieved.

Whenever video signals are distributed, levels, frequency and phase response, and other transmission parameters must be held to extremely tight tolerances. Whenever video signals are switched, the switching system must be designed so that the integrity of the timing as well as the transmission parameters is observed. And whenever video signals are combined, whether by mixing, keying, or special effects generation, the relative timing relationships between the signals must be carefully maintained.

THE VIDEO SIGNAL

Fig. 1 is an oscillogram of a typical video signal. The peak to peak amplitude of the signal is 140 IRE units, or 1 volt. This is the standard level for signal distribution in all professional television facilities. The signal is comprised of +100 IRE units (714 mV) of picture and -40 IRE units (286 mV) of sync.

Even though video is an ac signal, proper operation of most equipment depends upon a fixed dc component. By convention, blanking (0 IRE) is assumed to be at ground (0 VDC). This reference is lost, of course, in portions of the system which are ac coupled, but when the signal is clamped or dc restored, standard practice dictates re-establishing blanking at ground.

The bandwidth of a "studio quality" NTSC video system is determined primarily by the state of the art and economic factors. And while it can be argued that the transmission system cuts off any information above 4 MHz, it is good engineering practice to strive for response which is flat to 8 to 10 MHz in the studio.

Timing integrity is ensured through the use of a master sync pulse generator. In nearly all installations, timing for all signals in the plant is derived from this single reference. In most cases,

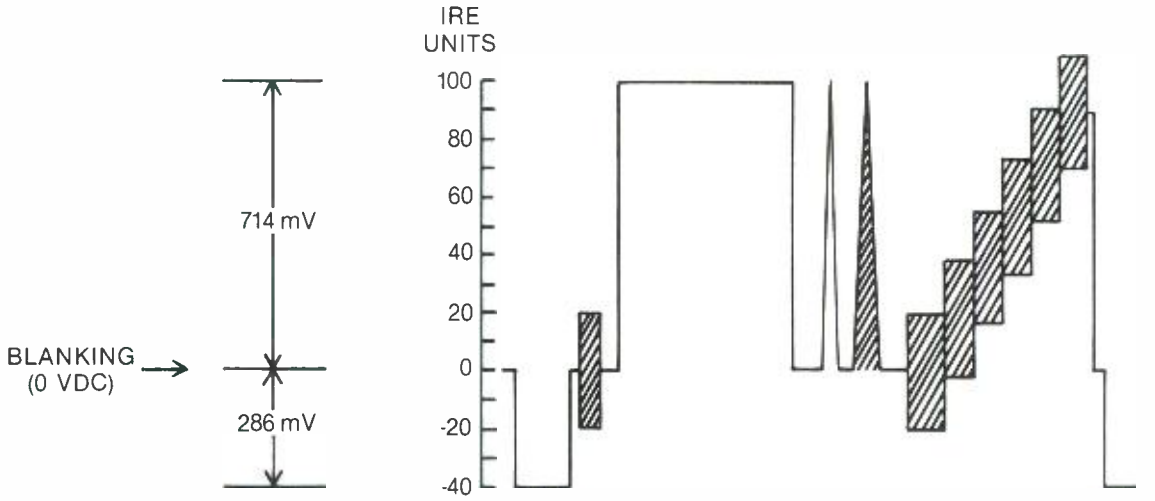


Fig. 1. Oscillogram of a typical video signal.

the master sync generator is driven from a high stability crystal oscillator. Occasionally, a precision rubidium or cesium "atomic" reference oscillator is used. Fig. 2 illustrates the relationships between the horizontal, vertical, and color timing signals.

INTERCONNECTION CONVENTIONS

All studio equipment is designed to be interconnected with coaxial cable having a nominal characteristic impedance of 75 ohms. In the simplest case, a point-to-point connection between two pieces of equipment, a continuous length of cable is driven from a 75 ohm source and terminated in a 75 ohm load. See Fig. 3.

When it is necessary to distribute the signal from a single source to more than one destination, two possible approaches exist. The first is entirely passive in nature: one end of the cable is driven from the 75 ohm source and, instead of terminating the far end in a 75 ohm load, a "loop-through" connection is made to the first piece of equipment. The loop-through is carried on to the next piece of equipment, and so on. A 75 ohm termination is placed on the loop-through connection on the last piece of equipment. This approach, shown in Fig. 4, will work well provided the loop-through inputs are properly designed and the cable lengths are kept short. The number of loop-throughs should also be kept as small as possible. If this is not done, frequency response errors and, in severe cases, signal reflections are likely.

Whenever possible, video signals should be distributed using an "active" device such as a distribution amplifier or routing switcher. This effectively results in the equipment being interconnected in the point-to-point manner described above.

Nearly all modern equipment uses BNC connectors for video input and output connections. Some older equipment still in service may use "UHF" (PL-259/SO-239) connectors. Occasionally, space limitations dictate the use of a subminiature connector such as a "BSM" series. However, the BNC is by far the most common connector in use.

A number of cable types are available which are suitable for high quality video interconnect. The most popular is Belden 8281, a double-shielded 75 ohm precision coaxial cable designed specifically for video use. 8281 provides a good balance between loss and physical size. Its double shielding helps reduce the likelihood of stray signal pickup. Where space limitations, increased flexibility, or other factors suggest the use of a smaller diameter cable than 8281, an "RG/59-type" cable is the usual choice.

POTENTIAL SYSTEM PROBLEMS

Most problems in television system design are a consequence of the fact that individual pieces of equipment must be interconnected by coaxial cable. All cable exhibits high-frequency losses which may result in the impairment of picture detail, especially on long runs. Stray signals, such as 60 Hz hum or noise may be coupled into cables. And since signals take a finite amount of time to travel through cables, there are time delays to be dealt with.

Fortunately, most of the problems are not new, and solutions have been developed over the years. For example, equalizers which compensate for

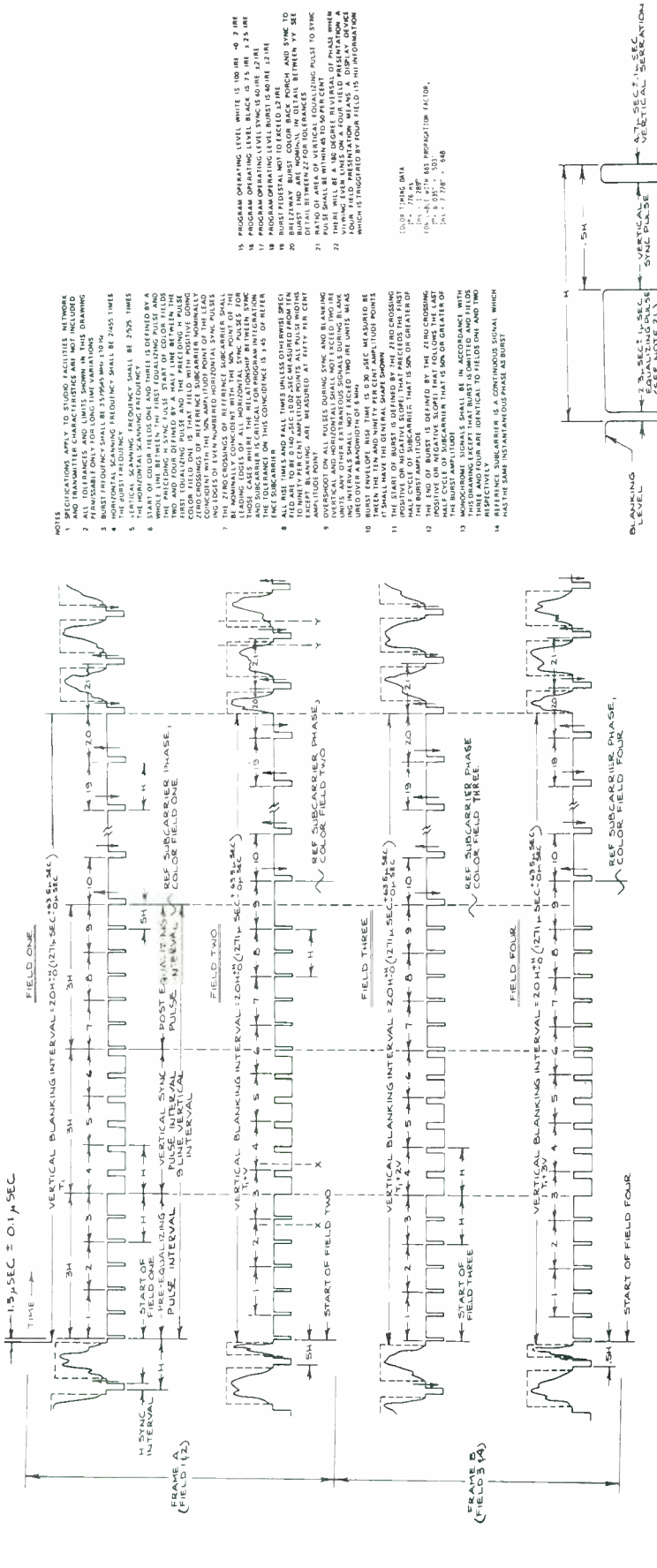


Fig. 2. NTSC timing parameters.
(Courtesy of The Grass Valley Group)
An updated version of the EIA Tentative standard RS 170 A.

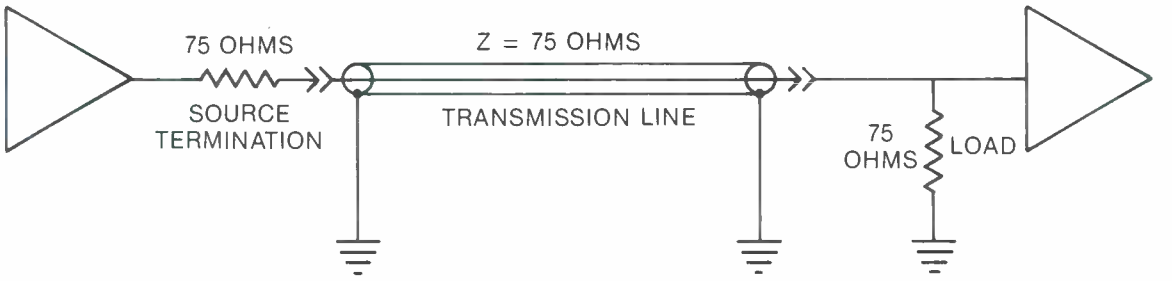


Fig. 3. Point-to-point video connection.

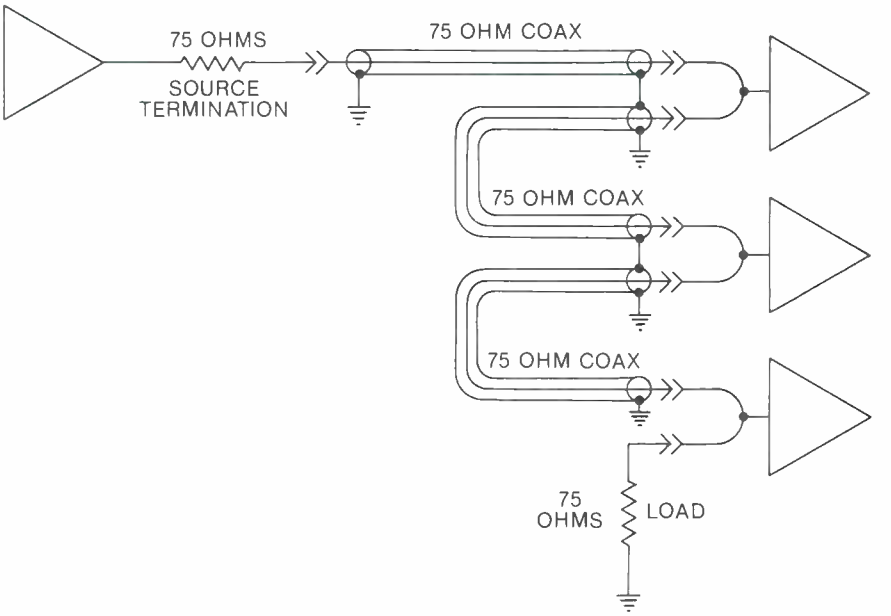


Fig. 4. Loop-through video connection.

high frequency cable losses can be found in a variety of modern video equipment. Quite often, a differential amplifier is used in the input stage to cancel the effects of common mode hum and noise; in some equipment, a clamp stage may be provided for hum suppression. Modern timing concepts have led to the development of a wealth of useful tools: pulse and subcarrier regenerators, slave sync generators, remote phasing sync generators, isophasing amplifiers, and frame synchronizers.

The tools exist to solve nearly any problem in video system design. The key is to anticipate the problems in new designs and to diagnose the problems as they develop in existing systems.

VIDEO SYSTEM DESIGN

Video system designs can be classified as falling into one of two broad categories: "hardwired" or "configurable." A hardwired system is one which is dedicated to a single function—a small ENG edit bay, for example. A configurable system is one which is designed to perform multiple functions, perhaps simultaneously—for example, a centralized VTR room which is used for on-air tape playback, commercial production, and dubbing.

Most systems were hardwired prior to the advent of video tape recorders because program production and presentation was done "live," in real time. VTR's made off-line production and program assembly possible. But the high cost of the early recorders made it necessary to design the system to ensure optimum equipment utilization. This was accomplished by making the system configurable.

The hardwired approach is fairly self-explanatory. Signals are routed point-to-point, using distribution amplifiers where a single source must

feed more than one destination. Quite often, patch panels with "normalling" (through-connection) jacks are interspersed throughout the system, thus providing a certain degree of configurability.

A truly configurable system is generally built around a routing switcher. In the limit, all signal sources in the plant appear as inputs to the switcher and all signal destinations in the plant are driven from a routing switcher output bus. Such a high degree of flexibility is rarely required, however. As a result, most video systems are partially hardwired and partially switched.

Source timing is an important consideration in any video system. As a general rule, the more flexible the system is, the more difficult timing becomes. In a hardwired system, for example, timing signals can be hardwired along with the video signals. But in a routing switcher based system, configurations may be possible which create timing problems. The most common of these is the problem of studio switcher delay.

It is standard practice to designate a point in the system as a "zero timing point." The timing of all sources in the plant is adjusted so that they are in time at this point, which is usually a patch panel or routing switcher output. Timing will be correct so long as the path from the source to that point is fixed. But when the system is flexible enough to allow the source to go through one or more studio switchers enroute to the zero timing point, the source timing will be upset by the cumulative delay through the studio(s). If one attempts to treat that source as fully timed (by mixing or wiping between it and another source, for example), the problem will be immediately apparent.

One way around the studio delay problem is to backtime all sources feeding the studio by an amount equal to the studio delay. This can be done quite easily if each source is equipped with its own sync generator. It is important to note, however, that if the source must feed other points in the system in addition to the studio, it may not be properly timed for those points.

The best way around the studio delay problem is to put frame synchronizers on the outputs of all studios. In that way, timing is guaranteed, regardless of how complex the path becomes. Where such an approach is not economically feasible, it is essential to analyze and fully understand the limitations of the system.

SYSTEM DESIGN APPROACH

More often than not, video system design is approached in a haphazard rather than systematic way. This is often due to the pressures of attempting to provide the latest technology to the end user while keeping a station on the air. Even though it is a rare occasion that one is able to start from scratch, any system design project stands to benefit from up front planning.

The task begins with a survey of the facilities. What signal sources are there? What destinations must they feed? What is the physical layout of the plant? What is its size and where will the equipment be located? What allowances have to be made for future growth?

The next step is to analyze user needs. Each operating area should be examined in light of what signals are needed, how frequently they will be used, and what level of quality is necessary. It is important to be realistic when asking these questions. For example, it might be nice to have a seldom used test signal available "on demand" in a particular operating area; but is it really necessary?

Frequency of use will help to determine whether a signal should be hardwired, switched, or patchable. Frequently used signals should be hardwired in order to eliminate possible operational errors. Signals which are used occasionally can be switched, if necessary. Seldom used signals can be handled with manual patching.

The desired signal quality is an important factor. Does the signal have to be timed? What about equalization, clamping, or other forms of signal processing? Unnecessary expense can be avoided if the answers to these questions are carefully considered.

When the research is complete, the planning can begin. During the planning phase, the details of the design will begin to take shape. The physical realities of the system will come to light: equipment layout, interconnect, electrical power requirements, etc. Notes gathered during the research phase will give way to sketches, which will eventually give way to final drawings.

The importance of accurate system documentation cannot be overemphasized. Good system-level drawings will prove to be invaluable when troubleshooting or when making changes. And the documentation will be much easier to follow if wire and rack numbers are used.

After the final "as built" drawings are completed, it is a good idea to produce a simplified drawing of the signal flow through each operational area. These can be posted, perhaps along with information on how to deal with "emergency" situations.

VIDEO DISTRIBUTION AMPLIFIERS

The distribution amplifier, or "DA," is the most elementary building block in a video system. Its primary function is to allow a single 75 ohm video source to feed multiple 75 ohm loads with

no apparent loss. Quite often, other functions such as cable equalization are included in the DA's circuitry.

Even though DA functions and designs vary, it is quite easy to construct a generalized model. As shown in Fig. 5, the typical DA consists of an input amplifier followed by a "conditioning" stage (gain, equalization, delay, etc.), followed by an output amplifier.

The input amplifier is generally designed with a rather high input impedance, on the order of several tens of kilohms. This allows the driving signal to be looped through the input without being loaded down. Quite often, a complex network is used at the input connection to cancel out any reactive components which might affect the loop-through. The input stage may be either single ended or differential, the latter being more common on high quality DA's.

A differential input stage can be very useful in combating one of the most serious problems encountered in unbalanced signal transmission: common mode hum and noise. In larger facilities, common mode hum due to ground loops may run as high as several volts. Even in small plants with excellent ground systems it is possible to have several tens of millivolts of difference in ground potential between different pieces of equipment. A differential amplifier will cancel any common mode signals while amplifying the (desired) differential mode signal. Common mode rejection ratios (CMRR) of 50 to 60 dB are typical of most modern differential input DA's.

The conditioning stage may be a wideband gain stage, an active equalizer stage, or a delay amplifier, depending upon what additional function the DA performs. If distribution is the only function, the conditioning stage will be omitted.

The output stage is an amplifier with very low output impedance. It is followed by source termination resistors which ensure that the cable "sees" 75 ohms at the sending end as well as the load end. Output to output isolation is guaranteed by the low impedance at the amplifier output.

Cable equalization is often required in video systems. This is due to the high frequency losses in coaxial cable. Belden 8281 has approximately 0.8 dB of loss per 100 feet at 10 MHz. Since runs of 100 feet or more are not uncommon in most facilities, achieving "flat" system response makes equalization of these losses necessary. The approach taken by most manufacturers is to construct an equalizer network whose response very closely approximates the inverse of the cable loss curve. When this equalization is applied to the cable/DA system, the result is flat overall response.

Cable equalizers must be designed for a specific type and length of cable. When a variable equalization control is provided, it usually serves to adjust the amount of equalization applied. Because cable loss is a complex function, the equalization curve is only "right" for one cable length. Slight response errors will be noted at other length settings.

Cable losses should always be equalized at the load end of the cable. The reason for this is simple: If a "flat" signal is applied to the input of the amplifier, the high frequency boost of the equalizer stage will be added to the signal and the output stage will have to track these larger than normal amplitude high frequencies. In cases where the amount of equalization is more than a few dB, the output stage will be unable to deliver the necessary current into its low impedance load. If, however, the DA is located at the load end of the cable, the cable losses have attenuated the high frequencies at the input of the amplifier. The high frequency boost of the equalizer stage restores the flat response characteristic to the signal, and the output amplifier does not have to deal with larger than normal swings at high frequencies.

Another function which is often required in video systems is clamping. Clamping is used primarily to reduce low frequency hum and tilt but may also be used to restore the dc component of a video signal which has passed through one

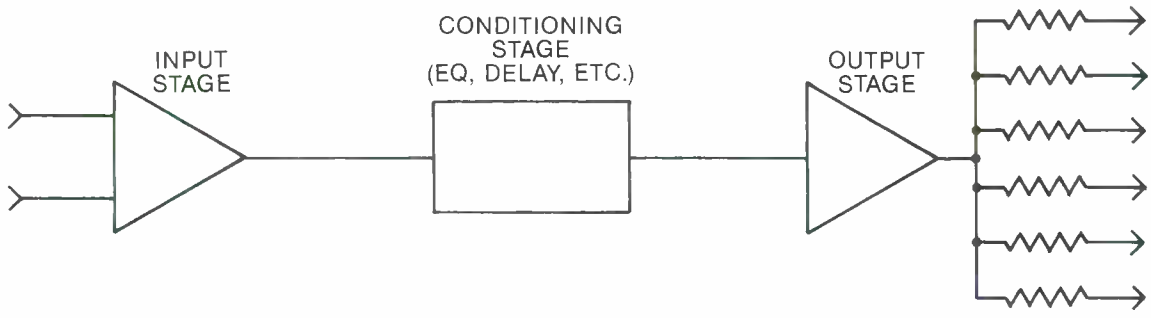


Fig. 5. Simplified block diagram of a video DA.

or more ac coupled devices. Clamps operate on a line-by-line basis and, as such, are fast acting. They can be triggered by noise impulses and should therefore not be used on noisy signals.

Dc restoration may be used in lieu of clamping to reduce the dc signal bounce due to multiple ac couplings. Because of the slow time constants employed in dc restorers, they are not affected by noise; but by the same token, they are not useful in eliminating hum.

Delay DA's are often used in place of coaxial cable or other passive delay elements. Delays of up to a microsecond or more are possible on modules no larger than a conventional DA. Many delay DA's include circuits to compensate for delay line response errors; they produce better results than a passive delay line and DA in combination. Some delay DA's also include other functions such as cable equalization.

PULSE AND SUBCARRIER DISTRIBUTION AMPLIFIERS

Despite the increasing use of color black as a locking signal, separate pulses and subcarrier are used in many systems as timing references. Pulses (sync, blanking, H drive, V drive) are generally distributed as 2 to 4 volt negative-going signals. Subcarrier is generally distributed as a 1 to 2 volt peak-to-peak signal.

Most video DA's will not accomodate signals larger than 2 volts peak-to-peak. So, while most video DA's would be suitable for subcarrier distribution, the typical video DA will not handle pulses.

DA's designed specifically for pulse distribution are optimized for large negative signal swings. They will not function as video amplifiers.

Pulse DA's fall into one of two general categories: regenerative and linear. Regenerative DA's include circuitry for pulse regeneration; typically edge detectors driving one-shots. Timing of the one-shots is usually adjustable, allowing the relative delay of the amplifier to be varied. Delays of up to several microseconds are common. Due to the inherent delay of the pulse regeneration circuitry, these amplifiers always exhibit some value of minimum delay.

Regenerative subcarrier DA's are also available. These amplifiers generally feature adjustable circuits to shift the phase of the subcarrier. The adjustment range is usually slightly more than 360 degrees.

When pulses and subcarrier are distributed through regenerative DA's, there is a good chance that SC/H phase will not be maintained throughout the system. This is because it is possible to adjust sync and subcarrier timing independently. For this reason, linear (non-regenerative) pulse and subcarrier DA's should be used in SC/H phased installations. Specially designed linear pulse DA's are available, and most high quality video DA's can be used as linear subcarrier DA's.

DISTRIBUTION AMPLIFIER SELECTION

As a signal traverses a typical path through a typical system, it may pass through ten or more DA's. Therefore, the performance of a single amplifier must be, for many parameters, an order of magnitude better than the system specification. Table 1 lists the performance specifications of a representative unit, the Grass Valley Group 3402V-A. This amplifier is pictured in Fig. 6.

Selecting the right DA for a particular application involves determining the desired level of performance and the features and functions required. Since most manufacturers offer a range of models which all fit into the same mounting tray, it is

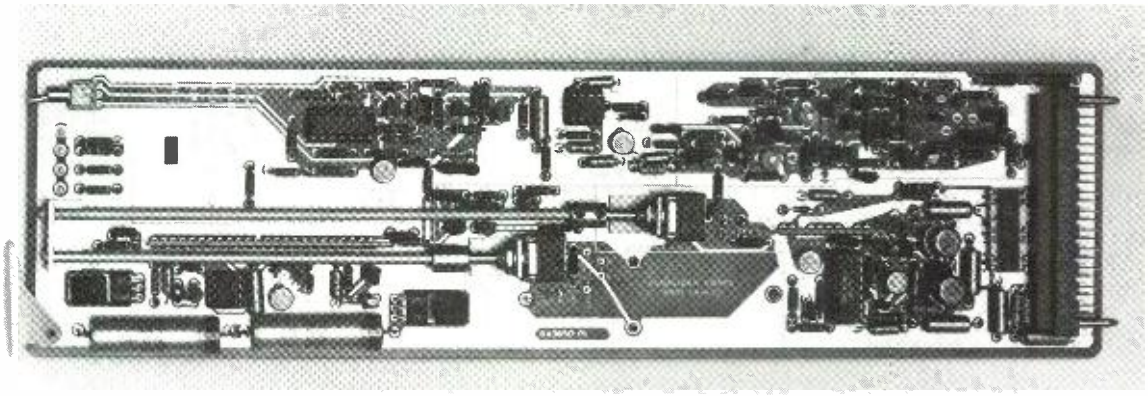


Fig. 6. A modern video distribution amplifier, the Grass Valley Group Model 3402. (Photo Courtesy the Grass Valley Group, Inc.)

wise to look at the sum total of all requirements and then choose the manufacturer who can best accommodate those requirements.

DA's fall into the "install it and forget it" category; low maintenance and long service are important factors. When selecting distribution amplifiers, consider the quality of the components which the manufacturer has used; will they hold up for ten or fifteen years? Is the design a conservative one, or are devices being run at their limits? Thermal stress will not only lead to equipment failure, it will cause drift as well.

VIDEO SIGNAL SWITCHING

Video signals can be switched by a variety of methods. Simple monitor selectors may be nothing more than passive mechanical switches. In some cases, electromechanical devices such as relays are employed. Most modern switching systems employ solid state switching devices.

Fig. 7 is a simplified block diagram of a video switching system. Input amplifiers buffer the input signals and provide drive to the switching elements (crosspoints). The crosspoints are bussed in horizontal rows (output buses) to an output amplifier. If the switcher has more than one output bus, the buffered input signals are bussed in vertical columns (input buses) which run across the output rows.

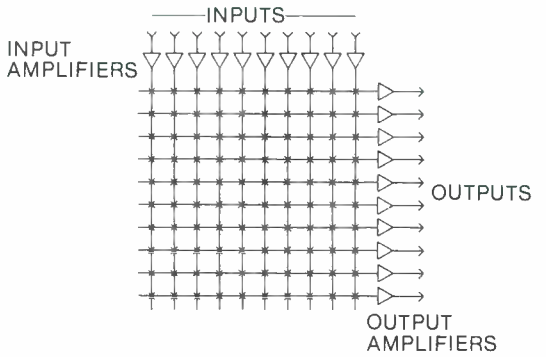


Fig. 7. Simplified block diagram of a video switching system.

Not shown in the block diagram is the crosspoint control logic. In single bus switchers with ten inputs or less, control is generally accomplished using a single wire per crosspoint. In single bus switchers with more than ten inputs, an encoding scheme such as BCD is generally used to reduce the number of wires required. Larger multiple bus switchers generally use some sort of serial control scheme.

Single Bus Switchers

Single bus switchers run the gamut from simple to elegant. For noncritical applications such as picture monitor input selection, a mechanical switcher is probably adequate. Most mechanical designs are entirely passive; that is, they have no input or output amplifiers. As such, they have terminating inputs and require dedicated (non loop-through) input feeds.

A slightly more sophisticated design adds an output amplifier only. Switching is still done using mechanical switches, but the bus is made high impedance to allow looping inputs. This approach makes it possible to "stack" units to provide an economical multiple input/multiple output configuration. In terms of performance, this type of switcher is no better than the passive type. If the input loop-throughs are not compensated, its performance may actually be worse.

Any single bus switcher which is in a program path should be designed more along the lines of Fig. 7. In other words, it should have input buffer amplifiers, solid state crosspoints, and an output amplifier. If it is being used for "live" switching, the buffer amplifiers should clamp or dc restore the input signals to provide bounce-free switching. If the unit is used in an actual program loop, the design should permit servicing with minimum disruption; that is, all active circuitry should be mounted on plug-in printed circuit boards.

Single bus switchers can be combined to make multiple bus switchers, but in most cases the result will cost more and lack the flexibility and performance of a true multiple bus design.

Multiple Bus Switchers

There are two basic architectures for multiple bus switchers. An output oriented switcher is one with all buses physically separated in the switcher electronics. A matrix switcher is one in which the circuitry for several output buses is packaged together.

Output oriented switchers are generally larger and more expensive than comparable matrix switchers. The reason for this is that there is more duplication of circuitry and more interconnect required. The chief advantage of an output oriented switcher over a matrix switcher is that circuit cards can be removed from the output oriented switcher without disturbing multiple signal paths. This is an important consideration in large facilities such as network switching centers.

Matrix architected switchers are smaller and less expensive than comparable output oriented switchers. They offer several other advantages as well: reduced power consumption, slightly higher reliability due to fewer mechanical interconnec-

Fig. 8. An example of a modern single-bus routing switcher, the Grass Valley Group TEN-X. (Photo Courtesy the Grass Valley Group, Inc.)

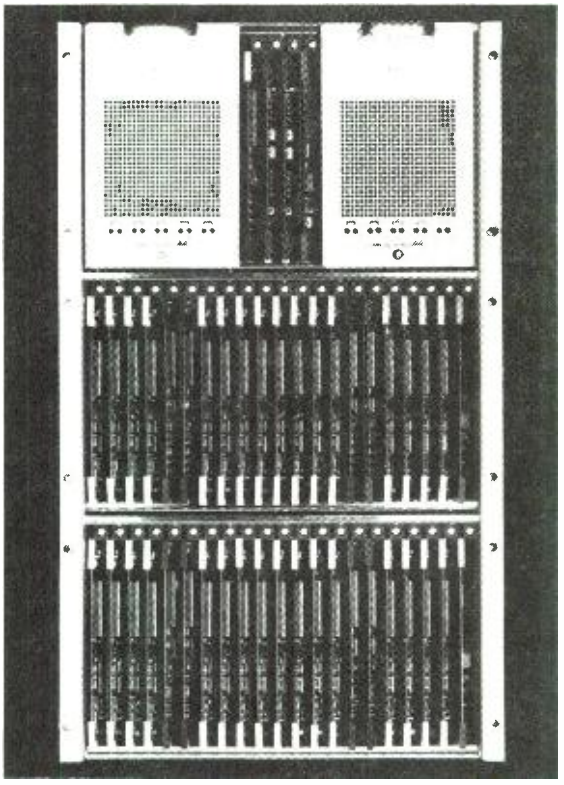


Fig. 9. A multiple-bus routing switcher system, The Grass Valley Group model HX-64. (Photo Courtesy the Grass Valley Group, Inc.)

tions, and shorter signal path. Matrix switchers are generally designed around a relatively small square or rectangular building block, making input and output expansion in bite-sized increments a simple matter.

Input signal distribution in both types of switchers can be handled using either looping techniques or distribution amplifiers. The cost objectives of most matrix designs suggests the use of looping while the large physical size of the output oriented switcher makes the distribution amplifier approach almost a necessity.

As is the case with single bus switchers, if "live" switches are made on a multiple bus switcher, the input signals must be clamped or dc restored to ensure transient-free switches. This signal conditioning may be done external to the switching system, but better overall performance will result if it is done in the switching system. The reason for this is that a common precision dc reference can be used for all inputs if the clamping or dc restoration is done inside the system.

Switch timing is also important if glitches are to be avoided. Most multiple bus switchers have a sync input which is used as a reference for a master trigger pulse generator. The trigger is set to occur during the vertical interval, thus ensuring glitch free switching between synchronous sources.

Timing "scatter" is an important parameter for any switching system which will be used in a studio environment. It is the measure of the delay difference between paths in the switcher. In a system which uses looping techniques to distribute the input signals, there will be a fixed amount of delay between output bus groups. But on a given bus, there should be very little path length difference from input to input; less than plus or minus one degree of subcarrier is a typical figure. In a system which uses DA's to distribute the input signals, it should be possible to achieve the same timing accuracy from any input to any output.

With respect to the use of routing switchers in video systems, two basic schools of thought prevail: the master grid approach, and the cellular approach. With the master grid approach, one large switching system is used with all switched sources in the plant appearing as inputs. This provides maximum flexibility, but at considerable expense. All sources are not needed at all destinations, so many crosspoints in the system are "wasted."

In the cellular approach, the plant is subdivided into functional areas (studios, master control, vtr/telecine pool, news editing, etc.) and a small switching system placed in each area. Each system has only those area sources it requires plus a few "master" sources common to the other areas (color black, bars, etc.) To accommodate occasional special setups, tie lines may be run between the systems.

The cellular approach can be considerably more cost effective than the master grid approach. But

the incidence of special setups must be carefully considered. Since multiple switching operations may be required in the case of specials, the chance for error increases significantly. This must be weighed against the additional cost of the larger matrix required for a master grid system.

Switching System Control

Switching system control has advanced considerably over the past few years. Most multiple bus switchers have microprocessor-based control systems. Control panels communicate with the switcher over twisted pairs or coax. Sources may be selected using their familiar names (eg "BLACK," "BARS," or "VTR 5") instead of input numbers. Simultaneous selections, or "salvo" switches, can be easily made.

A recent development in control system capability has been made possible through the availability of a semiconductor device known as an EEPROM (Electrically Erasable Programmable Read Only Memory). This device can be programmed, erased, and reprogrammed just like an ordinary PROM. But, unlike a PROM, the EEPROM does not require a special programmer; more importantly, it can be erased electrically, in circuit.

The system pictured in Fig. 9, a Grass Valley Group HORIZON series, uses EEPROMS in its control system for non-volatile storage of installation dependent information. This information is loaded into the system using an ordinary ASCII data terminal.

The HORIZON system is a representative state of the art routing switcher. The unit pictured in Fig. 9 is a 64 input by 64 output video matrix complete with dual power supplies and dual control cards. The unit occupies 18RU (31.5″) of vertical rack space. It is a matrix architected system. Performance specifications are listed in Table 2.

VIDEO SIGNAL TIMING

Timing requirements stem from the fact that a video signal is a serial stream of analog data which is used to electronically reconstruct a picture. Horizontal timing information is used to trace out each line of the picture on the face of a display tube in exact synchronism with the camera tube beam which scanned the original scene. Vertical timing information is used to signal the end of each "still" picture in the frame-by-frame reconstruction process. Color timing information in the form of a brief burst of subcarrier each line is used to ensure that the color at each point on the screen is accurately reproduced.

Timing in the television studio is the responsibility of a ubiquitous black box called a sync generator. In the early days, a monochrome sync generator filled two six foot equipment racks. Today, color units which are several orders of magnitude more accurate and stable can be packaged on a single printed circuit card.

The size and complexity of the early generators prompted the "master" generator approach to plant timing. Since it would have been impractical to include a sync generator with each source, a set of signals was defined which would provide the information necessary to generate and process a television picture. The responsibility for generating these signals fell to the "master" sync generator. These signals were then distributed to each piece of equipment requiring them. They included sync and blanking (used mainly in video circuits) and horizontal and vertical drives (used to drive the sweep circuits in cameras).

The emergence of color meant that the 3.58 MHz subcarrier had to be generated by the same master generator and distributed throughout the plant. In addition, another pulse called burst flag was needed to gate the color burst. Six separate signals, just to keep everything locked to the same time reference.

The advent of solid state devices led to a dramatic reduction in the size of the master sync generator. At the same time, integrated circuit logic made it possible to easily derive horizontal and vertical drives and burst flag from sync. Before long, timing input requirements dwindled to sync, blanking, and subcarrier on most equipment.

The capabilities of Large Scale Integrated circuit (LSI) technology has made it possible to reduce most of the circuitry required for pulse generation to a single chip. For this reason, most modern equipment has its own sync generator built in. In addition to making standalone operation possible, this reduces the input timing reference requirements to a single wire signal such as color black.

Fig. 10 is a simplified functional block diagram of a sync generator. A precision oscillator is used to drive a set of complex logic which generates all of the required timing signals. Buffer amplifiers convert the logic levels to the required 4 volt negative-going pulses and 2 volt peak to peak subcarrier.

The FCC requires that subcarrier frequency be maintained within 5 Hz of 3.579545 MHz. Therefore, an ovenized or temperature compensated crystal oscillator is generally employed.

Most modern sync generators utilize a single LSI integrated circuit as the "heart" of the pulse generation logic. Numerous off the shelf and custom parts exist which have 90% or more of the logic required. External parts are often needed to provide additional features such as variable pulse width.

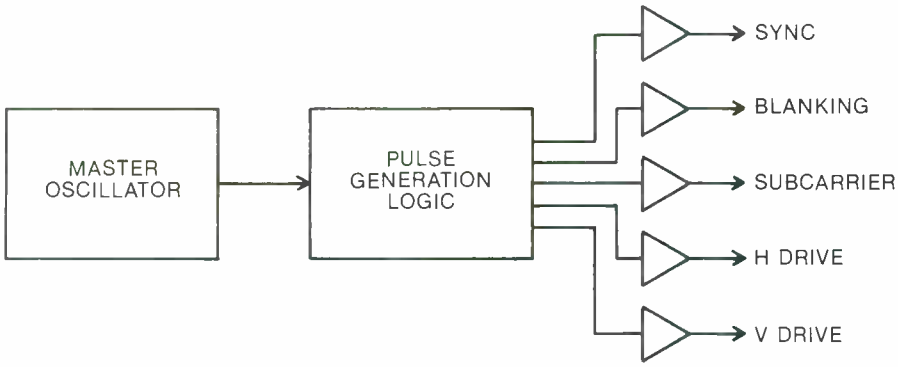


Fig. 10. Simplified block diagram of a basic sync generator.

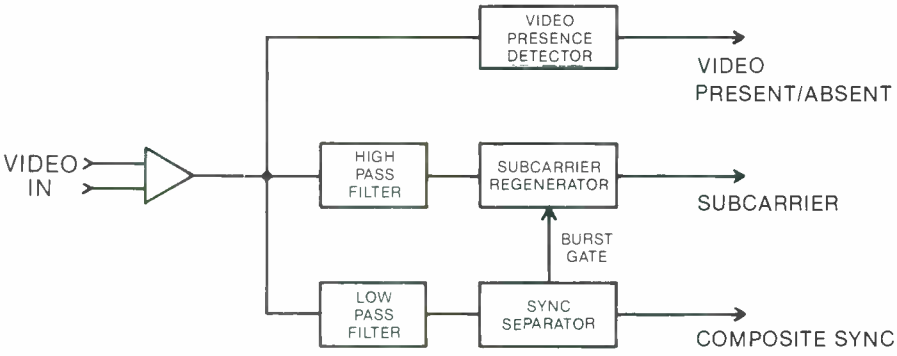


Fig. 11. Simplified block diagram of basic sync generator genlock circuits.

All IC logic families produce pulses with very fast risetimes. So, in addition to providing the proper impedance and voltage levels, the output buffer stages often include shaping or filtering circuits to control the risetimes of the output pulses. Controlled risetimes help to ensure the reliable and predictable operation of pulse detection and regeneration circuits in the equipment being driven by the sync generator.

GENLOCK

A considerable amount of additional circuitry is required to enable a sync generator to lock to a composite video signal such as color black. Fig. 11 shows the basic functional blocks: an input amplifier, subcarrier regenerator, sync separator, and video presence detector.

The input locking signal may contain common mode hum or noise which could upset the operation of the circuits which follow. For this reason, a differential input amplifier is generally used, followed by a clamp.

Since the locking signal may not always be present, the genlock circuitry includes a video presence detector. The output of this detector is a logic level signal which tells the sync generator whether to select the "free run" or "locked" mode of operation.

The buffered and clamped input signal is low pass filtered and then fed to a sync separator which outputs sync and burst gate. The burst gate, along with high pass filtered video, is used to regenerate the 3.58 MHz subcarrier impressed on the input locking signal. The separated sync and subcarrier drive phase locked loops in the generator. Adjustments on these locking circuits permit the generator phase to be varied with respect to the phase of the input signal.

The generator may be genlocked to the input signal in one of two basic ways: by independent locking of sync and subcarrier or by dependent locking of sync and subcarrier. With the independent method, the generator's sync and subcarrier locking circuits are continuously referenced to the input signal's sync and subcarrier. With the dependent method, lock is initiated in the same manner as the independent method. But once full genlock is achieved, the input signal's subcarrier is used as a reference for both loops.

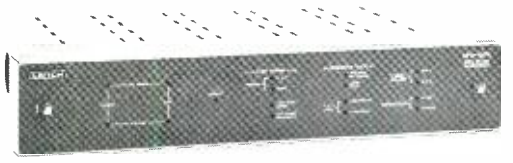


Fig. 12. A common sync generator feature or option is the capability to lock the generator to an external signal so that any equipment using the generator's output will also be in sync with the external signal. This model uses the chroma burst of the external signal to lock a 14.3 MHz oscillator from which it then derives its chroma and pulse outputs. (Photo courtesy of Leitch Video Limited.)

An independent locking generator will track the SC/H (Subcarrier to Horizontal) phase of the input signal. It will also lock to a non-standard color signal (one in which the subcarrier and sync are not phase locked at all).

A dependent locking generator will maintain correctly SC/H phased outputs regardless of the SC/H phase of the input signal. It will also lock more reliably to signals with occasional noise hits or with sync-only timebase error.

Genlocking the master generator to a non-synchronous source such as network has given way to the use of frame synchronizers. However, genlocking is still used in "master/slave" sync systems where individual sources or groups of sources are driven off "slave" generators which are locked to the plant's "master" generator. And, as was previously mentioned, many of today's cameras and vtr's contain their own (genlockable) sync generators.

As a result, it is not uncommon to find situations where three or more sync generators are cascaded. This makes it very important that the first generator in the line (usually the plant's master generator) has very good timebase stability. It is equally important that all slave generators exhibit very low "jitter." A figure of 5ns or less is typical for timebase stability, while 2ns or less is a reasonable jitter spec.

Where genlocking to an outside source such as network is done on a regular basis, a feature called "protected genlock" is highly desirable. With protected genlock, the local generator is locked to the outside source using the independent locking method. Any horizontal timing jumps on the locking signal will not disturb the generator; it will remain frequency locked to the locking signal's subcarrier. If the input signal disappears or becomes monochrome, the protected genlock logic will instruct the generator to make a smooth switch to the free run mode.

TIMING CONCEPTS IN THE MODERN STUDIO

In the early days of color, the system designer's attention became focused on the importance of color timing. While timing errors as large as several hundred nanoseconds could be tolerated in monochrome systems, color systems demanded accuracy at least two orders of magnitude better. The vectorscope took its place alongside the waveform monitor as an indispensable measurement tool.

As monochrome systems were converted to color, these new timing tolerances had to be addressed. The required degree of precision was not difficult to attain if reasonable care was exercised.

Unfortunately, the importance of the interrelationships between sync and subcarrier, especially SC/H (Subcarrier to Horizontal) phase, were not fully appreciated at the time. It wasn't until color video tape recording and editing came along that these issues came to light.

When the NTSC color system was devised, the frequency of the color subcarrier was chosen to be an odd multiple of half the line scanning frequency. This was done so that the subcarrier peaks would occur in alternating positions on adjacent scan lines, thus minimizing the visibility of the subcarrier on monochrome receivers.

The multiplier which was finally chosen was 455/2, or 227.5; this is also the number of cycles of subcarrier per scan line. Since there are 525 lines per frame, there are 227.5 times 525 or 119437.5 cycles of subcarrier per frame. The extra half-cycle of subcarrier means that it takes two frames (or four fields) for the color sequence to repeat.

When a video tape is edited, the machine must ensure that the continuity of this sequence is preserved. If it is not, there will be a noticeable horizontal shift in the picture at the edit point. Many machines incorporate "color framers" to prevent this from occurring. They operate by matching the color framing of the signal recorded on the tape with that of the house reference.

Reliable operation of these color framers is dependent upon the maintenance of consistent SC/H phase throughout the plant. Furthermore, when tapes which have been recorded in another facility are edited, the SC/H phase of the off tape signal must match the local plant's SC/H phase. For this reason, an industry-wide standard has been established which defines correct (or "zero") SC/H phase as the coincidence of the 50% point on the leading edge of horizontal sync and the zero-crossing of subcarrier. (See Fig. 2.)

Fig. 13 shows two methods of displaying SC/H phase. A third method, used with the GVG 3258, provides a digital readout of SC/H phase in degrees or nanoseconds plus time base error measurement and comparative SC/H phase between two sources.

Maintaining SC/H phase depends upon careful selection of equipment and periodic measurements of actual performance. Sync generators with low SC/H phase drift are key elements in any SC/H phased plant. It is equally important to avoid system design techniques which might lead to SC/H phase problems (such as the use of regenerative pulse or subcarrier distribution amplifiers).

SC/H phase should be checked as routinely as video levels or color phase.

Timing Tools

Numerous approaches to plant timing exist, but they all fall into one of two general categories: adjusting the relative phase of the source timing reference, or delaying the source video. In general, it is always better to move the timing signal around. This is because even the best video delay systems introduce a certain amount of signal distortion. Obviously, video delay is not a viable solution where a source must be advanced in time with respect to other sources.

Video delay lines are often used when a single source must feed different timing points. This is quite often the case in a system where a source must appear as a direct input to a studio production switcher, but the same source may be selected on a routing switcher which, in turn, feeds the production switcher. This is illustrated in Fig. 13.

In general, it is better to use a delay DA than a passive delay line/video DA combination. This is because a properly designed delay DA will include circuits which compensate for response errors in the delay elements. Where passive delays are used, they should be of the highest possible quality and the shortest electrical length required to get the job done.

Other devices which can be useful in plant timing are regenerative pulse and subcarrier DA's. They should be applied with caution, however, since they can create system SC/H phasing problems.

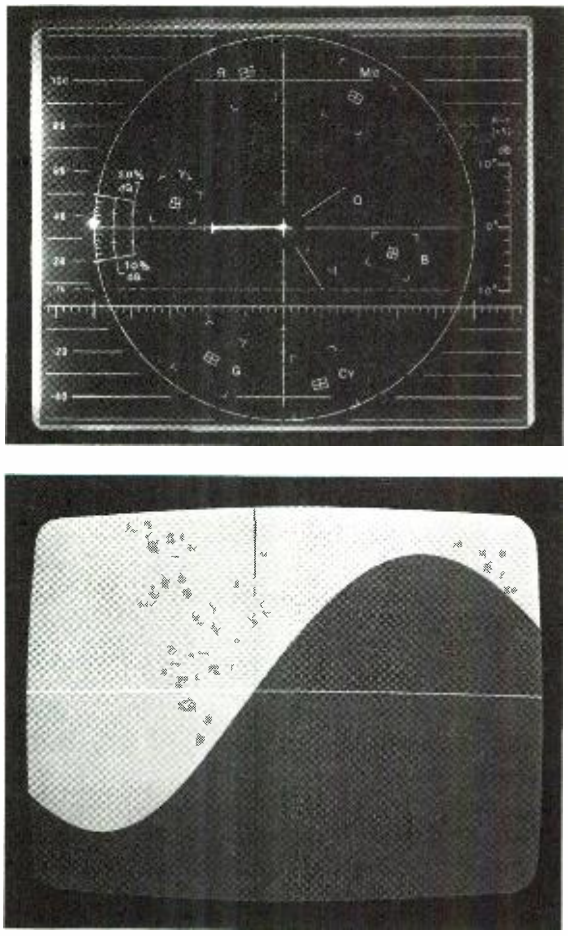


Fig. 13. Two methods of displaying SC/H phase relationships. Top: The Tektronix 1750 waveform and vector monitor shows the relation between the burst phase vector and the "sync dot" as either an absolute value or relative to an external reference. Phase may be read out from the graticule or by adjusting and reading calibrated controls. Bottom: The Lenco Videoscop generates an output to a picture monitor showing the relationship of the leading edge sync in line 1, field 1 (vertical line), the 50% point (horizontal line), and one cycle of the subcarrier (sine wave). (Photographs courtesy of Tektronix, Inc. and Lenco, Inc.)

GUIDE TO PLANT TIMING

At first glance, timing a television plant may appear a formidable task. Like anything else, though, the task can be whittled down to size through a systematic method comprised of analysis, synthesis, and execution.

Analysis entails the careful examination of the timing requirements in each individual operating area of the plant. This information, along with a clear understanding of the capabilities of the equipment, can be used to synthesize a plan for overall plant timing.

The demands placed on most plants are constantly changing and ever-increasing; today's special setup may be S.O.P. tomorrow. It is important to realize, therefore, that the "plan" which has been put together so carefully may change. If this happens, it may be necessary to add or replace equipment or perhaps even alter the system design.

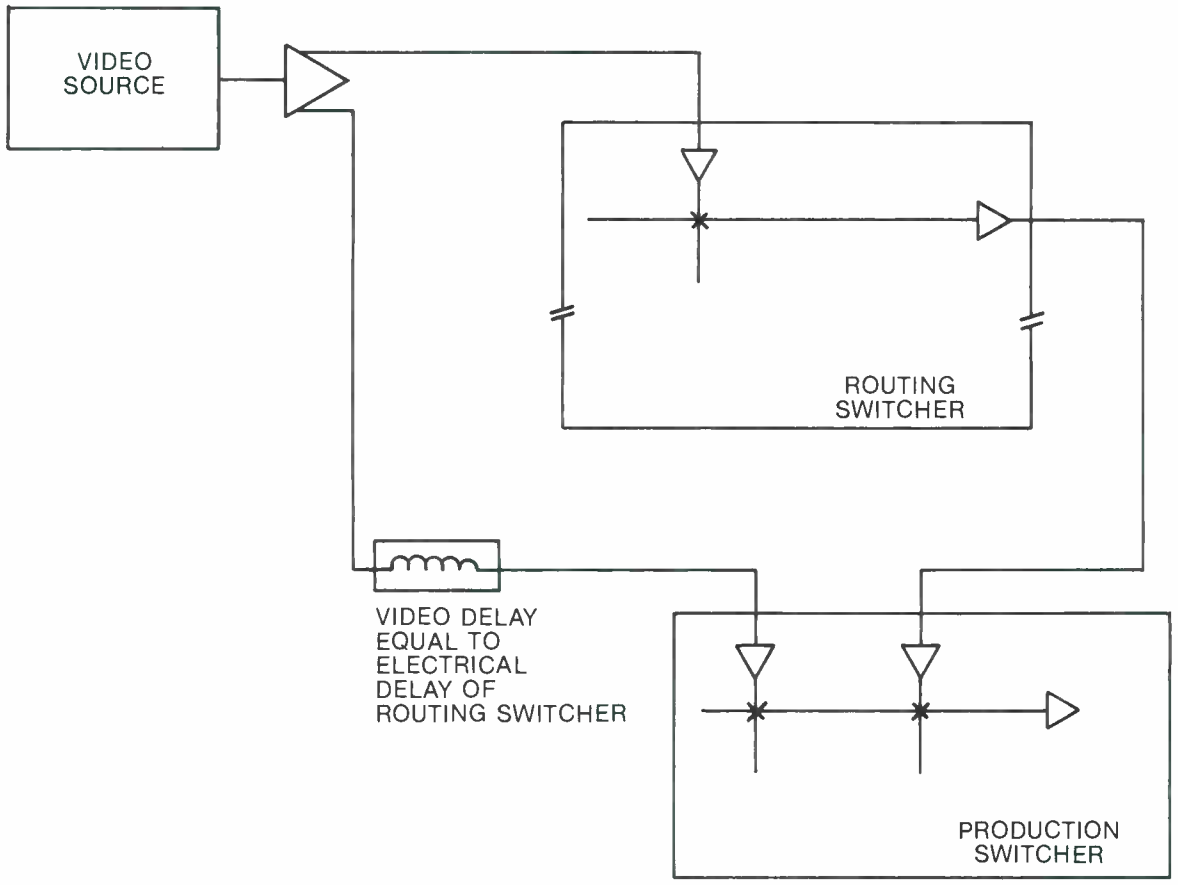


Fig. 14. Timing a single video source to two different timing points.

Studio Timing

The studio (or edit suite) is an excellent place to begin a discussion on system timing, since it is the place where proper source-to-source timing relationships is most important. This is due to the fact that the studio is the primary area of the plant where multiple sources are combined. If visible picture jumps and/or color shifts are to be avoided when making mix, wipe, or key transitions, all studio sources must be carefully timed.

Timing the inputs to a studio switcher is a very simple, straightforward process:

1. Identify those sources which do not have timing adjustments or whose timing can only be adjusted over a very limited range. These will more than likely include the color black and background generators in the production switcher itself and MAY also include test signal generators, character generators, and older studio cameras or film chain cameras.
2. Using delay DA's or delay lines, match the timing of all of the sources identified in item 1 above to the "latest" in the group of fixed sources. Designate one of these sources as the reference source for setting the timing of all of the adjustable sources. Note that if there is only one fixed source, it should be used as the reference source.
3. Adjust the timing of each of the adjustable sources to match the timing of the reference source.

All timing adjustments should be made by selecting each source, in turn, on the production switcher. An externally referenced waveform monitor, vectorscope, and (optionally) SC/H phase meter connected to the output of the production switcher provide the necessary monitoring capability. Timebase and/or gain magnification should be used on the test instruments to ensure the accuracy of timing adjustments.

The output SC/H phase of most equipment will change when timing adjustments are made. If the plant is to be SC/H phased, it is imperative that this parameter be checked whenever source timing is adjusted. On equipment which uses separate pulses and subcarrier for timing, care should be taken to maintain consistent phase relationship between the input sync and subcarrier once the output SC/H phase of the source is established.

If the plant is equipped with multiple studios, the procedures outlined above should be repeated

in each studio. On those sources which feed more than one studio, extreme care should be taken to ensure that cable lengths are made equal. If this is not done, it will be impossible to achieve proper timing in all locations.

Timing in Master Control

For all intents and purposes, master control is just another studio and can therefore be timed using the above procedure.

One timing problem which is fairly common in master control is that of studio delay. It generally shows up as a slight timing disturbance when master control switches from a given program source to that same program source through a studio switcher (a common occurence going into or coming out of a live program such as news). An easy solution to the problem is to re-synchronize the output of each studio (see "CASCADING STUDIOS," below).

Timing Through an Assignment Switcher

If routing switcher buses are used as input preselectors for a studio switcher, the propagation delay through the routing switcher must be taken into account when timing the plant. This is usually accomplished by setting up both direct and delayed paths for any sources which feed a studio switcher both directly and through a routing switcher (see Fig. 14).

In plants where the routing switcher is used for source assignment, it is a good idea to designate the output of the routing switcher as the zero timing point for the plant. If this is done, a bus on the switcher can be designated the plant "quality control point"—one location (with one set of accurately calibrated test instruments) where the signal levels and timing relationships of all sources in the plant can be observed and compared. The generalized timing procedure for studio switchers can be used to time sources into the plant routing switcher.

Cascading Studios

Occasionally, it may be necessary in some plants to cascade studios. In order to preserve overall system timing, the delay through each studio must be taken into account. One approach to keeping everything in time is to time all sources into the first studio "early" by an amount equal to the studio delay. However, if more than two studios are involved and timing into a routing switcher and/or master control are a factor, altering source timing may not be practical.

A far better approach is to re-synchronize the output of each studio using a frame synchronizer. The timing of each studio can then be set to match that of all other sources in the plant.

A word of caution is in order, however: since nearly a frame of video delay is required to re-synchronize a source which is only a hundred nanoseconds or so "late," the video from the studio when passed through a frame synchronizer will be out of sync with the audio by approximately 33ms. While this amount of time difference might not easily be perceived by most individuals, the cumulative effects of several passes probably would be. Therefore, it is a good idea to insert an audio delay line in the program output from the studio.

TABLE 1. Typical video DA performance specifications.

Frequency Response	±0.05 dB to 5 MHz, -0.3 dB at 10 MHz
Differential Phase	<0.1 degree
Differential Gain	<0.15 %
T-Pulse to Bar	<1.0 %
Tilt	<0.5 %
Chrominance/Luminance Delay	<10 ns
Hum	>60 dB below 1 volt p-p
Noise	>70 dB rms below 1 volt p-p
Common Mode Rejection	>60 dB
Input Return Loss	>40 dB to 5 MHz
Output Return Loss	>40 dB to 5 MHz
Output Isolation	>40 dB to 5 MHz

TABLE 2. Typical video switching system performance specifications.

Frequency Response	+0.1 dB to 5.5 MHz, -0.5 dB at 8 MHz
Differential Phase	<0.1 degree
Differential Gain	<0.1 %
2T-Pulse to Bar	<0.25 %
Tilt	<0.5 %
Crosstalk	−60 dB at 5 MHz, worst case
Noise	>75 dB rms below 1 volt p-p
Input Return Loss	>40 dB to 5 MHz
Output Return Loss	>40 dB to 5 MHz
Switching Transients	<30 mV
Timing Scatter	± 1 degree max. input to input on any one output bus

5.5

Video Tape Recording

Charles E. Anderson
Managing Partner
Monaco Video
San Francisco, California

HISTORY

The introduction of the first practical video tape recorder at the 1956 National Association of Television and Radio Broadcasters Convention substantially changed the operational aspects of television broadcasting and eventually made substantial changes in how material is produced for broadcasting.

The first recorders, known as Quadruplex recorders, were crude by present standards, but over a period of more than 20 years, continual improvements were made which exploited nearly all of the abilities of the recording format. By the late 1970's, in spite of all the improvements, quadruplex recorders still suffered from several major shortcomings; they were physically quite large, expensive to purchase, and expensive to operate. Head costs were about $4.00 per hour, and tape consumption amounted to 30 square inches per second. Finally, because the format divided the picture into 17 horizontal bands of 17 scan lines each, it was often difficult or impossible to eliminate differences between the bands that made them visible.

By the mid 1970's the users had made known through various bodies, such as the European Broadcasting Union and the NAB, that smaller, better recorders using less tape and costing less to operate and to maintain were needed. Four major manufacturers of television equipment responded to the pressure and introduced four different recorders employing four completely different formats, all of which employed the helical scan technique in one way or another.

The helical scan format had been thought of and extensively tested during the early development of the video tape recorder by the Ampex engineers. It was obvious that it was a simpler format and that a VTR using it would be less expensive in several areas. It was also obvious, however, that there were two major problems which at that time seemed insurmountable. In a helical recorder the video track is at a very small angle with respect to the direction of tape motion, thus instability of the tape movement caused very large time base errors that caused wild swings of several microseconds of the picture when it was displayed on a monitor with a long time constant in the horizontal AFC circuit. At that time most receivers did employ very long time constant AFC circuits. It seemed unlikely that the scanner with its large mass and inertia could be made to respond to these rather rapid variations, and of course the first electronic time base corrector had not been invented. Because in quadruplex format the tracks are almost at right angles to the tape motion, only insignificant amounts of the longitudinal speed errors are introduced into the video signal. This problem plagued the helical format for professional use until wide range digital time base correctors were introduced much later.

Additionally, a great deal remained to be understood about the tape-to-scanner and guiding

Fig. 1. Ampex AVR-2 Quadruplex Recorder.

elements relationship. Because of the large area of tape rubbing against the scanner and the tension build-up as the tape passed around stationary guides, many, many problems were encountered. In extreme cases tape would stick to the scanner and refuse to move. In other cases tape was deformed by the excessive tension needed to pull the tape past the guides and around the scanner. Only gradually were these problems understood and solved through the forming of new tape surfaces and development and use of new materials and design techniques for scanner and guides.

One of the new recorders introduced fell by the wayside fairly early on, but three remained. In Europe Bosch introduced the BCN series of recorders that employed a small scanner, a 180 degree wrap of the tape around the scanner and which segmented the picture as had the quadruplex format. It used 1" tape and consumed 10 square inches of tape per second. In the United States Ampex re-introduced an older format it had employed for some years on its line of industrial recorders and introduced the new VPR-1 recorder at the NAB show in 1976. In Japan Sony Corp. developed a recorder employing a format that superficially resembled the Ampex format and introduced its BVH-1000 recorder at the 1976 NAB show as well.

The Sony and Ampex recorders were close enough to each other that there was some hope that they could be brought together in a common format. Both used 1" tape, an omega wrap in which the tape was almost completely wrapped around the scanner, and one television field was recorded for each revolution of the scanner. A small gap of about 10 television lines existed where the wrap was incomplete. The Sony recorder employed an extra set of heads on the scanner to record the missing scan lines near the bottom of the tape, but the Ampex format simply ignored the missing lines. The scanner diameter, the tape speed and other characteristics were tantalizingly similar. The Bosch format, however, was strikingly different from the other two.

The Society of Motion Picture and Television Engineers, (SMPTE), formed an Engineering committee to see if a common format could be found to which everyone could agree. It became quickly apparent that the Bosch format was too different and that Bosch could not see its way clear to change. The other manufacturers did at least seem willing to consider the possibility of a change. In about one year the SMPTE committee had drafted a format that borrowed from each of the two formats, added a few embellishments of its own, and to which everyone on the committee had agreed. Many technical experts and users participated in the committee's work, and the expertise of these people was recognized by the manufacturers. In a relatively short time there were four suppliers of equipment that conformed to the new format that had been assigned the arbitrary letter C as a designation by the committee. Thus was the C Format born. The Bosch format was given the designation of B. The A designation was never assigned permanently.

The characteristics of the two formats are spelled out in several ANSI Standards and SMPTE Recommended Practices that are reproduced later in the text. Copies of these documents may be purchased from the Society of Motion Picture and Television Engineers, 862 Scarsdale Ave., Scarsdale, New York 10583.

QUADRUPLEX RECORDERS

Many quadruplex recorders are still in service and are expected to be around for a number of years, so a brief overview of their characteristics is in order. The previous edition of the NAB Handbook contained a complete description of the format and is recommended for those who wish to know more about it.

The tape transport closely resembles similar mechanisms found in high quality audio recorders of that day. The tape is pulled from a supply reel

and across the erase, record, and playback heads by a rotating capstan and then wound by a motor-driven takeup reel as shown in Fig. 2. The primary longitudinal tape speed is 15 inches per second, the secondary is 7.5 inches per second. Not many people use this secondary speed.

As the tape is drawn past the erase head and idler it is deformed to form a canoe shape as it passes by the rotating video head wheel upon which are mounted four video heads spaced precisely 90 degrees apart around the wheel. The tape is positioned exactly by the vacuum guide as illustrated in Fig. 3.

In 525 NTSC operation, the head is rotated at 240 rps. The result is a series of video tracks written across the tape at almost 90 degrees to the direction of tape travel. Audio and control tracks are written along the two edges of the tape. Servos control the rotation of both the capstan and the video head wheel so that the signals are replayed with minimal timing errors. A 240 Hz Control Track (4 × Field Rate) is recorded along a longitudinal track concurrently with the video and audio recording. In playback the recovered 240 Hz signal is compared to a reference frequency to position the video heads exactly over the recorded video tracks. In recording, the headwheel motor is driven by the same 240 Hz signal recorded on the control track. In playback the off-tape sync signal is compared to the reference sync signal and the drive to the headwheel motor modulated to vary the speed of the motor and thus the timing of the reproduced sync and video signal. Residual time base errors (amounting to about .15 microsecond peak-to-peak at this time) are removed by time base correctors that reduce the residual errors to just a few nanoseconds.

The first timebase correctors were analog devices that employed voltage-variable delay lines and had a correction range of about a microsecond or so. The earlier variants usually had first a unit to correct gross errors in which off-tape sync pulses were compared to reference pulses. A second unit compared the off-tape burst phase to a reference color subcarrier, and a correction voltage, proportional to the phase error, was applied to the delay line. Finally a third unit corrected for velocity errors. Near the end of quad's life, digital time base correctors were used that combined all the time-base correction functions as well as video processing into one unit that became known generally as the TBC. Video processing prior to the advent of TBCs was accomplished in a separate unit that cleaned up the sync signal, clamped the signal, inserted new burst and clipped noise and switching transients.

The quadruplex video head assembly was a complex affair that was relatively expensive. The position of the vacuum guide with respect to the center of rotation of the head wheel was critical and had to be adjusted both vertically and horizontally if hooks and other geometric distortions were to be avoided in the reproduced picture.

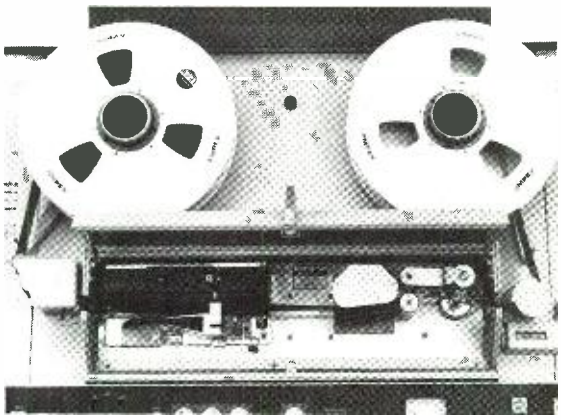


Fig. 2. An early quadruplex tape transport showing the tape path.

THE C FORMAT HELICAL RECORDER

The Tape Transport

In general the tape transport can be described in a way similar to that for the quadruplex transport; tape is pulled from a supply reel and across the erase, record and playback heads by a rotating capstan. In detail, however, the C format transport is very different from a quadruplex transport. The familiar full-width erase head, control track head, and audio heads are still there, but the scanner replaces the quadruplex head wheel. A diagram of the tape path of an Ampex VPR-3 is shown in Fig. 4.

Tape unspools from the supply reel and is looped around a tension arm that senses the tension in the tape as it leaves the supply reel. Data from the tension arm is used to adjust the holdback torque of the supply reel. The tape then passes over the full width erase head, past a guide and approaches the scanner and is about to enter the most critical part of its journey to the take-

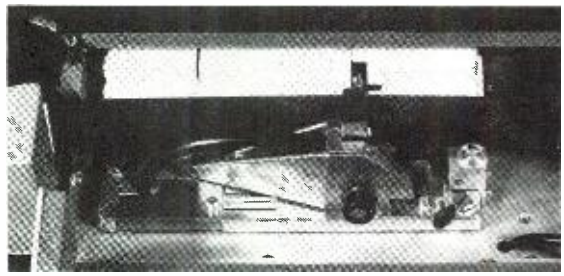


Fig. 3. Head assembly of AVR-2.

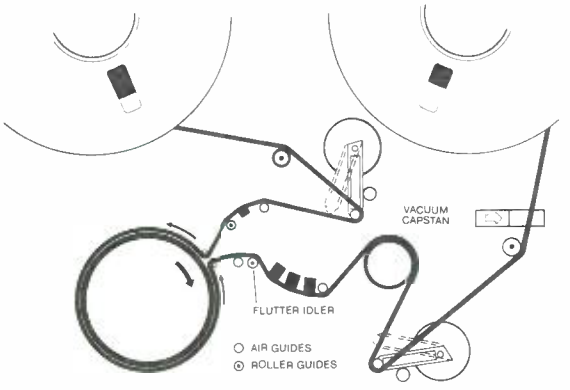


Fig. 4. Tape path of Ampex VPR-3.

up reel. The entrance guide very near to the scanner deflects the tape upwards as it starts around the scanner, and the adjustment of this guide is critical. The tape describes a helix as it climbs around the scanner and finally exits the scanner at the exit guide, thus the name of helical recording.

The upper half of the scanner in which the various video heads are mounted rotates and not only sweeps the heads past the tape but also pumps air between the tape and the scanner to reduce friction between the two. In the C format there can be six heads mounted on the scanner. The position of these heads is defined in ANSI Standard V98.18 and is shown in Fig. 6.

Because the entrance and exit guides must have a small space between them to allow the tape to pass, there is a brief period during which video is not recorded. Upon playback there will be a gap of about 10 video lines where no information is available. This gap is positioned in the vertical interval, starting approximately at line 6 on odd numbered fields. Since the missing information contains known, defined information, it can easily be reconstructed. At this time there is no use of these lines for transmission of data, such as VITS, other than vertical synchronizing pulses.

Provision is made, however, for the recording and recovery of the missing information by employing a separate group of heads, referred to as Sync Heads. Each of the two groups of heads contains an erase head, a record head, and a playback head. The C format defines the Sync head group as optional, but if it is not used, dummy heads must be installed to minimize velocity errors. These errors can arise because as a video head travels across the tape it produces a bow wave just as a ship does, and just as a wave does when it strikes the edge of a canal the bow wave from the head is reflected back into the path of the following head. If the wave were present during recording on one machine but were missing during playback on another machine, velocity errors would be generated, and for this reason six heads or three heads and three dummy heads must generate six bow waves.

After leaving the scanner the usual array of audio erase and record/playback heads is encountered. The capstan meters the tape, and

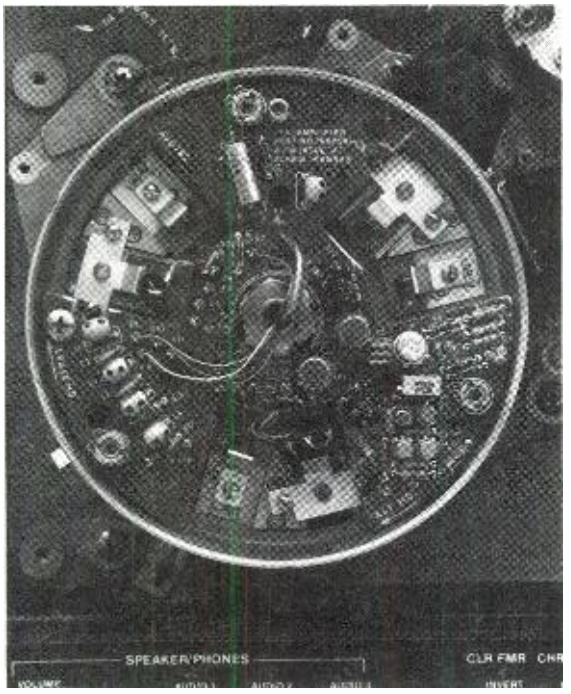


Fig. 5. C format scanner showing six heads.

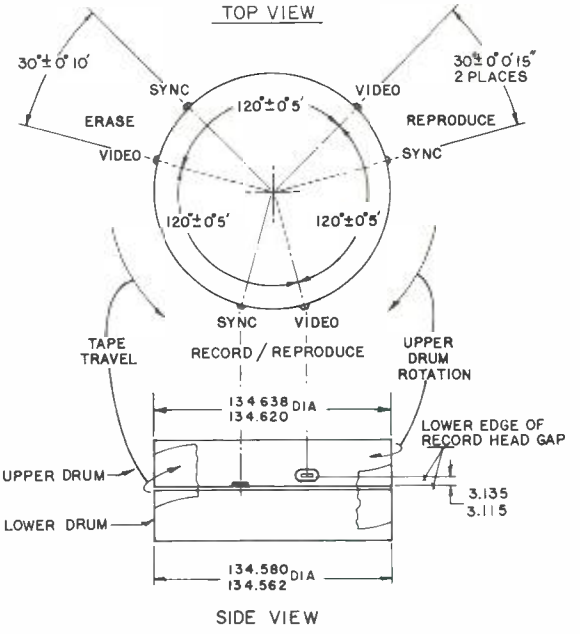
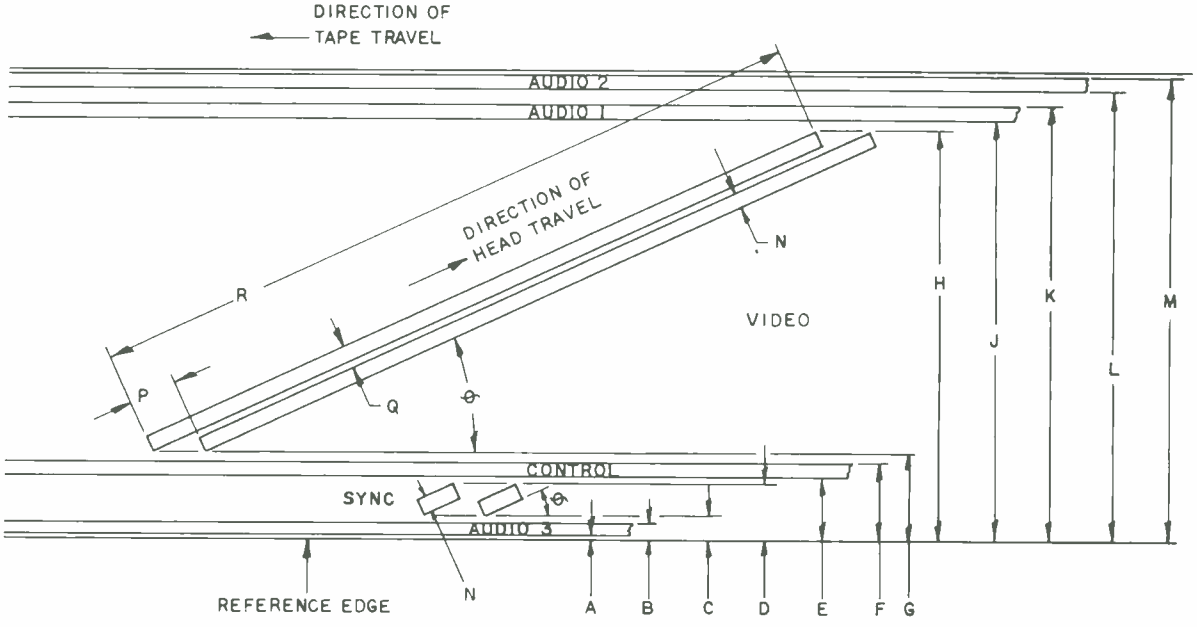
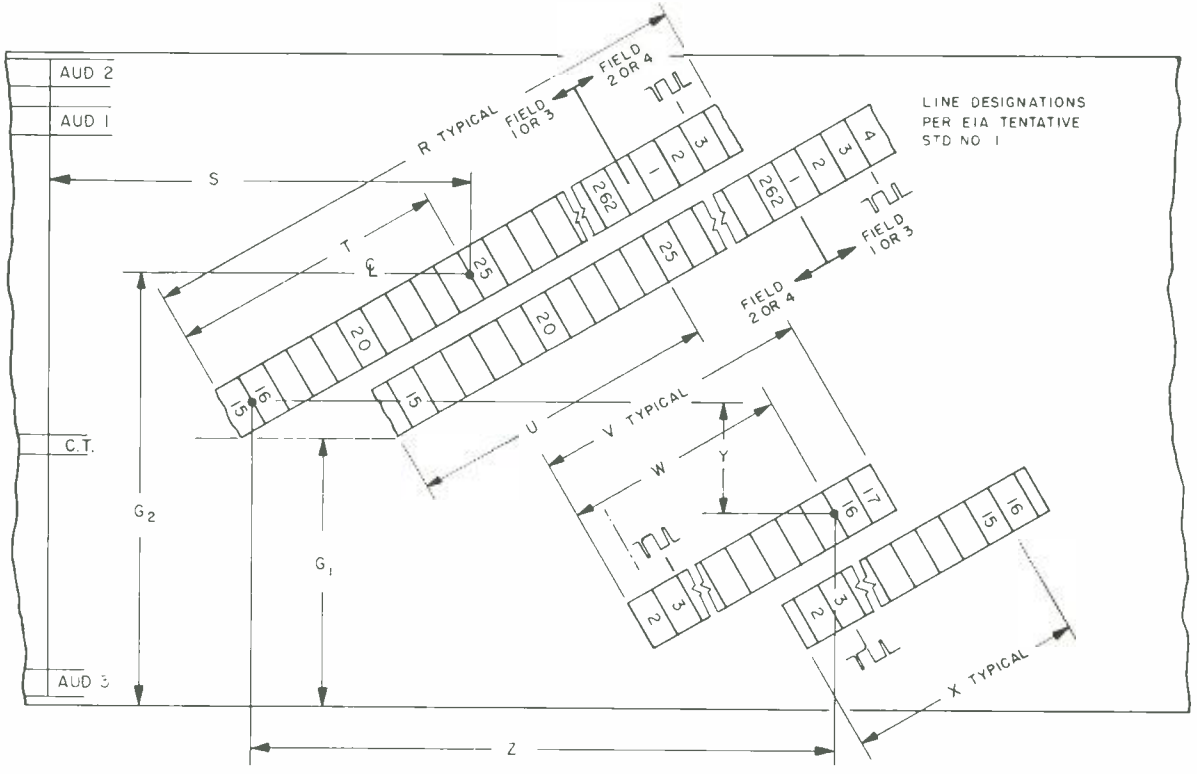


Fig. 6. Pole tip locations and drum dimensions.

Copyright © 1983 by the Society of Motion Picture and Television Engineers. Reprinted by permission.



Record Location and Dimensions



Video and Sync Record Location

Fig. 7. Video and sync record location.

Copyright © 1983 by the Society of Motion Picture and Television Engineers. Reprinted by permission.

Record Locations and Dimensions

	Dimensions	Millimeters Minimum	Millimeters Maximum	Inches Minimum	Inches Maximum
A	Audio 3 lower edge	0.000	0.200	0.0000	0.0079
B	Audio 3 upper edge	0.775	1.025	0.0305	0.0404
C	Sync track lower edge	1.385	1.445	0.0545	0.0569
D	Sync track upper edge	2.680	2.740	0.1055	0.1079
E	Control track lower edge	2.870	3.130	0.1130	0.1232
F	Control track upper edge	3.430	3.770	0.1350	0.1484
G_1	Video track lower edge	3.860	3.920	0.1520	0.1543
G_2	Video line 25 start	4.650	4.710	0.1831	0.1854
H	Video track upper edge	22.355	22.475	0.8801	0.8848
J	Audio 1 lower edge	22.700	22.900	0.8937	0.9016
K	Audio 1 upper edge	23.475	23.725	0.9242	0.9341
L	Audio 2 lower edge	24.275	24.525	0.9557	0.9656
M	Audio 2 upper edge	25.100	25.300	0.9882	0.9961
N	Video and sync track width	0.125	0.135	0.0049	0.0053
P	Video offset	4.067 (2.5H) ref		0.1601 ref	
Q	Video track pitch	0.1823 ref		0.00718 ref	
R	Video track length	410.764 (252.5H) ref		16.1718 ref	
S	Control track head distance	116.23	117.03	4.567	4.607
T	Vertical phase odd field	16.270 ref (10.0H)		0.6406 ref	
U	Vertical phase even field	17.080 ref (10.5H)		0.6724 ref	
V	Sync track length	25.620 (15.75H)	26.420 (16.25H)	1.0087	1.0402
W	Vertical phase odd sync field	22.360 (13.75H)	23.170 (14.25H)	0.8803	0.9122
X	Vertical phase even sync field	23.170 (14.25H)	23.980 (14.75H)	0.9122	0.9441
Y	Vertical head offset	1.529 ref		0.0602 ref	
Z	Horizontal head offset	35.350 ref		1.3917 ref	
θ	Track angle	2°34′ ref			

Fig. 7. Video and sync record location. (Con't.)

Copyright © 1983 by the Society of Motion Picture and Television Engineers. Reprinted by permission.

a second tension arm senses the take up tension and supplies data to the take up reel servo.

The pattern of the various tracks on the tape is defined in ANSI Std V98.19 and is shown in Fig. 7.

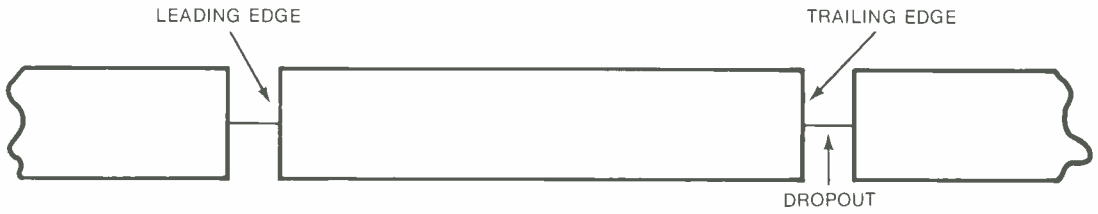
Guiding of the tape around the scanner is particularly critical because of the very long length of the video track. Ideally, the track should be perfectly straight. If it is, a rectangular burst of modulated carrier will be obtained on interchange playback. If it is not, then shapes such as those in Fig. 8 will be obtained. There are a number of factors that influence track straightness of which, the most critical that can be adjusted by the operator are the following.

1. Supply and take up tensions. These tensions can be most easily measured by use of a tensions gauge such as the one shown in Fig. 9. The manual for the particular machine being adjusted will explain how to set the correct tension.

2. Entrance and exit guides. A standard reference tape is used as a practical way to check for correct alignment. If adjustments are provided, they are used to playback a burst of carrier whose envelope is as rectangular as possible. If severe problems in interchange are encountered, the manufacturer of the equipment should be consulted.

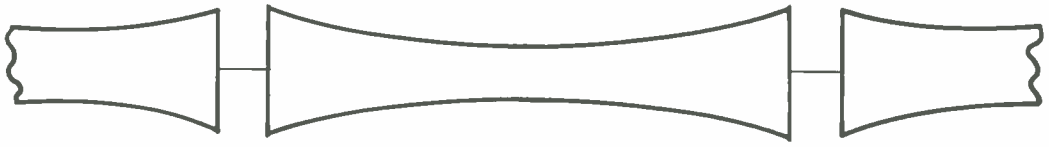
As scanners wear after many, many hours of use it may be necessary to replace either the entire scanner or at least the upper rotating half of it. A note here that one manufacturer provides for replacement of individual heads on the scanner while another requires that the upper, rotating half of the scanner be replaced.

There may be adjustments as well for positioning of the vertical drop out by moving the entrance and exit guides circumferentially around the scanner, and for positioning longitudinally of the control track head. As always, the operating manual for the equipment should be consulted and followed, and also as always the transport should be kept clean and free of oxide build ups. Generally the transport can be cleaned with xylene except for the capstan pressure roller which, if used, may be damaged by the use of such a solvent. Instructions by the manufacturer should be followed carefully to avoid such damage.



IDEAL RF ENVELOPE

GUIDES MISADJUSTED



GUIDES MISADJUSTED

Fig. 8. Drawing of RF envelopes.

Fig. 9. Use of tape tension gauge.

Servo Systems

Capstan and Scanner Servos

Of the several servo systems within the recorder, the capstan and scanner servos are most interdependent, and in broad terms they are similar to the quadruplex capstan and headwheel servos. During the recording process these two servos are referenced to the synchronizing information in the video signal to be recorded. Capstan speed, and thus longitudinal tape speed, is directly related to the vertical synchronizing signal, and a control track signal derived from the video synchronizing signal is recorded on the tape. This signal's waveform is defined in SMPTE Recommended Practice RP-85, and its location in Standard V98.19 illustrated earlier. The position of the scanner, and thus the rotational position of the video record head, at the instant of the vertical synchronizing pulse is controlled by the scanner servo that compares vertical sync against a pulse generated by the scanner and whose location is known with respect to the video record head. Usually there is a maintenance adjustment that assures correct positioning of the record head, and the service manual should be consulted for instructions on how to make the adjustment.

During playback the servo system most often uses a reference video signal such as color bars or sync and burst, but lacking those, an internal oscillator can be used. Vertical sync is compared to the recovered control track signal, and the speed and phase of the capstan motor adjusted. The recovered vertical sync signal off tape is also compared to the reference sync and the speed and phase of the scanner adjusted to provide coincidence in time between reference and off-tape vertical sync. Additionally, reference and off-tape horizontal sync signals are compared and the error signal used to modulate the drive to the scanner motor in order to minimize errors in the timing of off-tape horizontal sync signals. Residual timing errors should be a few microseconds peak-to-peak.

The major component of these errors is relatively large as noted above, but because the large mass of the rotating upper scanner and its drive motor limits the scanner servo's ability to compensate for time base errors that change value rapidly, several smaller, rapidly changing errors are also left along with the large peak error just mentioned. Mentioned earlier were velocity errors that could be caused by a bow wave if six heads were not included on the scanner. Even with six heads, the effects of the bow wave may not be exactly compensated for. Additionally, scrape flutter cause by passage of the tape over guides or over the stationary lower scanner where the tape is not supported by an air film can result in small but significant high frequency time base errors.

Tape Tension Servos

If tension on the tape around the scanner is not the same as it was during the recording process, a major error results that is evidenced by the familiar hooking at the top of the reproduced picture when displayed on a monitor with a long horizontal oscillator AFC time constant.

To be sure that tape tension is the same during record and palyback, both the supply and take up reel motors are servoed during record and playback. The components sensing the tensions are the tensions arms near the supply and take-up reels.

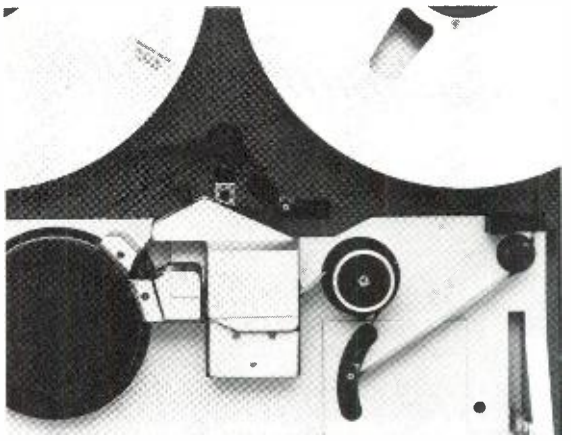


Fig. 10. Tape tension arms on modern C format VTR.

Attached to these arms are sensors that translate the position of the arms (which is an indication of the tension) into an error signal that can be used to control the drive to the reel motors. Tape tension should be checked on a periodic basis, for if allowed to drift too far from the norm it can seriously affect interchangeability.

Video Head Position Servo

A significant event in the maturing of helical recording technology was the development of a method of mounting a video head on a flexible beam that could be deflected by electrical means. The system was developed by Ampex engineers and is now employed by all manufacturers of type C helical VTR's as well as on some of the more sophisticated 3/4" U-Matic recorders. Ampex chose to call the system Automatic Scan Tracking or AST for short. The other manufacturers have chosen other names, but the principal is the same in all cases.

A thin metal plate is anchored firmly at one end, and the video head is mounted at the far,

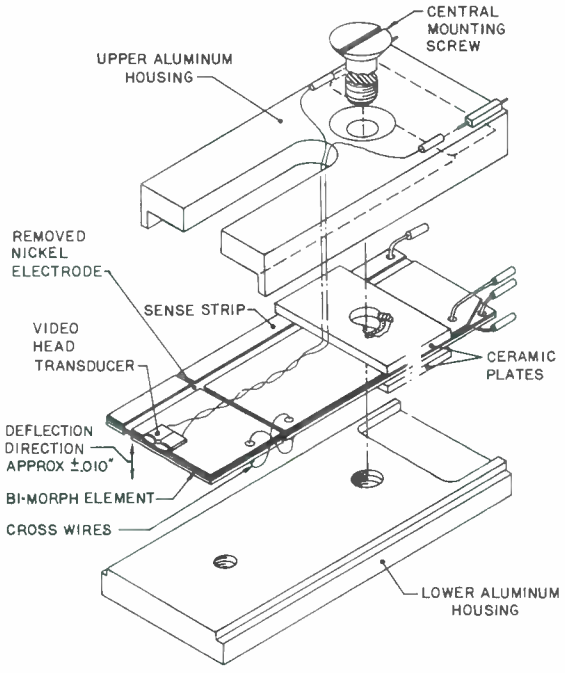


Fig. 11. Drawing of AST head.

unsecured end. a material exhibiting piezo-electric qualities, such as barium titanate, is attached to the top and bottom of the plate. When a voltage (about 200 volts) is applied to the piezo-electric material, the material will contract or expand, depending upon the polarity of the applied voltage, and cause the plate to bend up or down.

A supplemental piezo electric element is attached to the plate to act as a transmitter to send a voltage back to the servo to tell it how far the plate has been deflected. When calibrated, a closed loop servo is obtained that can move the head at the end of the plate to a precisely defined position. The amount of movement is relatively large and is enough to deflect the head over two video tracks, approximately 0.020 inches. Fig. 12 shows an AST head from a VPR-2B.

The introduction of such a head made several outstanding features possible on helical VTRs. With proper care there is no reason there should be interchange problems with VTRs conforming to the C format, but every user knows that proper care is not always a reality; curved, non-standard tracks do occur in practice. The use of moveable heads was first seen as a way to allow playback of such non-standard tapes without degradation in quality.

During playback a sine wave voltage is applied to the piezo electric material at a frequency of 450 cps, causing the head to cross back and forth over the video track as it travels along the recorded track. The result is a modulation of the envelope of the recovered FM carrier. If tracking is perfect the phase and frequency of the modulation will be one thing. If tracking is not perfect the modulation pattern will be different, depending upon which side of the track is experiencing the greatest loss of tracking. This difference can be used as an error signal to generate a correction voltage that will deflect the head back to the center of track, even if that center is not where it is supposed to be.

When longitudinal tape motion is stopped on a helical recorder and the scanner is allowed to continue rotating, a recognizable picture is obtained because one sweep of the track reproduces one field of the picture. Tracking is not perfect, however, and a noise bar is usually evident in the picture. When the AST servo is engaged, however, and given the ability of the head to be deflected enough, the track can be followed and a noiseless picture reproduced. The time to travel the track will be slightly wrong, but a properly arranged TBC can correct that problem. It can also be quickly seen that if the tape is moved slowly in the longitudinal direction, and if the head has sufficient mechanical deflection ability, slow motion playback is possible. Time base errors remain, but with proper coordination between the VTR and the time base corrector, the errors can be eliminated and a perfect slow motion picture obtained. The coordination between VTR and TBC is relatively simple inasmuch as only direction and tape speed need to be given to the TBC, but the extra circuitry needed in the TBC to sort out the proper timing can become complex and add to the cost of the TBC.

With the introduction of VTRs that can provide slow motion capability, the older disc slow

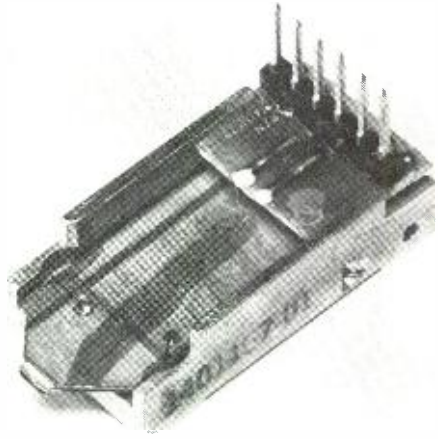


Fig. 12. AST head assembly.

Fig. 13. HS-100 slow motion recorder.

motion recorders were rapidly retired from service. The Ampex HS-100 slow motion recorder introduced in 1967 used two double-sided, hard-coated discs that provided 30 seconds of continuous recording time. Because analog recording, rather than digital, techniques were used, heads were flown very close (about 12 microinches) to the surface of the disc, and head crashes were frequent. The HS-100 was endured (and hated) only because there was nothing better. Very few, if any, remain in service at this time.

Video Heads

General

Quadruplex recorders have, for the most part, used video heads with metal tips attached to ferrite around which the coils are wound. It was recognized very early that if the pole pieces themselves were made of ferrite, wear would be better since the ferrite was much harder than the metal; however, there was one major problem that prevented the use of ferrite. When the heads of a quadruplex recorder encountered the tape, they struck it relatively suddenly and immediately dug deeply into the tape and stretched the tape within narrow confines. Shock and pressure were high. When an attempt was made to use ferrite under these conditions, the ferrite simply could not withstand such abuse and broke up and chipped away. Only in the latter days of quadruplex recording were techniques developed that allowed the use of ferrite.

Helical recorders are much easier on heads since there is no vacuum guide as in quadruplex recording to confine the tape in the area around the head, and the head encounters the tape in a much gentler fashion. Accordingly, ferrite heads have been used on helical recorders for many years. The hardness of the ferrite and the gentleness with which it encounters the tape contribute to the large number of hours of use that can be expected from helical heads in contrast to quadruplex heads.

Because ferrite is brittle, rough handling and carelessness when cleaning helical heads can destroy the head. Follow instructions given by the manufacturer to the letter. In general, cleaning should be done with circumferential motion rather than motion across the head.

Head Construction

The actual transducer is small and is usually mounted on a larger supporting structure. Fig. 14 shows a record/playback head from a VPR-2B. The actual transducer is mounted at the very end of the large structure. This particular head assembly can be replaced by the user in the field. The helical head is made up of two pieces of ferrite whose inner surfaces are carefully lapped. The two pieces of ferrite are brought together with a non magnetic material between the surfaces in the front part of the transducer to produce the head gap.

The Scanner Assembly

Signals are brought to and from the video heads by rotary transformers. Unlike quadruplex head assemblies, the reproduce preamplifiers are mounted within the rotating scanner and send

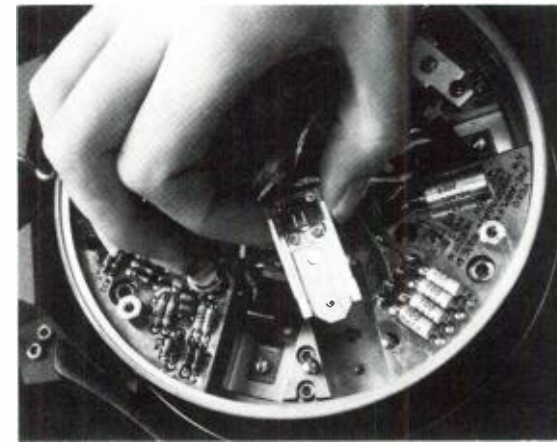


Fig. 14. Record-playback head from Ampex VPR-2B.

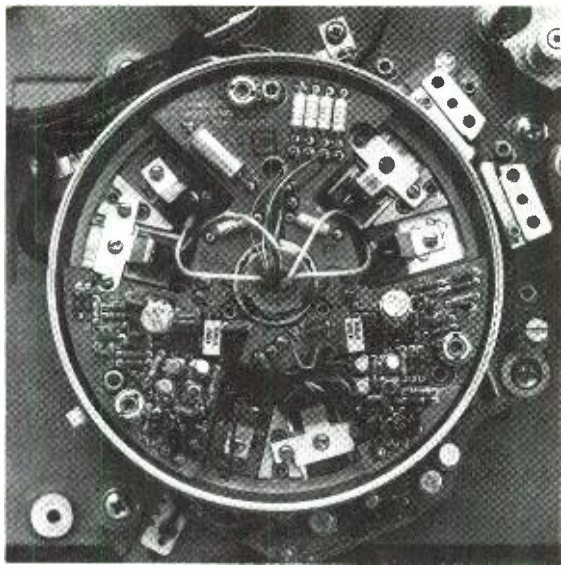


Fig. 15. Top, rotating part of scanner, including pre-amps.

highlevel playback signals to the signal system through the rotary transformers.

The scanner assembly is reasonably complex. It must contain the drive motor, the rotary transformers, and slip rings which bring control voltages to the AST head and to the preamplifiers. It also contains bearings to allow rotation of the upper scanner, and the preamplifiers, themselves.

Video Head Life

Measurement of Head Wear

The tips of the video heads protrude a few thousandths of an inch beyond the circumference of the scanner and thus actually dig into the tape. The amount of protrusion is an indication of the amount of life left in the heads. When new, the heads protrude about 0.0036 inches. At end of life the protrusion is about 0.0012 inches. End of life usually comes when enough material is worn away to allow the back of the gap to break through.

Most manufacturers provide as an accessory a dial indicator and holding fixture that can be attached to the transport and used to measure the projection of the head tip beyond the surface of the scanner.

Factors Affecting Video Head and Tape Life

Video head life and video tape life are related. Video head wear is affected by the characteristics and condition of the tape used, the cleanliness of the equipment, the environment of the operational area, adjustment of the VTR tape transport, and the general handling procedures of the VTR and the video tape. Similarly, the video tape life and condition are affected by the condition of the video head, the tape path surfaces of the video recorder and all of the environmental conditions mentioned in conjunction with head life. Additionally, the condition of reels and the circumstances of packaging, shipping, storage, and above all by the video tape handling procedures exercised by the VTR operator.

Video head wear is of great concern in relation to the cost of operation as well as providing high quality performance of the video recorder. Helical recorders generally exhibit lower rates of video head wear than do quadruplex recorders because head-to-tape mechanical pressure is less and the abrasion by the tape is less. One can reasonably expect head life on a helical recorder to be at least three times the head life of a quadruplex recorder.

All magnetic recording tapes present an abrasive surface to the video head tips, and head wear begins the moment the first tape is recorded or reproduced. The abrasiveness of tape is one of the critical characteristics and should be determined before large quantities of a brand are purchased. The rate of head wear produced by good quality tape is finite but relatively low; damaged tape is quite another matter. Head wear is also related to the moisture content of the tape binder. The higher the moisture, the higher the rate of head wear. The moisture content is determined by the humidity at which the tape is stored and by the humidity of the operating environment. There is a marked increased in wear when the humidity is much above 40%; therefore, the storage environment as well as the operating environment relative humidity should be maintained in the range of 35 to 45%.

A real killer of video heads, helical or quadruplex, is damaged tape. The head and tail ends of tape become creased and frayed with use, and

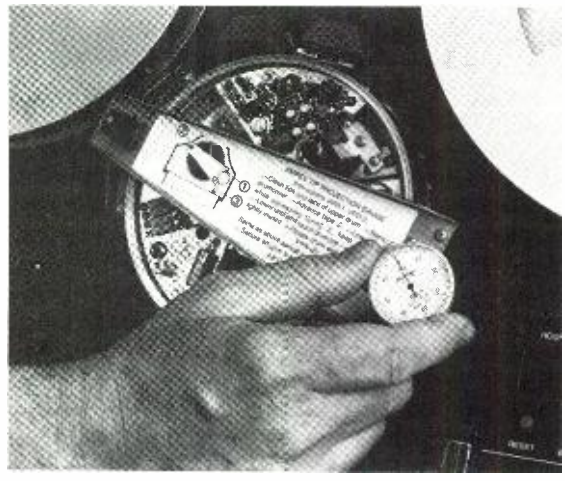


Fig. 16. Tip projection gauge.

if these damaged ends are not cut off they can and will destroy catastrophically the video heads as the tape end flies by the heads when tape is being rewound or spooled off a reel.

Tape that has been physically damaged by creasing, crumpling, or scratching causes high wear rates. And sharp deformation or scratching of the oxide coating interrupts its continuity and uniformity and results in an action somewhat akin to that of a file. It also loosens individual particles of oxide that may be picked up and retained by the video head tips, the scanner surface or any of the other guiding surfaces or the audio head stacks.

As a minimum, before each day of use, closely inspect all metal surfaces such as tape guides, idlers, compliance arms, scanner, and audio head stack, which touch the tape for an accumulation of oxide and dirt. If any is present, remove it by using a cotton-tipped swab moistened with head cleaner. On quadruplex recorders there is a tendency for oxide to build up on the head wheel, and the wheel should be cleaned before every recording or playback.

While tape is being manipulated by hand, use care to avoid creasing or crumpling. Do not handle the tape any more than necessary, for in addition to mechanical damage, oil from the skin will cause difficulties.

The environment in the area where the tape is actually used should approach as closely as possible, while still being practical, that of a "clean-room." Such an area is free of normally expected airborne dust and lint. Various airconditioning filtration systems are available to accomplish the cleaning.

Surrounding walls and ceilings should be painted and free from material that will attract and hold dust. Air intakes should be well-filtered to eliminate outside dust and dirt from entering. Anything, such as empty boxes or packing materials, that tend to collect dirt and dust should not be brought into the area. Video tape equipment, racks, shelves, and video tape reels must be kept clean and free from dust and dirt.

The design of the equipment area should be such that control of temperature and relative humidity can be exercised. Variations of temperature should be held to ± 5 degrees Farenheit and the relative humidity should be kept constant to within $\pm 10\%$. The general recommendation is to have an environment that is comfortable for the operating personnel, for such an environment is also good for tape. Generally this means a temperature in the low 70's and a relative humidity of about 35%. Cigarette ashes are not good for tape; therefore, smoking in the area should be discouraged, and food and drink should be restricted. Small food particles can be easily transmitted to the video tape and recorders from the operator's hands and result in excessive drop out activity.

Aside from the direct benefits gained from a clean, well maintained, temperature and humidity controlled environment, the psychological effect on the employee is also of great importance. Operators will exercise more care and be concerned about quality when working in such an environment. Cleanliness in video tape areas is absolutely essential to the long-term life of video tape material stocks and to minimum video head wear.

Tape should be stored in clean, temperature and humidity controlled areas. Humidity should be 35-45% and temperature should be 60-65 degrees F. It should be stored in boxes and on edge, not flat. When brought from storage into an operating environment, the tape should be spooled at slow speed (100-150 ips) back and forth and allowed if possible to sit for several hours.

When shipping tapes it is best to use high-impact, plastic cases available from most manufacturers of tape.

The Signal System

General

All video recorders, both professional and consumer, use essentially the same type of signal system since the function is identical; a varying amplitude video signal is converted to a frequency modulated carrier for recording on the tape. A carrier is used for recording on the tape because the tape can only accommodate a limited number of frequency octaves and a video signal requires many octaves. If the same video signal is modulated onto a high frequency carrier, the number of octaves that must be reproduced is small and can be accommodated. Frequency modulation is used because of its performance in the presence of noise. This is important because the recovered RF signal is not of constant amplitude or signal-to-noise but is varying as a function of mistracking and head-to-tape conditions. Both of these are quite variable, and observation of the recovered RF envelope shows that it is constantly varying in amplitude.

The frequency modulated carrier is amplified and split into the required number of channels to match the number of record heads employed by the format. On quadruplex machines this is four channels, and on C format this is only one channel. The amplified signal is coupled to the rotating scanner or head wheel by rotary transformers. Each head on a quadruplex recorder receives the signal continuously and records the signal while the head is in contact with the tape.

In C format helical recorders, the current to the head is turned on and off at precise times to insure the recording is made only where desired on the tape.

During playback the very weak signal from the heads is coupled to preamplifiers mounted as closely as possible to the heads. On quadruplex recorders the signal is first sent to the rotary transformers for coupling to the preamplifiers mounted on the head assembly. On professional helical recorders the preamplifiers are mounted inside the scanners and rotate with the video transducers. The amplified signal is then coupled to the equalizers, limiters, and demodulators through the rotary transformer(s). The bandwidth of the signal system extends from approximately 2 MHz up to approximately 18 MHz, or just slightly over 3 octaves.

Modulation

There are two basic types of modulators used, multivibrator and heterodyne. The Ampex VPR-2B recorder, for example, uses a multivibrator operating at twice the desired frequency to avoid second harmonic problems. It is divided later by two to the desired frequency.

Usually the video input signal to the modulator is band limited by a low pass filter to prevent spurious sidebands generated by frequencies above those normally encountered in the standard being used. It is then clamped to provide a stable reference point defined by the back porch of blanking. All professional recorders, both B and C format as well as some U-Matic recorders, now use High Band frequencies in which the blanking carrier frequency is 7.9 MHz, peak white is 10.9 MHz and tip of sync is 7.06 MHz for 525/60 systems. Quadruplex recorders before 1964 used low band frequencies, one set for color, and another set for monochrome. Both high and low-band frequencies are defined in SMPTE Recommended Practice RP-6. Some of the old, archival recordings that might be encountered may use these older low-band frequencies, and of course some of the home VTRs and lowband U-Matic VTR's also use lower carrier frequencies.

Some degree of pre-emphasis is applied to the video signal before it is delivered to the modulator in order to improve the signal-to-noise ratio of the reproduced signal. This is a well known technique and its use here is completely conventional. The amount of pre-emphasis employed is also defined in the SMPTE Recommended Practices just mentioned in association with carrier frequencies.

The choice of carrier frequencies is determined by the level of performance desired. Generally speaking, the carrier is made as high as possible consistent with the ability of the VTR to recover the carrier in order to minimize moire or spurious frequency components caused by folded sidebands generated when significant sidebands are produced by the modulating signal and these sidebands approach zero frequency and then fold back to produce sidebands at the "wrong" frequency and thus cause spurious signals in the demodulated signal.

The Playback System

The frequency modulated signal recovered by the head is transferred by rotary transformer to a further amplifier. After amplification to a reasonable level the signal is applied to an equalizer that compensates for frequency response characteristics of the video head to provide a flat response. Trim controls are also provided to minimize differential phase and gain errors. If more than one head is used in the format, such as in the B format or in quadruplex recorders, each head output is equalized separately, and then a switcher, timed by the position of the scanner or head wheel, switches between the heads just as one head leaves the tape and another enters the tape. Thus a continuous signal is provided to the limiting amplifiers.

There are a number of ways the video can be recovered from the frequency modulated carrier. Early quadruplex machines employed a simple slope detector, but over the years many methods have been employed. Recent Ampex VTRs employed carrier crossing detectors. In other VTRs the manufacturers have produced integrated circuits represented as a simple block on the circuit diagrams and the inner workings of the IC remain a mystery to the user.

After demodulation the video signal is clamped on the back porch employing conventional techniques, and the vertical dropout, if there is one, is clamped to remove noise caused by the loss of signal as the head transists the gap between the exit and entrance guides to the scanner. If separate heads are employed to recover all of the vertical sync signal, the recovered synchronizing signal is inserted into the 10 line gap. Finally the signal is amplified and supplied at the output of the system at the customary level of one volt peak-to-peak at an impedance of 75 ohms.

A glance at the schematics of a variety of 1" and 3/4" recorders reveals a variety of circuits and techniques used to recover the signal and to process it before the output of the recorder. The user must judge the entire system of signal recording and recovery by the results obtained in terms of signal-to-noise of both the luminance and chrominance signals, and of the residual spurious signals (moire) in the video signal and, of course, by such other criteria as sine squared response, differential gain and differential phase.

Time Base Correction

General and Historical

If a video signal is to be replayed with each picture element positioned in time with respect to any other picture element exactly as it was in the original signal, the head to tape velocity on playback must match exactly the head to tape velocity at all instants during the recording. In spite of the use of servo mechanisms to control the rotation of the drum or scanner as precisely as possible, only so much can be done. Not only may there be instabilities in drum or scanner rotation, but there may also be instabilities in the longitudinal speed of the tape. Additionally, there are other disturbing things that tape has a habit of doing such as fluttering in local areas. The net result of the instabilities is that the reproduced signal has time base errors that must be removed for professional use of the signal. Home class VTRs usually have substantial time base errors, but newer receivers usually can ignore them and various schemes are used to recover the unstable chrominance information. Quality suffers considerably using these techniques. For professional use, however, where highest quality is required and editing and other post production techniques are to be used,the recovered signal must be time base stabilized.

Before discussing time base correction it is well to remember that there is no continuous, coherent signal that can be used as reference in the composite television signal. Even the chrominance subcarrier is suppressed and not present at all times. Two recurring signals are, however, present at all times, the scanning synchronizing pulses and the color burst that is present after each sync pulse other than those in the vertical interval. It is these two signals that are compared to a reference, stable signal in order to measure the amount of time base error present.

Time base correction occurs in four stages. The first step involves control of the rotational velocity of the scanner, or head wheel, and of the longitudinal motion of the tape. This step is discussed separately under Servo Systems. The residual jitter or time base stability after this step in quadruplex recorders is about ± 0.07 microseconds and in helical recorders, such as the Ampex VPR-2 series, is about 7 to 10 microseconds. Any following correction circuit must be able to accept this magnitude of variations.

Earlier quadruplex recorders such as the VR-1200, VR-2000 and TR-70 employed analog techniques. The heart of the system was a delay line of about one microsecond in length which was made up of pie sections of L and C. The capacitors were varactors whose capacity was changed by varying a dc voltage across them. As the value of the capacitors changed, the delay of the line changed. About the practical limit of delay variation that could be obtained was ± 0.5 microseconds. This was more than adequate, however, for quadruplex recorders. Off-tape sync pulses were compared to reference sync pulses and an error voltage created proportional to the time difference between them. This voltage was applied to the voltage variable delay line just described.

The time base stability at the output of such a device was about ± 30 nanoseconds, still not good enough for direct color recovery. It has been determined that about 5 degrees of phase error in the 3.58 MHz color subcarrier is just detectable to the eye. Since the period of one cycle of the subcarrier is 280 nanoseconds, the time base error must be reduced below 3.9 nanoseconds. This was done by employing a second, shorter voltage variable delay line which was controlled by an error voltage derived by comparing off-tape burst to a reference 3.58 MHz color subcarrier (related of course to the synchronizing pulses used earlier.) The output signal from such a device was usually about ± 2 nanoseconds and was limited by the signal-to-noise of the recovered burst signal off-tape.

The final step corrected for velocity errors. Because the sync and burst signals occured only once every line, head-to-tape velocity changes that took place during the line sweep time were still uncorrected. If a field of one full color were reproduced, these errors showed up as hue shifts from left to right on the screen. Velocity compensation consists of looking at what has happened to the time base errors over a period in the past and predicting what they will be in the future and then applying a correction throughout the scan line. Velocity errors do exist in helical recorders and must be dealt with.

Digital Time Base Correctors

So far only older analog time base error correction techniques have been discussed, but modern TBC's, as they are called, employ digital techniques. The first digital, wide range time base corrector was introduced by the ADDA Corporation in 1973 at the NAB show in Washington D.C. Ampex introduced its first digital TBC as part of its AVR-2 quadruplex recorder at the next NAB show in 1974. As one might expect, the first units were large and expensive. Present units are very small and reduced in price.

The first step in a digital TBC is to convert the analog video signal into a digital signal. The signal is sampled at a rate well above the Nyquist frequency for the highest video signal to be passed by the system. The first TBC's used a sampling frequency exactly 3 times the color subcarrier or 10.737 MHz. Each sample was then converted to an 8 bit binary word. Through the

work of the SMPTE a standard has been proposed for composite NTSC color signals that involves a sampling frequency of four times the color subcarrier, or 14.32 MHz. Most but not all modern correctors now employ this higher sampling rate. A few use nine bits to define each sample. The first Analog-to-Digital converters (A/D converters) were made up of discrete components, but VLSI chips are now available to perform the same task. At the output of the TBC, the task must, of course, be reversed and the digital signal converted back to an analog one to be compatible with the rest of the TV plant. When the day of the all-digital studio arrives these A/D-D/A steps will not be necessary.

The digitized, off-tape video signal is clocked into a random access memory, time base errors and all, by a clock derived from off-tape sync and color burst. This same clock is used to derive the sampling frequency in the A/D process. A short time after the video signal is clocked into the memory and while it is still being clocked into a spot farther along in the memory, a second stable clock can be used to bring the signal out of memory at a constant rate and free of time base errors. This is an obviously oversimplified version of what happens, but it is in fact the heart of what happens along with certain embellishments to accommodate velocity errors and slow and fast speeds.

If a video signal is sampled and each sample defined by eight bits, the serial bit rate will be about 100 megabits per second. Circuitry to handle such a rate will be extremely expensive, so the digital signal is not processed in a serial fashion but is handled in parallel with maximum bit rates of either 3 × 3.58 MHz or 4 × 3.58 MHz which are quite reasonable bit rates to be handled by fairly conventional techniques.

Velocity errors are compensated for in the clocking-in process. Remembering that there is no continuous reference signal during a TV line and that high frequency time base errors may occur during the line it should be obvious that a clocking-in frequency derived from burst at the start of the line may clock errors into memory at the wrong time. As in analog TBCs discussed earlier, several previous bursts and horizontal sync pulses are examined and a prediction is made about what probably will happen during the line currently being clocked into memory. This prediction is used to modulate the timing of the clocking signal during the TV line.

If a TBC were to be used only to time base correct a signal from a VTR in normal play mode, the TBC would be complete as described; however, users expect a TBC to also provide full color-stable signals during reverse, stop, slow, normal, above normal speed (possibly 3 times play speed) and to provide recognizeable pictures during fast shuttle in both directions. Circuitry to accomplish these tasks becomes complex. Information must be sent to the TBC from the VTR that tells the TBC which direction the tape is moving and whether the tape is above or below normal play speed. Numerous clocking oscillators in the TBC must lock to the incoming off tape sync and burst through a wide range of frequencies and provide clocking frequencies for moving data into the memory.

Dropout compensation is also considered a part of the TBC's duty today; fortunately it is relatively easy in a digital TBC. Sensing of a dropout is easily accomplished by looking at the RF envelope recovered from tape. Once a drop out is sensed, information from a previous horizontal line of video information can be substituted for the missing information. Since digital TBCs store several lines of information, no particular problems are evident. Some TBCs have separate memories for storing two lines of information just for drop out compensation. While in some cases information from a line twice removed may not be suitable, most of the time it is, and DOCs based upon this principle are very effective.

Finally, TBCs must deal with playback signals from helical VTR's that use color-under techniques. The C and B format machines do not use such techniques, but often the TBCs from these machines may be used to stabilize the outputs of such color-under machines. Some such VTRs allow an unstable color subcarrier to be fed back to the VTR upon which the color information can be remodulated, but when this is not the case, the chrominance signal is demodulated in the TBC and remodulated upon a stable subcarrier after time base correction. A front panel switch usually allows normal or heterodyne (color-under) type of correction.

Control Systems

One has only to remove the trim panels from some of the older and less expensive audio and video recorders to encounter a collection of mechanical, sheet metal levers and springs and latches that at one time provided a cheaper but maddening way of controlling tape transports. When remote control of equipment was required, as was the case in most professional service, pushbuttons and relays were used. The early quadruplex recorders were full of relay logic, and the practice continued for many years until the advent of integrated circuits that provided inexpensive logic chips. The changeover occurred about 1970 when Ampex introduced the AVR-1 and continued until 1982 when microprocessors were introduced by at least two manufacturers. The technician of today must have a good understanding of microprocessors and of software. So far

Fig. 17. Early razor blade editing.

all of the software associated with control of VTRs is provided via PROMs (Programmable Read Only Memory.) The use of such techniques adds greatly to the complexity and problems of the repairman when something is wrong, but it allows sophistication of control not dreamed of a few years ago. The caveat is that technicians expected to service such equipment must be chosen with care.

VIDEO TAPE EDITING

The reader will find this subject covered in another chapter in this book, so the intent here is only to provide an overview and a bit of the history so the reader can appreciate the flexibility available today.

Historical

The first attempts made to edit video tape were made early in the development of quadruplex recorders and made use of a razor blade to cut physically two pieces of tape in a defined way and to place and join the two pieces with splicing tape. An edit pulse was added to the control track signal to mark which field (odd or even) was adjacent to the pulse and to guide the editor's razor blade. The tape was developed with a mix of carbonyl iron and a solvent that evaporated and left the iron particles attracted to the recorded areas. Fig. 17, a view of early razor blade editing, shows that it was a crude arrangement at best, and very soon a method of turning video heads off and on as well as a full tape width erase head were developed.

Next, a programmer was developed to control the electronic editor with its operation based upon counting edit pulse (or frames) and marking the edit points by placing cue tones on a low quality cue track. This was a great improvement, and the method served the industry well for a number of years. Ultimately, however, the need for a more sophisticated system of editing was needed, and it became obvious that every frame of a TV signal should have a unique identification if video tape was to be a flexible as film is with its edge numbers and sprocket holes. Several companies developed codes, and ultimately SMPTE again was asked to standardize the code. The result was the now familiar and (improperly identified) SMPTE Time Code that is properly identified as ANSI Standard V98.12.

The SMPTE Time Code

Each television frame is uniquely identified by an 80 bit digital address. A few of these bits are used for synchronizing purposes, a second group identifies each frame by hour, minute, second and frame. 32 bits are left over in groups of four that can be used as desired by the user. The distribution and use of the bits is shown in Fig. 18 which is a reproduction of ANSI Standard V98.12.

When first used the code was recorded on the longitudinal cue track on the quadruplex recorders. The pratice was carried over to C and B format helical recording, but it is now also inserted into the vertical interval. This practice is defined in SMPTE Recommended Practice RP-108.

Once a TV frame is uniquely identified, all things are possible. An exact frame can be looked for and found, two tapes can be run in synchronism with a defined offset in time code, audio and video recorders can be synchronized, and film and video transports can be locked together. The time code is video tape's sprocket hole.

Editors

Almost all modern VTRs have some sort of built-in editor that allows programming of a simple cut at a specified point defined. Shown in Fig. 19 is the editor section of the control panel of the Ampex VPR-80, the least expensive model in Ampex's product line.

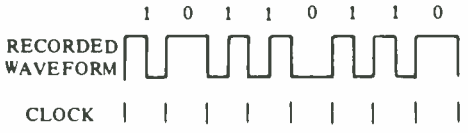
When truly sophisticated editing is desired, however, and external controller must be used that will control not only the actions of the VTRs but also of switchers, special effects units, graphic generators and other parts of the video system. These units are covered elsewhere in this volume.

OTHER FORMATS

As with Editors, other significant formats will be covered elsewhere in this volume, but they will be mentioned here to give perspective to the position of professional formats such as the B and C formats.

80 BITS PER FRAME

32 USER BINARY SPARE BITS
16 SYNC
28 ASSIGNED ADDRESS
4 UNASSIGNED ADDRESS
ALL UNASSIGNED BITS ARE ZEROS.



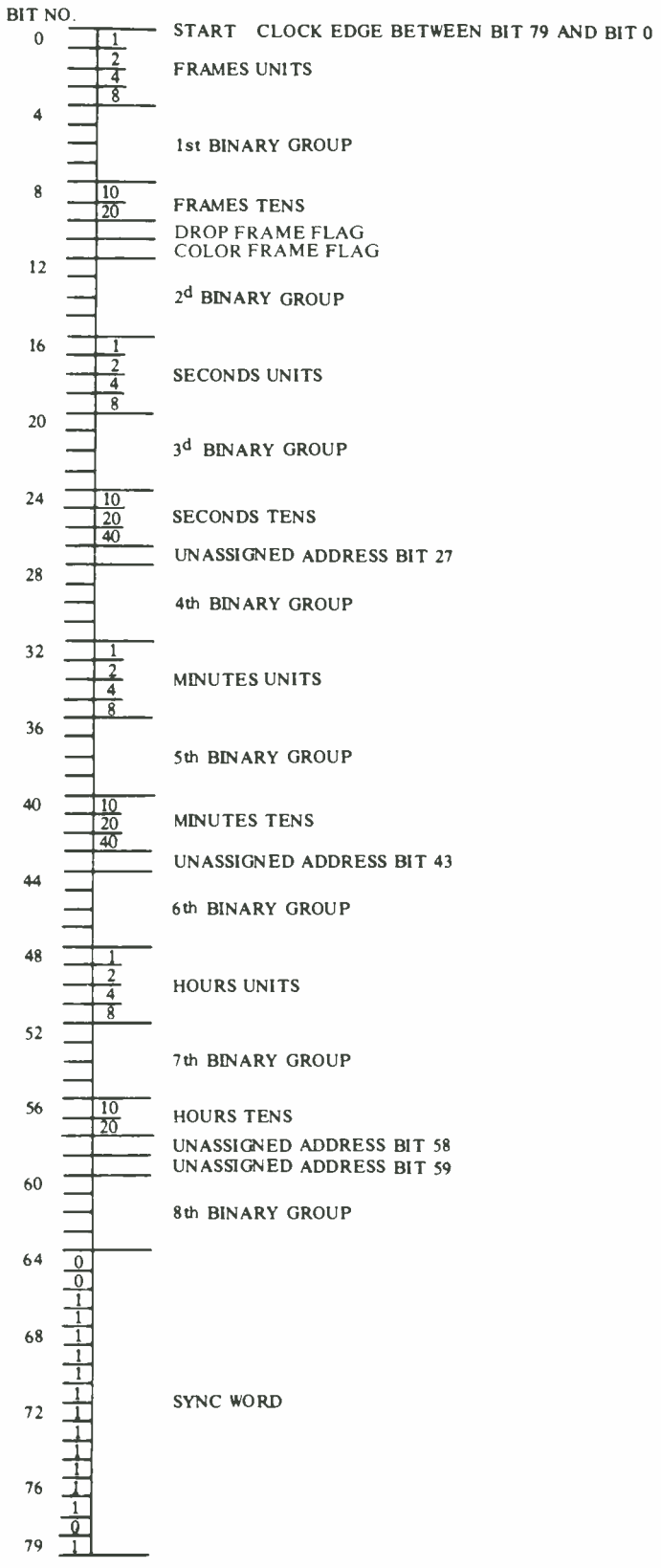


Fig. 18. Partial reproduction of ANSI Standard.

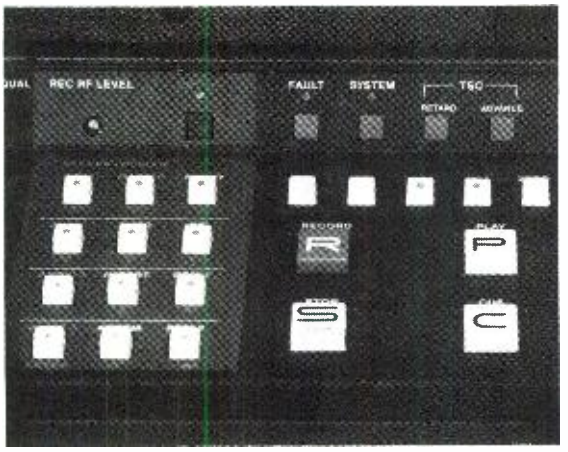


Fig. 19. Editor section of VPR-80 control panel.

During the evolution of helical recorder there have been dozens of formats, some intended for home use and some for professional use. The first of them to gain reasonable acceptance were the IVC 1″ format exemplified by the model 960 and the Ampex models VR-1500 and VR-660. Sony corporation as well as a number of other manufacturers produced a number of formats too numerous to mention here. It was with the U-Matic format that Sony found the magic formula, and this format is still in wide use today.

It is unfortunate that a major split came when a recorder was designed for the home market. Today we have both the Beta and the VHS formats, and the unsophisticated user is subjected to a number of conflicting claims through advertising. Both formats have been adapted for professional use, and at this point it is not clear which, if any, will be successful in this role. Many of these Beta and VHS machines are in use in the professional world for off-line use in reviewing material to be edited or for having a quick-look at dailies or programs being offered for sale.

At this time 8mm and 1/4″ formats are on the horizon as possible replacements for the Beta and VHS formats for both home and professional use, but it is too early at this time to predict which, if any, will survive. Digital and possibly component recording are on the horizon, and it is certain that digital recording will be a reality soon, but at this writing it is impossible to make predictions about what the format will be.

MAGNETIC DISC RECORDERS

Historical

There were a number of experiments with the use of discs for the recording of TV frames, particularly in West Germany, in the early sixties, but the first two practical uses did not occur until much later. Memorex developed an editing system, the CMX-600, in 1970 that used computer disc drives and packs to store monochrome television signals in short segments. The result was an editing system that resembled film editing. Unfortunately, as good as it was, it was ahead of its time. Analog recording was used, and the resolution of the reproduced signal was poor and was monochrome. It also was not very cost effective since a number of relatively expensive disc drives was used, thus making the system very expensive.

Ampex used two hard discs with four flying heads that could be moved radially in and out on the discs at variable rates to achieve the first practical slow motion recorder. This was the HS-100 Instant Replay recorder that revolutionized the telecasting of sports. It also was an analog device but was able to reproduce color directly by dint of violating the rules of the computer world where heads were flown over hard discs at an altitude of about 50 microinches and flying the HS-100 heads at about 12 microinches. The low altitude made the system very susceptible to dirt and contamination, and the units were touchy and difficult to maintain. They quickly became indispensible to the broadcaster, however, so their crankiness was tolerated. About 30 seconds of action could be recorded on the four disc sides.

Today, discs are widely used for the storage of still images and are known generically as Still Stores. Several manufacturers supply such units, and Fig. 20 illustrates one of the models available. Conceived of originally as a simple store for still images and a slide replacement system, it soon became obvious that they could be used as a creative production tool as well. The units offered today allow the creation of montages from images stored on the discs, and at least one has built-in titling capability as well.

Fig. 20. ESS 3 Electronic Still Store.

5.6

Radio Studio Audio

Walt Lowery
Director of Engineering
David Green Broadcast Consultants Corp.
BWI Airport, Maryland

In spite of what sales managers and others may say, the hub of activity in any radio station is the studio or studio-control room. The quality of the station's sound, its only product, is determined largely by what is going on in the studio. Even the best air talent, when burdened with inadequate equipment, will produce only marginal results. The point is that the right equipment, properly configured in the studio, translates to AQH numbers and rate cards.

TYPICAL STUDIO LAYOUTS

No two studios are exactly alike. Each design is affected by such factors as programming needs, available space and the ideas of the current and previous engineers, not necessarily in that order. Some stations, particularly older ones and those in very active markets, have gone through many changes as formats, managers, engineers and equipment have changed. The variety of equipment available and the number of ways all this equipment may be connected means that the number of studio designs is, if not infinite, certainly very large.

It is, nonetheless, possible to catalog most radio studios under one of a few general categories, depending on whether the emphasis is on music and other pre-recorded program material or on live material such as news, sports and telephone call-in.

The music-talk format is probably the most common, particularly in smaller stations. The basic setup includes an audio console, two turntables, and two or three cartridge machines arranged on a "U-shaped" desk. Assorted other equipment might include patching and transmitter monitoring and control, telephones and so on. This is in response to the programming needs which are fairly simple. The combo announcer-engineer on duty plays records, talks and reads announcements, plays commercials on carts, and switches in hourly the satellite news feed. Announcements prerecorded by the station may be produced in this same studio after signoff or in a second studio.

A variation on this theme is found in more competitive markets where records are transferred to cartridge before being aired. A separate studio is usually used for this as well as for production of spots. In this case, the air studio may have four, five or more playback cartridge machines and no turntables. The production studio has the turntables and record-playback cartridge machines, its own mixer console and an assortment of equipment to alter the characteristics of the recorded sound during transfer: multi-band frequency response adjustment, reverbation and so on. The production studio is also usually arranged so it can go on the air as a backup.

In a station where live or fairly immediate materials, such as news, sports and call-in, are a major part of the programming schedule, the sys-

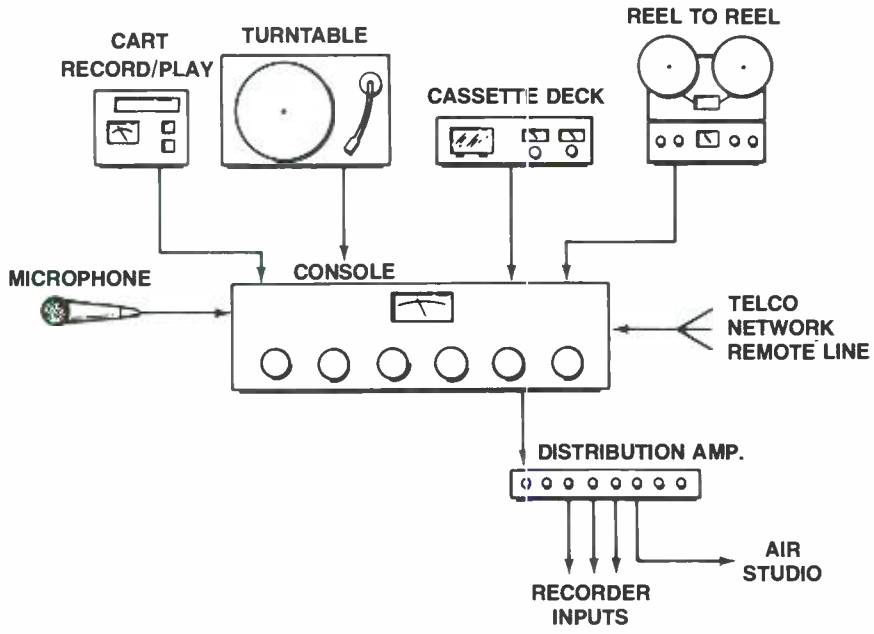


Fig. 1. Typical small production/news studio.

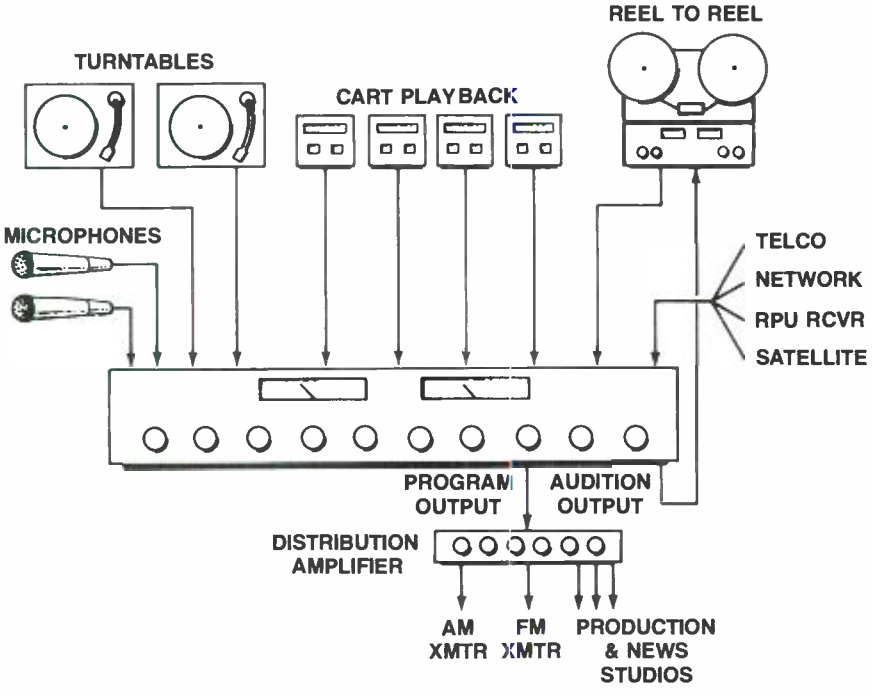


Fig. 2. Typical on-air studio.

tem must support some combination of live studio announcements, prerecorded announcements, various types of local, and network feeds. It may be necessary at times to operate with separate announcers and engineers due to the tight timing and fast switching between numerous sources. Here the studio must be arranged to accommodate several people at the same time. Alternatively, the studio and control room are separated, and there may be several studios and announcement booths controlled from one control room. Here, the control room can serve as a master control for announcement booths with small mixers and, perhaps, a playback cartridge machine. All these variations impose different requirements on the audio console and its internal and external switching and patching capabilities.

THE AUDIO CONSOLE

Centered in the control room, just in front of a "disc jockey" and the corresponding worn spot in the carpet, will be the audio console. This can be anything from a pristine BMX to a twenty year old RCA, but there will be at least one, of some nature, in every station. The smaller four to six mixer consoles are typically found in news rooms and production studios and on the air in smaller stations. The number of available mixing channels limits the number of audio events which can occur simultaneously or in rapid succession, and this can be a problem when a small unit is used as the main air console to save money. Also, many of the smaller units will not have an audition buss, the lack of which can severely limit versatility. One important feature to look for in a console of this size is a greater number of switchable inputs for each mixer; otherwise, the money saved in buying a small console will be spent on the patch panels necessary to get all of the inputs to the mixers.

As part of the planning process for building a new facility, buying a new console or just moving things around, it would be advisable to list all possible sources and assign some sort of priority depending on how often or how quickly they would have to be accessible to the console operator. This rating would help evaluate the number of mixing channels and switched inputs the console should have and what should be on a control room patch panel or master control patch panel or routing switcher.

The console found in most stations has eight to ten mixers. These will generally be of the rotary type, but slide attenuators are rapidly gaining popularity. For heavy on-air use, step attenuators are generally preferred as they require only occasional cleaning to maintain silent operation. Attenuators which depend on a contact sliding over the resistive element (usually carbon) are subject to wear and a build-up of dirt. Wear changes the element's resistance and the build-up of dirt (including the worn-off carbon) will cause erratic changes in the contact between slider and element. The results are uneven operation and noise. In step attenuators, attenuation is by a series of fixed resistors permanently wired to metal contacts over which a slider moves. The steps are in small increments and the slider makes the next contact before it breaks the last contact, resulting in smooth, quiet, and stable operation.

The trade-offs are generally in initial cost, size and maintenance. The continuous carbon potentiometer is typically less expensive, smaller, and requires more frequent cleaning and replacement. On the other hand, a good quality unit, not the

	Direct	Switched	Patched
Microphones			
Control Room			
Studio A			
Studio B			
News booth			
Other & Spare			
Total			
Recorded Program			
Turntable			
Compact Disc			
Cartridge Player			
Cassette Player			
Reel-to-Reel			
Automation			
Other & Spare			
Total			
Live Sources			
News Wire			
Satellite			
Telephone			
Telco Loop			
Production CR			
CB Monitor			
Studio			
RPU Receiver			
Other & Spare			
Total			
Special			
Filter			
Reverberation			
Oscillator			
Other & Spare			
Total			

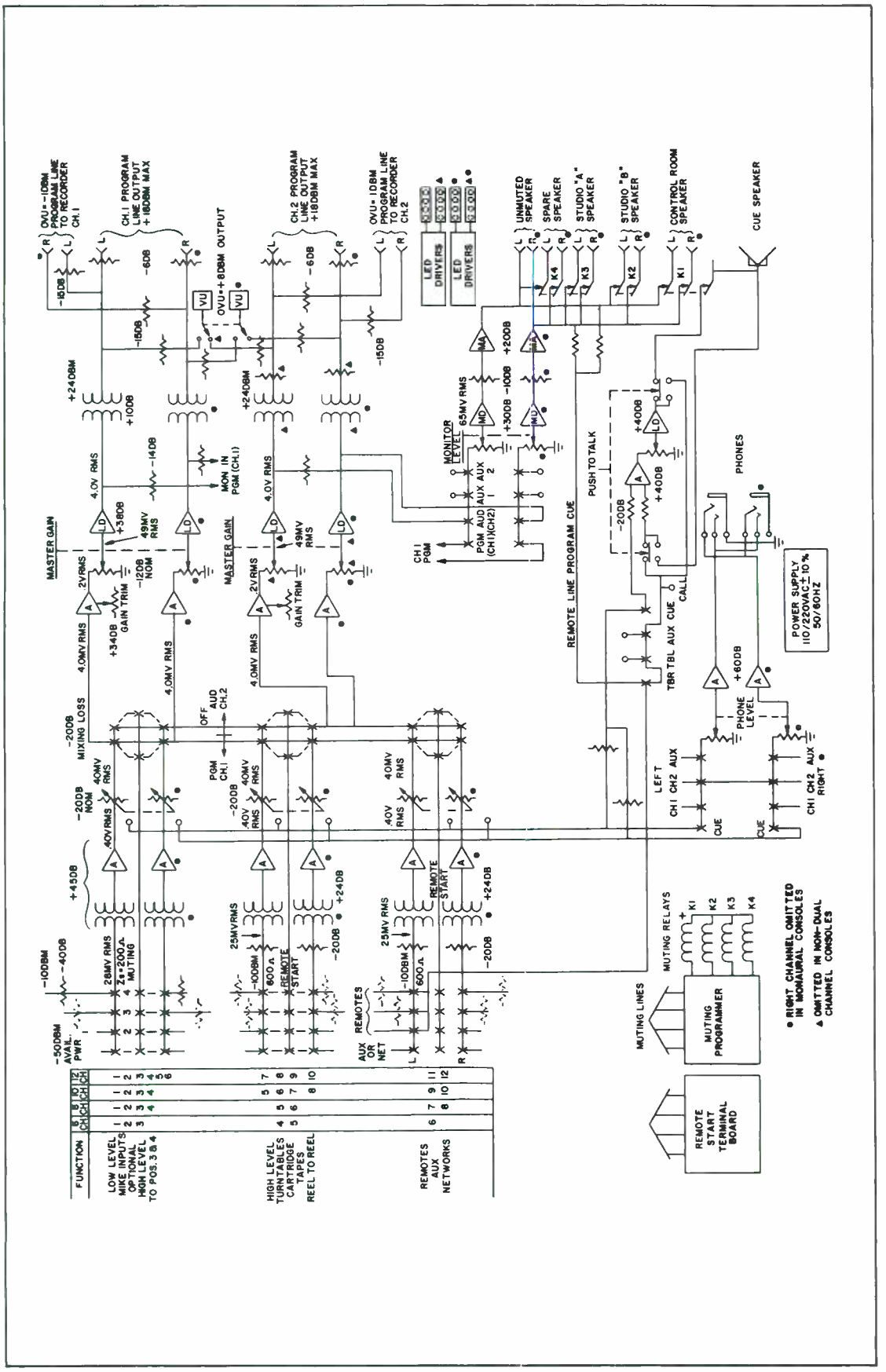


Fig. 3. Functional block diagram of AMPRO LC Series Console. (Courtesy of Television Technology Corp.)

"volume control replacement" type, can be expected to give reliable service for a long time. It is well-suited to small, portable remote units.

The step attenuator has a potential operational drawback when used by someone not trained in proper board operation. If the operator sets the level too high on either the master control or the output of some source such as a cart player, the mixer will bring the source up in only a few steps. When used this way, the jump in level between steps becomes noticeable and riding gain is difficult.

A relatively recent alternative is the use of voltage controlled amplifiers (VCAs). With this system, the audio signal does not pass through thetiometer but, rather, through the VCA. The gain of the VCA is, in turn, controlled by a voltage which is adjusted by the potentiometer. The audio is isolated from potentiometer noise. In the worst case, level control may become erratic, but listeners will not be subjected to scratchy audio. As with any amplifier, however, the VCA will introduce some thermal noise and distortion into the signal; how much is often a function of price. A quality console should have an overall distortion figure of 0.05% or less.

Fig. 4. Microtrak 6510 Console.

For most air work, an audition or cue channel is necessary to allow the operator to cue music, set up remotes, or listen for cues from network feeds. Even if the station has it's music library on cart, a cue circuit is an absolute must for previewing program material for use on the air and receiving cue signals from the news network and programs off "The Bird".

In an air studio the announcer's microphone is generally put on mixer number one. The turntables would be on mixers two and three. Cart playback would fall on four, five, six and seven. Eight, nine and ten would be assigned to reel to reel playback and the variety of remote feeds that the station would have, EBS, news network, remote line, etc. Autogram, Broadcast Electronics, LPB, Howe Audio and several other manufacturers have good medium size audio consoles.

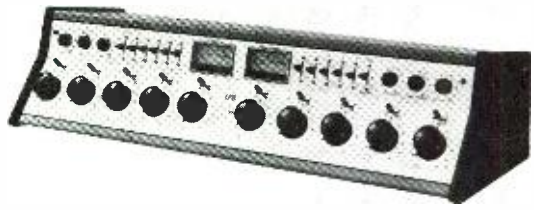


Fig. 5. LPB S-20 Console.

Console Features and Options

In medium and large market stations the consoles are generally ten channels or more and mostly the slider attenuator type. These larger units give the operator the luxury of not having to do any switching, as each audio source is assigned it's own mixer. They will also have a larger number of options available which make them more "user friendly" and at the same time "idiot proof". Clocks and timers are available on most consoles in this class, and are even standard equipment on some models such as the Radio Systems ESA 10. Monitor amplifiers in these are mostly of higher power than in the smaller consoles. Some manufacturers, as Howe in their 7500 series, treat the monitor amplifiers as an option. They assume that the station might want to use more than the eight watts found in some consoles to drive their JBL 4411's and opt for a Crown or other more powerful amplifier mounted in the equipment rack. One feature which should be added is a mono/stereo switch on the monitor amplifier to allow the operator to check for out-of-phase program material. This is easily added by the engineer with a switch at the monitor gain control.

A well designed console will have interchangeable input cards so that input sources can be moved to different mixers or changed later to allow for modifications in the studio or format changes. Remote starts for cart machines and turntables is a fact of life on the top-of-the-line models. This allows the operator to start the equipment by turning on the appropriate channel on the console and in some cases the equipment can be stopped when the channel is turned off, allowing for almost automatic operation using logic circuits. One important feature to look for with remote starts is switching of the start function with the switching of the input selector. This eliminates the annoyance of having a cart machine start everytime another piece of equipment wired to the same mixer is used.

The more expensive consoles offer a choice of standard analog VU meters or an LED "Light Show" in at least two colors which gives a more

accurate tracking of audio peaks. Some manufacturers claim that this latter type of meter reduces the number of times the operator runs the board with the meters "buried in the red" but there seems to be no solid support for this, at present. There are several models of LED VU meters available for retrofit into consoles which do not offer this as an option. Some models replace existing VU meters in the console and at least one model show peaks and RMS values on both left and right channels on the same display.

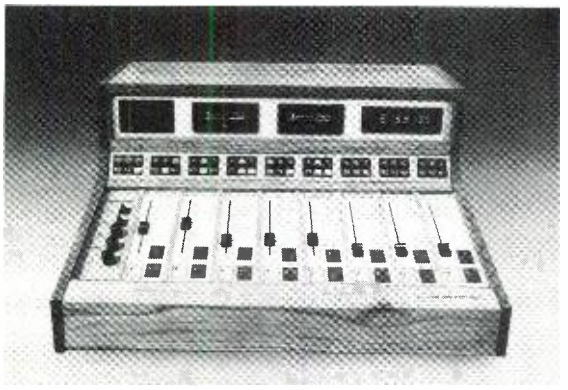


Fig. 6. Howe Audio Series 9000 Console.

Planning and Wiring

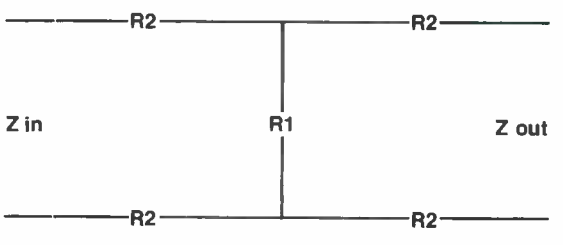
With the coming of multitrack recorders in broadcast production, there has come a need for consoles with more than single left and right outputs. Those consoles in the medium and large class can provide four output channels using the Program and Audition outputs to feed the inputs of a four track recorder. For eight tracks or more, some patching will be necessary or the station will have to consider a recording studio type console. This will give the necessary outputs, individual equalization on each channel, pan pots and a ration of other features for added versatility. There is, however, generally a trade-off on other features as the console was not designed for radio station use; and the cost is very much higher.

Before the new console arrives, the planning for its wiring should have been completed. This is something that cannot be trusted to trial and error because one the wiring is in place and the studio is being used those corrections that will be made "later" never seem to get done until a serious problem arises. The first step is to determine which audio source will be assigned to the various mixer inputs and the wiring for the patch panel and console documented so that trouble shooting and changes made later will be easier. In most cases it is best to run all the wiring, except the microphone inputs, through a patch panel to increase the versatility of the system. This is particularly important in the case of smaller consoles and in production studios to allow equipment to be brought in for special effects and emergency situations. Always bring the output of the production studio console up on the patch panel in the air studio so in case of the failure of the main console the production console can be patched into the audio chain and the station can go on the air from the production room.

Part of the planning for a new console is determining that the levels from all of the audio sources are compatible with the input levels required by the console. If this is not done the operating positions of the mixers will be inconsistent, making it difficult for the operator to run the board properly. In extreme cases you may not be able to open the pot more than a small fraction of a turn before driving the meters to the pin, or you may not be able to get enough gain from the channel even with the control fully open. Neither situation is acceptable and in most cases results in poor signal to noise figures. All studio sources should be set to their normal output operating levels, and H pads should be installed as needed between the source and the console input. In many cases these can be mounted inside the equipment. Pads of 10 dB or greater value are also useful in correcting impedance mismatches. The accompanying chart gives resistor values for 600 ohm H pads.

Patch panels, or jack fields, come in two basic types. The tip and sleeve which consists of one conductor and one shield, and the tip, ring and

Loss (In DB)	R1 (Ohms)	R2 (Ohms)
3	1.8K	51
6	820	100
10	430	160
15	220	200
20	120	240
30	39	270
40	12	300



H-PAD

Z in = Z out = 600 Ohms

Fig. 7. Typical H Pad values.

sleeve type which consists of two conductors and a shield. The tip and sleeve dates back to the days of the first jack field and is mostly obsolete. With this system it would be necessary to use four individual cords to patch one piece of stereo equipment. The most practical system is the tip, ring and sleeve jack which allows stereo connections to be made with one double plug cable, mono systems would use a single plug cord. The engineer has the choice of wiring the jack field and its terminal block or buying one that has been prewired, easily saving about two day's work and a soldering iron tip. The prewired patch panels are available with several types of terminal blocks, the old "Christmas Tree" solder terminals, wire wraps, telco punch blocks and a new split cylinder terminal developed by ADC that operated on a punch-down principle. This split cylinder design was developed for broadcasters and the voltage levels found in audio systems rather than for the 48 volts that the #66 telco blocks were designed to carry.

Another option available with prewired patch panels is that of having the "normals" brought out to the terminal. Normals are jumpers which connect the circuit of the upper jack to the one below it in the jack field when no cords are plugged into either of the jacks. This jumper circuit is broken and the audio transferrred to the patch cord when it is plugged into a jack. In a typical application the console output is wired to the upper jack and the input of the next piece of equipment, usually a limiter, is wired to the jack below. With no patch cord plugged in, the audio from the console is normally connected to the input of the limiter; thus the term "normals". However, sometimes this feature is not wanted, and having the normal jumpers at the terminal block makes it easy to change.

Stealing a little of the patch panel's thunder is the audio routing switcher. This unit replaces the jack field in that it accomplishes the same function, except with a routing switcher the audio is moved around by a series of mechanical or solid-state switches rather than by cords and jacks. The system is useful because it eliminates looking for patch cords in an emergency and with some units audio can be routed to more than one feed at a time. These are, however, active devices subject to component failures and they do add an amount of noise and distortion to the audio chain. The main reason why patch panels will be around for some time to come is economics; some routing switchers cost ten times as much as a prewired patch panel.

TURNTABLES

The most often used audio source in a radio station is the turntable. Until recently, at least, the most common broadcast turntable has been the idler drive type which uses a motor that turns at 1800 RPM driving an idler wheel which then drives the platter. There are two variations of this system. With the rim drive turntables the idler wheel runs against the outer rim of the platter. These are cheaper to manufacture as a smaller motor can be used to drive the heavy platter. In the better system, the idler wheel drives a hub near the center of the platter. This design minimizes wow and flutter caused by fluctuations in the motor speed. Also, vibration generated by the motor is not transmitted across the entire width of the platter as would be the case if it were driven from the rim. This type of drive system requires a large, powerful motor for the rapid starts necessary in broadcast operation.

The idler wheel type of turntables require periodic adjustment to insure that the idler is positioned properly with respect to the multi-diameter motor shaft. The idler wheel hardens with age and if left engaged while the motor is stopped, will develop flat spots. If either condition exists the turntable will be noisy and the idler will have to be replaced.

Finding increasing use in the broadcast station is the direct drive type of consumer turntable, in which the platter is the rotor of the motor. These turntables all but eliminate wow and flutter and make speed control more accurate. Their speed control circuits constantly monitor speed and make adjustments, keeping it more accurate than if it were left to depend on line voltage and frequency. This makes the practice of "speed enhancing" a science by giving the operator the ability to dial up an exact speed. By eliminating the idler wheel there are no adjustments to make and maintenance is eliminated. Repairs are much more difficult because of the complex circuitry in these models, and with some models, no schematics or service information is supplied to the purchaser. Remote starts are also difficult with some models and require additional outboard circuits to accomplish this function. The situation may change, however, as at least one manufacturer is building a direct drive turntable for broadcasters.

Interfacing directly with the turntable is the tone arm. There seem to be relatively few true broadcast tone arms as most are designed for consumer use. These arms track quite well and are easily adjusted but are not designed for the constant use that they receive in a broadcast studio. The easy adjustments are often misadjusted by well-meaning operators, especially on weekends. The ideal broadcast arm is set up once for its cartridge and then left alone, unless someone steps on it. It has happened!

When installing a tone arm, use the template from the turntable manufacturer and follow the instructions supplied with the arm, otherwise the tracking error will be greater than optimum and even the best cartridge will not sound good. The manufacturer's recommended tracking weight for the cartridge and stylus being used should be strictly adhered to even though it may take some effort in getting the proper amount of weights in place. This job should not be rushed; a tone arm is a precision device.

The choice of a phone cartridge depends on the level of quality that you want to obtain. The less expensive models are generally rugged and give the greatest life in on-the-air use, but better separation and high frequency response is gained by moving up to more expensive, though generally less rugged, models. The majority of cartridges are designed for the consumer market and will not stand up to continuous use and back cueing that they will be subject to in a radio station. The stylus needs to be cleaned and inspected daily and replaced when it shows wear or if a defect is suspected. The engineering department needs a supply stashed away so regular replacement is not a problem.

The next element in the turntable "system" is the preamplifier. This item, like the tone arm, is often not given proper attention. It is easy to buy the cheapest one, since it will never be seen again once it is bolted into place and levels are set. The important specifications to look at are the noise and distortion figures. This task is not as easy as it sounds as the many manufacturers express these figures in as many ways. Noise will be referenced to different output levels and may be stated in decibels or RMS voltage.

The more expensive models offer features including filters for warp and resonance, high frequency cut and boost, and adjustable cartridge loading. These are nice to have, but should be kept out of reach of tinkering programmers. The best designed preamps put the RIAA equalization circuit in the second stage to eliminate non-linear loading of the cartridge by interaction with the filter components. The most important concern for the engineer is the preamp's resistance to RF. This is a high gain amplifier and one of the first places that RF interference will make itself known in a studio. Some units are designed to operate in an RF environment, others are not; take this into consideration when you buy. The general rule of thumb, you get what you pay for, applies to preamps. With it being the first, and sometimes the weakest link, in a station's audio chain this is not a place to economize. A poor preamp can kill a station's air sound, as the only thing that goes through a preamp is *all* of your music.

Although not a conventional turntable, the compact disc player is serving the same purpose in many radio stations. Its use began in classical music stations but spread to others as record companies issued a wider variety of titles on compact disc. The discs, themselves, are one-sided, 12 centimeters in diameter and will reproduce up to 75 minutes of program material.

Sound is encoded as digital "bits" which are recorded as minute, etched marks on the surface of the disc. These bits are read, in the player, by focusing a light beam, from a semiconductor laser, on the disc. There is no stylus contacting the disc as with conventional recordings so there is no wear. A transparent plastic coating protects the surface so that only the most severe accumulations of dirt or scratches will affect playback quality. In general, compact discs are much less susceptible to mistreatment than are conventional recordings.

In the recording process, audio is sampled at brief, regular intervals. An analog to digital converter measures the voltage at each sampling point on the waveform and generates a digital code representing that voltage. These codes are recorded; and, with appropriate digital equipment, may be used to mix and manipulate the sounds they represent as has been done with conventional analog recording.

In playback, the codes are used to drive a digital to analog converter which reconstructs the original audio waveform by generating a series of voltage steps. These steps are smoothed out by filtering.

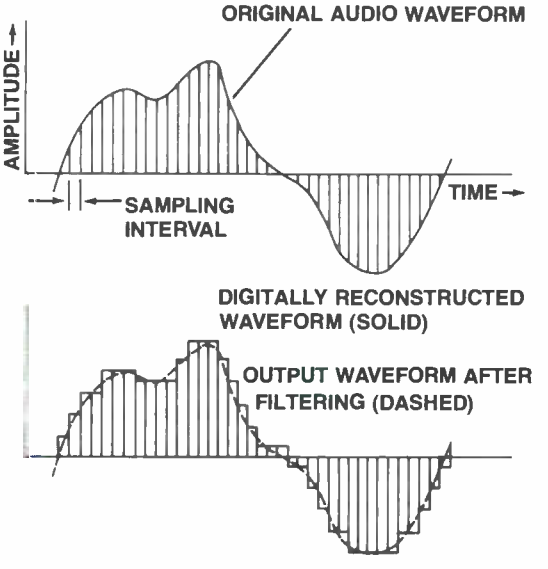


Fig. 8. Digital recording and reproduction of analog signal.

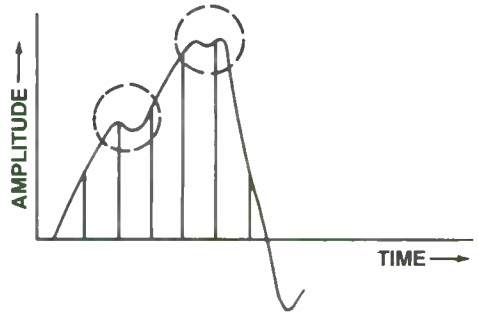


Fig. 9. Errors resulting from too low a sampling rate.

Although much of the noise and distortion of conventional tape and disc recording is eliminated by digital techniques, there two sources of errors which affect digital recordings. Both are related to the sampling rate, and in both cases, a higher sampling rate is preferable. Since the amount of information any disc (or tape) can hold is limited by the nature of the medium, the trade-off is between noise and recording time. As of this writing, most master recording is done with sampling rates in the range of 44 kHz to 50 kHz while playback discs use 44.1 kHz.

If the audio signal is changing very rapidly with regard to the sampling rate, it is possible for the sampling device to miss or inaccurately measure certain changes. The reconstructed waveform will reflect these inaccuracies. As an extreme example of inaccuracy, consider a 10 kHz frequency being sampled 10,000 times per second; the apparent result would be a continuous, dc voltage.

Upper harmonics may be missed or, in being reproduced inaccurately, they may appear in the output as new components not harmonically related to the original sound. This is called *aliasing*. To reduce this source of noise, sampling should be done at a rate at least twice the frequency of the highest harmonic to be reproduced accurately. In addition, a low-pass filter should cut off system input above the highest desired harmonic.

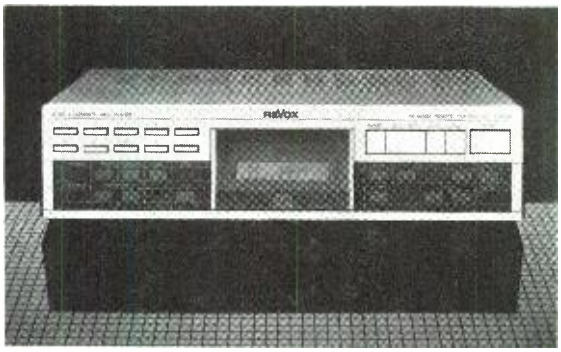


Fig. 10. REVOX B225 Compact Disc Player.

Quantizing error is another source of distortion, which also appears as noise in the output. The analog to digital converter samples voltages at discrete levels. If the waveform voltage at a given sampling point falls midway between two levels, it is uncertain which will be selected by the circuit. This means that, at any point in the reconstructed waveform, there is a possible error of one voltage step. The result is random distortion which may be masked by the introduction of a small amount of random noise.

MICROPHONES

The choice of a microphone for use in a broadcast studio is unfortunately often left to chance, and quite often in a smaller market station it turns out to be whatever is lying around. The choice is not always an easy task as there are a vast number from which to choose from many good manufacturers. For the radio studio we can disregard the lavalier types. This is also true of the wireless systems, except for use on remotes and events outside the station. Again, shotgun mikes are mainly the property of the news people and found on TV sets. This narrows the choice to the general purpose studio microphones of which there are several choices.

The dynamic microphone is the most common type found in use today. Its construction consists of a coil of wire attached to the diaphragm, which moves in the field of a permanent magnet as the sound waves strike the diaphragm. A voltage is generated as the coil is set in motion. This design lends itself to the construction of a very durable microphone which will tolerate an amount of physical and acoustic abuse, such as rock and roll disc jockeys. The quality of this and any other type of microphone depends on the finesse exercised by the manufacturer in its design and construction. The more intricate the design and construction, the wider and more linear the frequency response. In the case of directional microphones, this results in a more consistent pattern and smoother off-axis response.

At one time, having the very best studio microphone meant having a ribbon mike. The ribbon microphone is constructed using a very thin corrugated ribbon of foil positioned in the field of a large powerful magnet. A voltage is generated across the ribbon as it moved with the sound waves striking it. Since the ribbon was very thin and light, this type of microphone is very sensitive and picked up many of the subtle sounds missed by a dynamic mike. Unfortunately because of the delicate nature of the ribbon, this type of mike is easily damaged by shock or a blast of

air. Some models, such as the RCA 44BX and BK11, are rather large and heavy due to the size of the magnet required. With the improvements made in dynamic mikes and the introduction of condenser microphones, the ribbon mikes are waning in popularity.

Taking over from the ribbon microphones are the condenser mikes, originally made famous by Neumann. Their construction consists of two plates, one fixed and the other moveable, forming a variable capacitor. As sound strikes the moveable plate, the distance between them changes. Since the plates are charged from a power supply, or battery, the movement of the one plate causes a change in the capacitance between them and resulting in a current flow from one plate to another. This current flow results in a voltage being generated across a resistor positioned electrically between the plates. A variation on this involves the use of a permanent electric field device, an electret, to provide the field. This eliminates a power supply circuit.

In another variation, the plates are used as part of an 8 MHz oscillator which swings in frequency as sound waves vary the capacitance between the plates. This results in an FM signal which is then demodulated to produce an audio output. This is known as an RF condenser microphone. Both of these microphone systems are relatively expensive and are found more in recording studios rather than in radio station control rooms.

The dynamic microphones, as well as the other types, can be constructed to exhibit directional characteristics. This design is best for a radio studio as it eliminates unwanted noise from equipment or people other than the announcer that may be in the room. The "cardioid" pattern is the most common which results in a heart-shaped pickup pattern in front of the microphone. In a dynamic mike, this is usually done with an acoustical phase-shift network which feeds sound waves from the rear of the microphone to the back of the diaphragm out of phase with the same sound arriving at the front so that they cancel out. A ribbon mike, by its construction, is bidirectional, as sounds from the sides, striking the edge of the ribbon, are not picked up. It can be made unidirectional by blocking the path of sound to the rear of the ribbon. Condenser microphones can be made directional by using more than one element in the microphone case and electrically combining the outputs to cancel voltages generated by sounds from one side of the microphone.

One drawback to using a directional microphone is that the off-axis pickup is not linear over the audio spectrum and the user (speaker, singer) needs to be positioned in front of the microphone for the smoothest response. This is easy enough in a studio situation but with news interviews, passing a microphone back and forth, it is not so simple. Also, directional mikes will not pick up a lot of the background sounds desirable in doing news coverage. Omnidirectional types are best suited for remote news and sports, except when noisy crowds can keep the announcer from being heard, and in soundproof studios. Directional types also suffer from what is known as "proximity effect". The low frequency sensitivity increases as the sound source gets closer to the mike. Many announcers use this to make their voices sound deeper on the air by working the mike close. Most directional microphones have adjustable bass roll-off circuits to compensate for the boost in low frequency response.

If it has not been done in recent memory, microphone wiring should be checked to assure that all microphones and connectors are wired uniformly. Since microphones, cables, mixers and accessories are often acquired by a station at different times from different sources and repaired by different people, a systematic check of all connections is a good way to bring all equipment into conformity with some standard.

Microphone polarity is defined in the Electronic Industries Association (EIA) Standard RS-221-A in terms of the microphone having terminals connected so the voltage is "in-phase" or "out-of-phase" with the sound wave producing that voltage. There are devices available for testing microphone polarity by producing a sound pulse; however there is a practical method which also gives good results. It will not identify the phase relation between sound and electrical waves but will permit uniform phasing of connections.

When using two or more microphones in the same studio, care must be taken to have all mikes phased alike. To check this, open the mixer channel for the first mike and adjust the attenuator for the proper level when the microphone is spoken into. Move the second microphone next to the first and adjust its attenuator to a similar setting as the first. When speaking into both mikes the overall level on the VU meter should stay the same or rise slightly. If the level falls, the microphones are out of phase as their outputs are cancelling each other out. Reverse the leads on one of the mike connectors.

For microphones having connectors meeting EIA Standard RS-297, the connections are as follows:

Out-of-Phase Terminal	3
In-Phase Terminal	2
Ground	1

Other connectors should have the in-phase terminal marked with a red dot or stripe. Cable connections are red (or color other than black) for in-phase and black for out-of-phase.

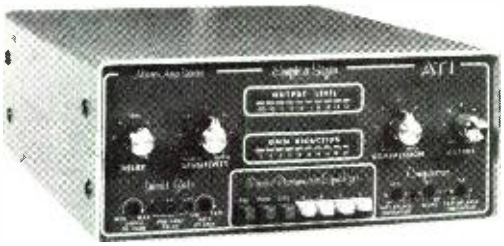


Fig. 11. The ATI Emph' a Sizer provides compression, equalization and gating for enhancing microphone performance.

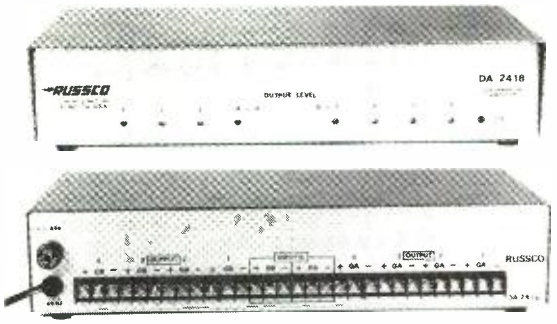


Fig. 12. RUSSCO DA 2418 Distribution Amplifier.

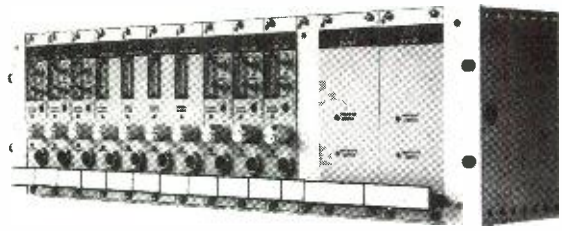


Fig. 13. ATI DA 10000 Distribution Amplifier.

Microphone Processing

The addition of compression and equalization to the announcer's mike can make his other voice more compatible with the processed program material played on the air. The result is a more consistent air sound when the transition from program material to live announcer is made. Some consoles offer this processing as a built-in option, others provide jumpers between mike preamps and the mixing buss of that external equipment can be easily wired into the circuit.

Many stations featuring morning teams on the air will "pan" each person's mike slightly to one channel augmenting the interchange between the two announcers with a slight stereo effect. This should be limited to about 3 decibels of shift or the artificial effect may be objectional to some listeners. *AM-FM Broadcasting* by Harold Ennes contains more information on microphone use and placement in studio situations and should be consulted for unusual situations.

STUDIO ODDS AND ENDS

The job of a distribution amplifier is to provide audio from a single source, such as a console output, to a number of inputs. This cuts down on time-consuming patching and switching in the production room. In the air studio it routes the console output into dual audio processing chains, one for AM and the second for FM in simulcast situations, and into recorders or monitors. The majority of the DA's in use are the straight forward type which are simply amplifiers with multiple outputs.

Output Choices

The main choice to be made is whether to have individual level controls for each output and the number of outputs. Several manufacturers have begun combining other features into the distribution amp which can cut down on the amount of equipment required in a studio. Options may include metering, compression, loss of signal alarms, and redundant power supplies. This system would find use in a large production facility in either radio or television stations.

Equalization

Equalizers are available in two basic types. The best known is the graphic in which the audio spectrum is divided into a series of bands represented by a group of slider controls on the front panel that the operator adjusts up or down to vary the level in that particular band. This is the easiest to use as the controls give a picture of the approximate frequency response that is being created. The parametric equalizer is more versatile in the hands of a trained operator. With a parametric equalizer a specific frequency can be dialed in and the amount of cut or boost can be set. The parametric also allows adjustment of the selectivity of the change being made. The operator can "notch out" a hum or buzz or give a gentle sloping boost to a band of frequencies to make them stand out. Equalizers can "brighten" a station's air sound and help in doing creative production.

Noise reduction systems can help reduce tape noise for stations having the majority of their pro-

gramming on tape. With the systems made by Dolby or DBX the audio is encoded, recorded on tape, and then decoded to reproduce the original audio with a lower level of noise than if the system had not been used. The companding type of noise reduction is also finding some use on auxiliary mediums such as on unprepared phone lines and SCA service. These systems cannot remove noise that already exists on the source material. There are other systems which attempt to reduce residual noise that exists on recorded material. These are basically gating devices which turn off all audio when it falls below a certain level. The better of these devices are frequency selective and target their action to the frequency range associated with most tape hiss. The theory of operation being that any audio below a fixed level must be noise and should be ignored. All of these noise reduction systems have some merit, but in professional broadcasting it might be more practical to spend the additional money on better equipment and tape that does not need help. These systems, for the most part, are designed more as consumer electronics.

AUDIO PRODUCTION

The most challenging use of equipment and talent in broadcasting is that of production. Whether it be a thirty second spot or a series of programs, it demands the most from the station's resources. On a small scale this may mean reading copy over a music background and getting both to end at the same time. One of the common problems is the agency tape which was produced on a machine aligned to no standard known to man. The simplest fix to this situation, other than calling the station engineer every time, is to extend the azimuth adjustment on the playback head out to a knob which can be tweaked by production people as necessary for the tape being used. With this adjustment in place all that is required is to "tune" in the playback alignment. Often tapes from outside the station will need "brightening up" with an equalizer in order to keep them consistent with the quality of the station's air sound. Those with hum or noise can be saved with a parametric equalizer being used as a notch filter tuned to the objectional noise.

The use of multitrack reel to reel recorders makes adding tags or reading copy into "doughnut" tapes a lot easier than the old method of using two recorders. The music bed or agency tape is put on one track and the copy is overdubbed or recorded on another track or tracks. If a mistake is made, the voice track is simply re-recorded until perfection is reached. To do this the machine will have to have the selective synchronization feature. This switches the record head to the playback amplifier on the tracks that contain the music bed, otherwise the bed and the voice track would be separated by the amount of distance between the play head and the record head on the recorder making this type of use impossible. When all tracks are successfully recorded the finished product of music bed, voice track, and sound effects is created by mixing all tracks together onto a cart or another reel to reel.

Most professional reel to reel recorders have a variable speed option which takes those 64 second spots and fits them into a 60 second space of air time. If only a few seconds of adjustment are required this will not cause any noticeable effect on the audio quality, but as more adjustment is required a device such as an Eventide Harmonizer will be necessary to restore the normal pitch to the audio. Eventide also provides a system that automatically adjusts the speed of the deck and adjusts the pitch of the audio the required amount.

A stereo effect can be created using a mono music bed and a stereo equalizer. The mono source is fed to both channels of the graphic equalizer and a boost on one band is set up opposite a cut on the opposite channel so that some frequencies are predominant on the right channel and others on the left.

Phasing or flanging is created by some of the new electronic devices on the market or can be done by playing back the same material on two reel to reel decks and varying the speed of one deck slightly by dragging your finger on the flange of the supply reel to slow it down and by giving the take-up reel a push to speed it up. The resulting phase differences will result in the spacey effect needed to accent production for special effects.

Reverb and echo effects are generated by electronic reverb units constructed with springs or large metal plates which are set into motion with the audio and the delayed vibrations picked up and mixed back into the audio at the required level. For adding reverb to program material the amount mixed back in should be about twenty decibels down from the normal program level or

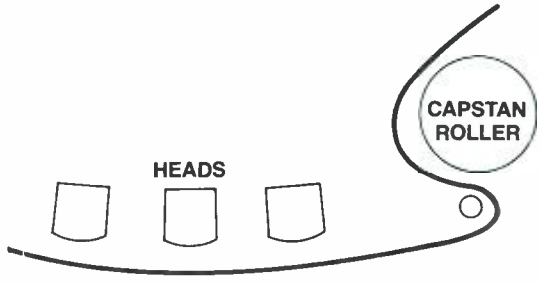


Fig. 14. Reverse tape path on an open reel recorder.

the effect will be distracting. If a compressor or limiter is used, the reverb should be mixed back in after the output of the limiter. This procedure will prevent the percentage of reverb in the program chain from varying with the operation of the limiter. Echo effects can also be added in production with a reel to reel recorder by simply opening the playback pot on the console slightly as a recording is being made. Reel to reel decks can be made to play backwards to create reverse echo and other special effects by simply threading the tape backwards around the capstan roller.

A good sound effects library is a definite asset to a production studio and there are several complete libraries on the market. Often an effect is necessary that has not been recorded, this is when the creative production man stands out in being able to create what he needs. How do you create a "Star Wars" light saber? By waving a handheld bulk tape eraser in front of a Sennheiser MD 421, of course! But don't let the station engineer catch you doing this! The list of production tricks goes on and they were created by someone such as Jack Elliot in Los Angeles or Jim Stanley in Virginia Beach, who are interested in doing a better than average job in creating a spot. There is additional incentive in doing good production in that a good production man is worth money to station management. He can be the reason why advertisers buy the station, to get his services. Many people specializing in this field have gone on to opening their own studios selling their services to advertisers and radio stations.

REFERENCES

1. Ennes, Harold E.: *AM-FM Broadcasting*, Howard W. Sams & Co., Inc., New York 1974.
2. Runstein, Robert E.: *Modern Recording Techniques*, Howard W. Sams & Co., Inc., New York 1974.
3. Studer Revox America Inc., "B225 Compact Disc Player", 1984.
4. Sennheiser Electronic Corp., *Revue 11*, 1981.

5.7

Magnetic Recording Media

Part I: Care and Handling of Magnetic Tape

Part II: Principles and Current State of the Art

Part I: Care and Handling of Magnetic Tape

Norman C. Ritter
3M Company
Minneapolis, Minnesota

INTRODUCTION

Magnetic tape recording plays an important role in many information storage applications. Those people involved with the recording and storage of this type material should be aware of the conditions and procedures that will help ensure the best overall results. The purpose of this section is to give some of the guidelines to achieve good tape life and tape performance. Although this information is aimed at the video tape recording field, it is basically applicable to other magnetic recording areas.

BASIC INFORMATION

Magnetic recording has proven to be a very viable, versatile, and reliable form of storing information. The electromagnetic media used in recording tapes are capable of retaining the signal for indefinite periods of time. The recorded signals will remain virtually unchanged for decades unless they are intentionally erased. Those problems that have been encountered with magnetic recording are mostly physical in nature, due to improper handling or storage conditions. These problems can be caused by malfunction of machines, improper operator care, or poor environment in either the operations area or storage area.

The following information is intended to help in achieving optimum tape performances by hitting upon certain key points with as little rhetoric as possible to simplify the reader's future reference to parts of this chapter.

The Recording and Operations Area Environment

Foreign debris from the environment is one of the reasons for the cause of dropouts, scratches, machine parts wear, head life, and tape life. This warrants important consideration today, and is becoming more important as the recording density on tape increases.

1. The area in which tapes and machines are used should approach "clean room" conditions, such as those found in main frame computer tape installations. This degree of air filtration, though ideal, is not realistically achievable in many video tape operations. It is recommended that at a minimum the filtration used must at least meet the efficiency rating of 90 percent based on the National Bureau of Standards Dust Spot Efficiency Test—Atmospheric Dust. Qualified air conditioning and air filtration firms are aware of the requirements to satisfy this need. The airflow system should be designed to maintain a positive pressure in the recording area.

This prevents dust particles from floating into the room from other locations. In addition the duct work sizes and placement, leading to this area, should allow the necessary amount of air flow to maintain the proper temperature and humidity control, without having air velocities at a level high enough to blow settled dust and debris around the room.

2. The temperature should be controlled at approximately 70 °F plus or minus 5%, and the relative humidity at 50% plus or minus 20%. Without this control the risk of head clogging, stiction, and higher headwear are increased. The old cliche is still true "what is comfortable for humans is a good environment for the tape."
3. To avoid inadvertent contamination of both the tapes and machines, smoking, eating, and drinking should be restricted to certain areas and preferrably out of the recording locations.
4. Special attention must be given to the floors in or near the recording area, as they are a source of debris due to pedestrian traffic. Cement flooring must be sealed and tile floors should not be waxed. Both should be mopped clean on a routine basis. The use of indoor-outdoor type carpeting that contains antistatic material is acceptable and may be most desirable, depending on the needs of an operation. The carpeting helps reduce room noise from equipment, and affords an atmosphere conducive to good operator practices. The use of industrial vacuum cleaners is recommended on carpeting or floors, and it should be done on a regular basis. The exhaust from these units should be located outside the recording area.
5. To aid in the reduction of debris due to pedestrian traffic, the recording area should be located such that it is not a normal passageway to other parts of the operation. This not only improves the cleanliness of the area but avoids continual distraction of the tape machine operator's function.
6. During times of construction in any area of the facility, the frequency of cleaning should be increased substantially. The area under construction should be sealed off with plastic sheeting as best as possible. Surprising as it may seem, cement dust can get through filters that water will not.
7. The tops of equipment and other exposed surfaces should be cleaned on a periodic basis to maintain the integrity of the operations area. This procedure will also give clues as to how clean the envrionment is in the area. The more dust and debris found during this routine is an indication of the amount of dust and debris that has found its way onto the tapes and into the recording equipment.

Operating Practice Recommendations

The video tape operations in a facility are usually involved with more than one type of tape machine; namely reel to reel type and cassette type.

The differences from a tape life or reliability point of view are only the questions of who or what is handling the tape during thread up, how exposed is the tape when on or off the machine, and the tape path conditions. The cassette approach virtually eliminates the human handling of the tape, and reduces the exposure to atmospheric contamination; however, the mechanical threading mechanisms require attention as well as the condition of the tape path. The recommended environmental conditions apply to both type systems. Before proceeding, the next comments may help put things in a better perspective.

People involved in any video tape recording operation, at some point, may ask whether all the emphasis put on cleaning, handling, and environmental control really accomplishes anything; that is, in other terms, "familiarity breeds contempt." Fig. 1 gives a good picture of the relative sizes of what is being dealt with. Not only is this debris capable of causing large drop-outs in the area they are located on the tape; but some of these particles, when wound into a tape pack, may cause impressions into adjacent layers which in turn will result in additional drop-out activity.

Wallace's law on signal loss due to head to tape spacing theoretically indicates that compacted debris contained in a one pint jar, if equally distributed, would be sufficient to put every video tape ever produced out of manufacturers' drop-out specifications.

Good housekeeping and operation practices are very important to a successful video tape operation.

Following are some of the operational recommendations that apply to the handling of reel to reel and cassette type video tape recording formats.

1. The components in a video tape machine that contact either the front or back side of a tape, should be cleaned before each tape is threaded to make a recording or playback. The recommended cleaning fluids are Freon TF (a DuPont trademark), Genesolve D (an Allied Chemical Trademark), isopropol alcohol, or other cleaners recommended by

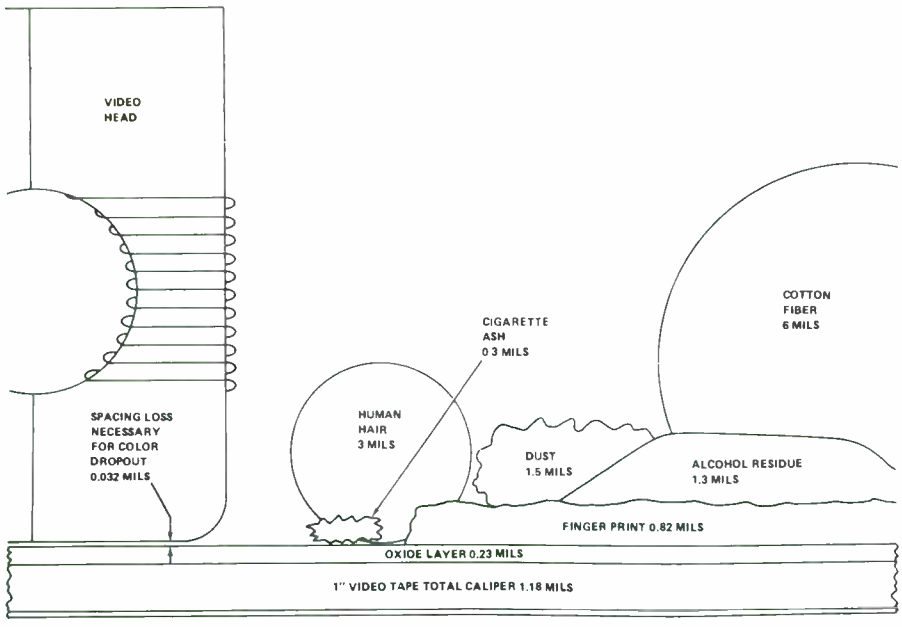


Fig. 1. Debris perspective on 1" video tape.

the machine manufacturer. The cleaning should be accomplished by applying the liquid to a lint free cloth, such as Texwipe (trademark), and gently rubbing the tape path surfaces with the dampened material. During this procedure extreme care should be exercised in cleaning the video heads. They can be easily broken or damaged with excessive pressure, particularly in the case where ferrite materials are used. Ferrite is the head material used in most all current day helical machines and in many rebuilt quadruplex heads. Since the video heads will not withstand a strong scrubbing action, compared to the other transport areas during cleaning, the stronger solvents such as isopropol alcohol, or machine manufacturers recommended solvents (usually Xylene type), are the best choices for removing debris build up on the video heads. They tend to help soften material buildup in addition to acting as a wash.

2. The cleaning of the capstan and the capstan pinch roller are especially important for two reasons. Any dirt or debris build up on these areas will cause impressions in the tape on each revolution that can cause drop-outs through a long period into the roll. Also the accumulation of material in this area may reduce the frictional pressures on the tape which are needed to maintain proper linear tape speed control. One word of caution: the material used in the pinch roller can be adversely effected by some cleaning solutions. The machine manufacturers recommendations should be followed for cleaning the pinch roller.

3. Cleaners, other than Freon TF or Genesolve D are relatively slow in evaporating, so give ample time for the transport to dry before threading the tape. This usually means about 30 seconds.

4. The video drum (scanner assembly) on helical machines have tape edge guiding surfaces that may accumulate debris. These surfaces need extra cleaning attention to ensure smooth tape handling and good interchange with other recordings.

5. The tape reel is specially designed for transporting magnetic tape. The reel should always be handled by the hub, which is the strongest portion of the reel. (See Fig. 2.) The reel flanges are designed to protect the tape edges, not to guide the tape. A reel should never be carried by the flanges. Handling the tape by the reel flanges or dropping an unprotected reel can bend the flanges. If the tape is rubbing against the flange of the reel, either the reel flanges are bent, or the reel pedestal or guides require adjustment. Avoid squeezing the flanges of a reel when putting on or taking off the transport.

6. The take-up reels should be cleaned at the start of each day. The tape winding surface of the hub and the inside surfaces of the

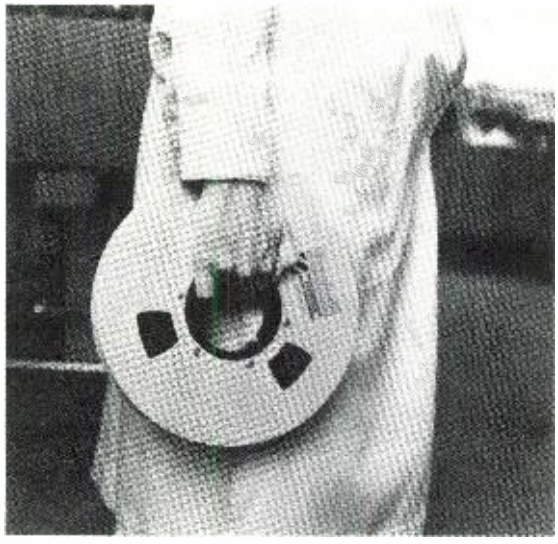


Fig. 2. Proper handling of a video tape reel.

flanges are the main areas of the reel needing this attention.

7. The sudden stoppage of a spinning reel of tape should be avoided in order to prevent the possibility of interlayer slippage that results in cinching or windowing of the tape. See Fig. 3. Newer machines have built in control that slows the spinning tape motion before stopping or reversing wind modes. Machines without this feature require the operator to slow the winding action down before stopping or changing wind directions. The break tension adjustments on the machine should also be checked according to the machine manufacturers operating manual to minimize problems of this type.
8. The condition of the pinch roller and its engagement with the capstan are very important in preventing creasing or edge damage to tapes. After much usage the pinch roller may become barrel-shaped, non uniform, hardened, or misaligned with the capstan. A straight-edge applied against the pinch roller, along with proper lighting, is one method of determining the flatness of its surface. One alignment check, proven to be helpful, is watching the vertical direction the tape travels when the pinch roller engages with the capstan. During repeated stops and starts, as the pinch roller is engaged, the tape should not show any signs of edge buckling on adjacent guides, if these parts are properly functioning.
9. The wear on capstans, pinch rollers, audio stacks, erase stacks, fixed guides (either front or backside), roller guides that don't turn, and fixed drum assemblies are key elements of the helical transport to consider if stiction or runability problems occur during editing or other modes of operation. As the stationary components wear, the land area the tape passes over increases. This increased surface area and a worn polished drum all create additional drag on the tape movement through the transport. How often these parts need to be replaced will vary with the type of video tape operation, but for machines dedicated to heavy editing service, based on field input, these fixed parts will require replacement more often. As a guide, they should be considered for replacement after approximately 1500 hours of use. An exception is the pinch roller which may require replacement on a more frequent basis.
10. The measurement and adjustment of the capstan pinch roller pressure against the capstan should be done after the machine has been running for approximately one hour.
11. The tape should not be touched or handled except at the ends, which is necessary for thread up on reel to reel machines.
12. The tapes and cassettes should be kept in their containers when not being used.
13. The cardboard debris from ripping open the master shipping cartons is a common source of debris. This unpacking should be done outside the operations area.
14. The outer wrap of reel to reel tape, when not being used, should be taped down with hold down tab material designed for this use. Proper hold down tab material will not leave adhesive residue on the tape after removal.
15. When threading the reel to reel machines, do not let the end of the tape touch the floor or table tops. This helps avoid pick up of dust and debris. Also any wrinkled or

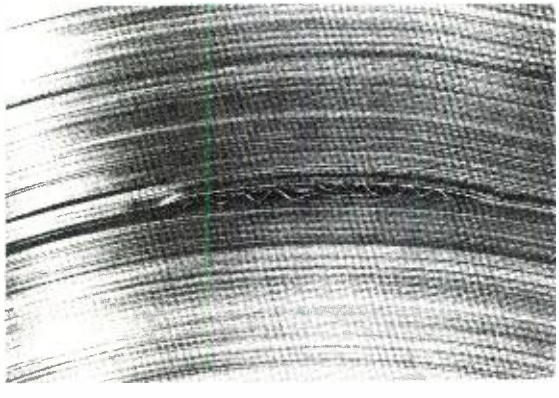


Fig. 3. Cinched tape. Note the complete fold over of one tape strand within the corrugated area.

creased ends of the tape should be cut off. Do not fold the tape on the take up reel when threading.

16. The tape edge guiding surfaces in the transport should be periodically inspected for wear. If grooves are visibly noticeable, the guides should be replaced.
17. The tension gauges used for making machine tension adjustments must be checked for proper calibration. The calibration check should be done with the same piece of tape that will be used during the machine tension measurement and adjustment. Tape thicknesses and other properties will effect the accuracy. Also, the calibration should be done with weights that will check the low and high ends of the scale.
18. Before attempting to use tapes that have just been exposed to environments considerably different than the operating environment, they should be given approximately 24 hours to stabilize in the operating environment.
19. The use of commercially available video tape cleaners on 2″, 1″, and 3/4″ formats has proven to be effective in extending tape life on old and used tapes. If these type units are being used, they also must be checked for proper alignment, tape tensions, and guide wear.
20. Reel to reel tapes and cassettes should be given a full length rewind to achieve a uniform and even wind before going to storage or preparing for shipment.
21. The recommendations for cassette type operations are basically the same as for reel to reel except for the obvious differences in the human tape handling aspects.

Storage Environment

1. At a minimum, the temperature and humidity should be controlled within the limits previously specified for the operations area; namely 70 °F plus or minus 5% and a relative humidity of 50% plus or minus 20%. This has been adequate for most operations' library needs; however, if archival storage times are being considered, it is recommended that the relative humidity be kept at 45% or lower and the temperature below 70 °F.
2. The tape reels or cassettes should be kept in their original containers and stored on end to assure the tape is being supported by the hub.
3. The air to this area should also be filtered to the same degree as previously recommended for the operations area.
4. When tapes are removed from the library, the containers should be inspected for accumulation of dust or debris and wiped clean, if necessary, before being taken to the operations area.
5. The storage environment must be controlled, but it should be pointed out that most tapes are designed to withstand relatively short periods of extreme environments, such as those encountered during shipment; namely, −30 °F to 120 °F.

Accidental Erasure

Because magnetic tape has the advantage of being erasable and then reusable, the question regarding the threat of accidental erasure arises. The following information should alleviate those fears as the chances of accidental erasure are extremely remote.

1. The coercivities of video tapes are in the range of 300 oerstads to over 1000 oersteds. Therefore magnetic field strengths below 50 oerstads have little effect on the recorded tape. Most sources of magnetic fields are well below this level. As an example the earth's magnetic field is approximately 0.6 oersteds. The field from an electric hand drill under full load is about 10 oersteds at the surface of the drill case.
2. The strength of a magnetic field drops dramatically as the distance from the field source increases. At a distance just 3 inches away from a 1500 oersted source the field strength is below 50 oersteds. Therefore, the mere spacing provided by a shipping container in separating the tape from external magnetic fields offers considerable protection.
3. Permanent magnets used in holding various objects to steel surfaces can have field intensities of about 1500 oersteds at the surface of their pole tips. These would present an eraseability problem only when held extremely close to the reel of tape itself.

5.7

Magnetic Recording Media

Part I: Care and Handling of Magnetic Tape

Part II: Principles and Current State of the Art

Part II: Principles and Current State of the Art

M. P. Sharrock
Memory Technologies Research Laboratory
3M Company
St. Paul, Minnesota

INTRODUCTION

The broadcast of audio and video programming is greatly facilitated by the ability to store and recover information, and sometimes erase or alter it. Despite the availability of photography and other means of storing images, sounds and symbols, magnetic recording has enjoyed a long pre-eminence in these applications because of a number of features:

1. Easy recording by inexpensive transducer (head)
2. Stable long-term storage
3. Simple playback process with good signal-to-noise ratio, possibly using the same head as for recording
4. Easy erasure and editing or updating, especially important in broadcast studio environment
5. Relatively high surface information density
6. Thin flexible media, which can be rolled up (unlike phonograph record or video disk) for extremely high *volume* information density
7. Inexpensive media—high-quality magnetic video cassette tape is available at a lower cost per square inch than the transparent tape used to mend books!

NOTE: Superscript numbers refer to references at end of the chapter.

This article will attempt to give a brief overview of the basic physical principles involved in magnetic recording, some of the leading types of recording materials, and the directions of current research and development. More thorough discussions of various aspects of recording theory and practice are available[1,2].

BASIC PRINCIPLES

Audio and video signals are handled as electrical quantities (voltages and currents); some fundamental physical laws that relate electrical and magnetic phenomena, and therefore make magnetic recording possible, are shown in Fig. 1. The changing flow of electrical current in the recording head gives rise to a changing magnetic field, which imposes a magnetization pattern on the recording medium (e.g., tape). During playback the reverse process occurs, as the changing magnetic field experienced by the head, due to the passing recorded magnetic surface, induces a signal voltage.

The inductive nature of the playback head dictates that only a *change* in the magnetic field experienced by the head leads to an output signal. Further, a faster change produces a greater output amplitude. A consequence of this is a frequency dependence in the output amplitude. Fig. 2 shows this dependence, for sinusoidal signals recorded at a constant depth and magnetic ampli-

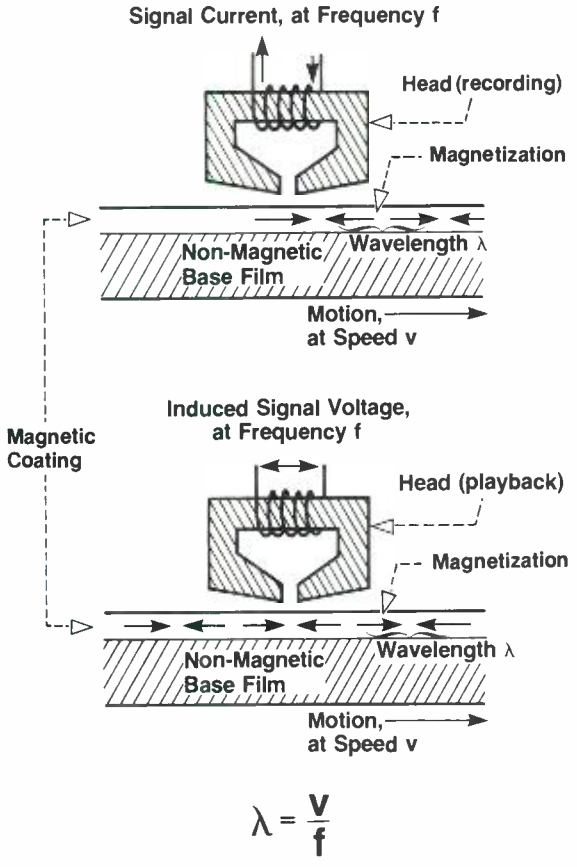


Fig. 1. The elements of magnetic recording and the relationship between signal frequency, transport speed, and recorded wavelength.

tude in the medium. The output is proportional to frequency over a large range; the fall-off at high frequencies (high recording densities or short recorded wavelengths) is due to signal loss from a number of sources which will be discussed later. The frequency dependence of the output is largely compensated for in many applications by the use of a frequency-dependent electronic gain; this process is called equalization.

The performance of a magnetic recording system depends, to a large degree, upon the magnetic properties of the material used to make the recording medium. The most significant properties are explained in Fig. 3, which shows a plot (called a hysteresis loop) obtained by placing a sample of the material in a varying magnetic field H and measuring its magnetization intensity M. The points at which the plot crosses the vertical M axis define the quantity known as the *remanent magnetization* M_r, which describes how much magnetization intensity the material is able to retain in zero field after being magnetized by a saturating field. The quantity usually specified (in the cgs system) is $4\pi M_r$, also designated as B_r, which is called the *retentivity*. The ratio of

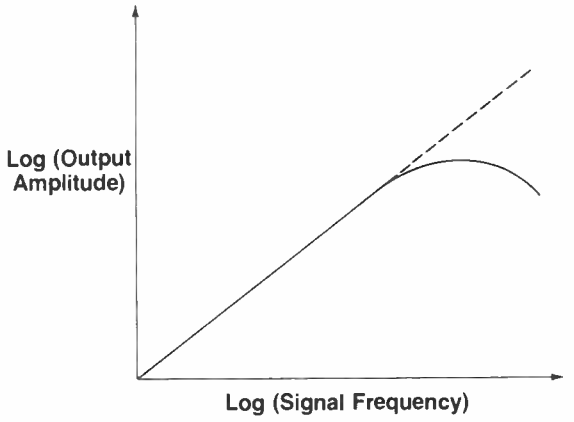


Fig. 2. Logarithmic plot of output amplitude vs. signal frequency, for sinusoidal magnetic recording at constant magnetization amplitude and depth. The slope of the linear rise is 6 dB per octave.

M_r to the *saturated magnetization* M_s is called the *squareness;* it helps to define the shape of the loop and therefore the recording properties of the material. The points at which the loop crosses the horizontal H axis define the *intrinsic coercivity,* often referred to as simply the *coercivity* and designated by H_c. This is the field needed to reverse half of the magnetization after saturation in one direction, resulting in zero net magnetization. The steepness of the plot as it goes from one direction of magnetization to the opposite one relates to the ability of the material to record a signal with sensitivity and precision. A quantitative measure of this steepness is the *switching-field distribution* (SFD), described in Fig. 4.

The response of a magnetic recording material to an applied field is clearly non-linear (see Fig. 3). In many applications, it is desirable to remove

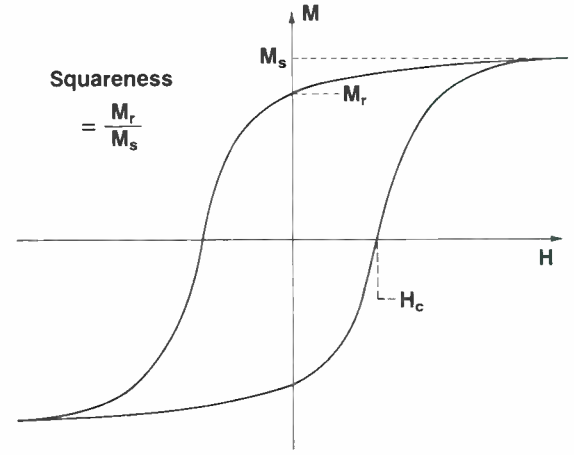


Fig. 3. Plot of magnetization M vs. applied magnetic field H, for a typical magnetic recording material.

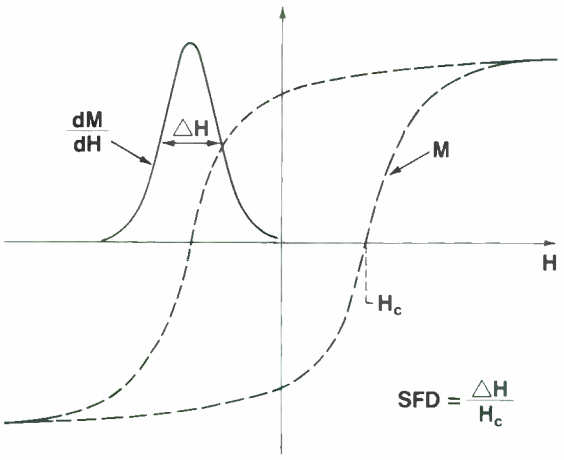


Fig. 4. Plots of magnetization M (broken line) and first derivative dM/dH (solid line) vs. applied field H. Width ΔH, used in the definition of the switching-field distribution (SFD), is measured at half the peak height.

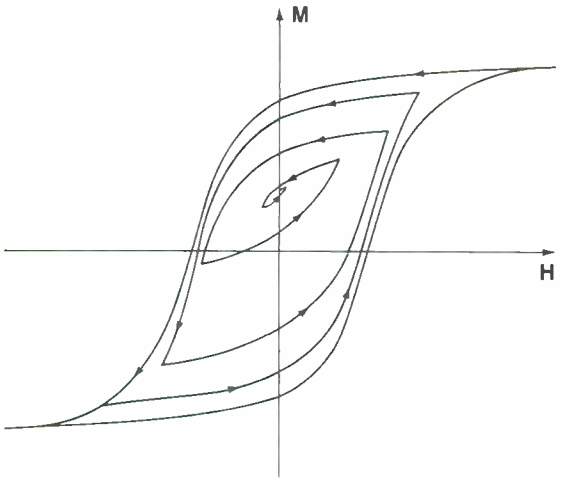


Fig. 5. The principle of ac-bias. As a specific small area on the tape moves away from the recording head gap, it is subject to a high-frequency bias field of decreasing amplitude. This causes its magnetization to vary as shown by the arrows, and to be left in a final state proportional to the signal field upon which the high-frequency field is superimposed.

this non-linearity so that the recorded magnetization can be made proportional to the signal current. The needed linearization of the response is accomplished through the technique known as ac-bias, in which the desired signal current is added to an alternating current of much higher frequency and amplitude before being applied to the recording head. The process and the result are diagrammed in Fig. 5; more complete discussions are available elsewhere[2,3]. The recording material is taken through a number of progressively smaller hysteresis loops as it leaves the vicinity of the recording head gap and is left in a state in which the remanent magnetization is very nearly proportional to the signal. The use of ac-bias is important in applications where the waveform read back must be an accurate reproduction of the input waveform, particularly in audio recording.

In some applications, the recorded information is contained in the timing of the zero-crossing points of the signal, rather than in the shape or amplitude of its waveform. Two of these applications, which do not usually utilize ac-bias, are digital recording and frequency-modulation (FM) recording. Digital recording is very simple in concept, although the applictions can be very sophisticated. Digital recording seeks only to convey reliably the strings of binary digits (abbreviated as "bits"), 0's and 1's, that make up the information used in computers and other data-handling devices. Fig. 6 shows a simple scheme for doing this. In practice, more complex procedures are used; some additional magnetic transitions are used for timing purposes and some convey information that is redundant but needed for the detection and correction of errors. Errors may occur through excessive random noise or through defects in the surface of the tape or disk.

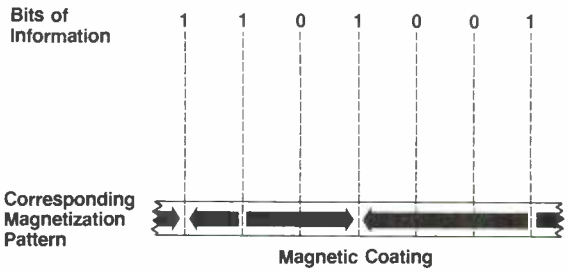


Fig. 6. A simple form of digital recording, in which 1's are encoded as magnetic transitions and 0's as the absence of transitions.

Digital recording, in addition to its obvious computer applications, is increasingly being used to replace analog recording techniques in audio and video applications[4,5]. The original signal is measured at precise intervals and the measurements expressed as a series of numbers that are then recorded digitally like any other data. The recovery of the signal consists of reading back the series of numbers (again, at precise time intervals), converting them into values of an analog quantity (e.g., voltage), and smoothing these discrete values into a waveform.

The first design consideration of a digital recorder is the frequency of sampling, which must be at least twice the highest frequency present in the signal to be recorded, according to the Nyquist theorem. Thus, for a high-fidelity audio

signal containing frequencies up to a 20 kHz, sampling might be done at a rate between 40,000 and 50,000 times per second. Next, the dynamic range of the final reproduction is determined by the precision of each conversion to digital form. If a final dynamic range of 60 dB (an amplitude ratio of 1000) is required, then the binary code for each sampling must be able to express integer numbers from 0 to 1000. This requires ten bits per sampled value, since $2^{10} = 1024$. Similarly, a dynamic range of 90 dB requires a minimum of 15 bits per sampled value. The dynamic range is essentially the signal-to-noise ratio of the reconstructed signal, since the steps between adjacent numerical values provide the only noise inherent in the final output.

The advantages of a properly designed digital system include an excellent dynamic range, an essentially perfect time-base (absence of "wow" and "flutter"), and the ability to do repeated editing or dubbing operations without signal degradation. The tenth-generation audio reproduction made on a studio digital recorder is virtually indistinguishable from the original. This resistance to degradation of the recorded signal is intrinsic to digital technology and results from the fact that the information is encoded only in the timing of transitions. As long as these can be reliably detected and are not shifted, substantial degradation of the amplitude or shape of the digital waveform can occur with no effect on the result.

Digital magnetic recording, while not requiring linear reproduction of a waveform, makes great demands upon the recording system because of the drastically increased bandwidth. If an audio signal of 20 kHz bandwidth is to be reproduced with the modest dynamic range of 60 dB, frequencies up to at least 225 kHz are needed to accomodate its digitally encoded representation. An actual studio recorder might operate beyond 600 kHz, depending upon sampling rate, dynamic range, and the digital code used. Such frequencies dictate very short intervals between the magnetic transitions on the recording surface if tape usage is not to become prohibitive. On the other hand, the signal-to-noise ratio of the digital waveform that is read back need not be as great as that required in an analog recording. In general, the lower the signal-to-noise ratio of the digital waveform the higher the probability of mis-read bits (bit errors), but these can be detected and either corrected or concealed through the use of encoding schemes that involve a certain amount of redundancy in the recorded information. These schemes can overcome not only isolated single-bit errors but also the effects of recording surface defects that delete a number of adjacent bits. (See, for example, reference 6).

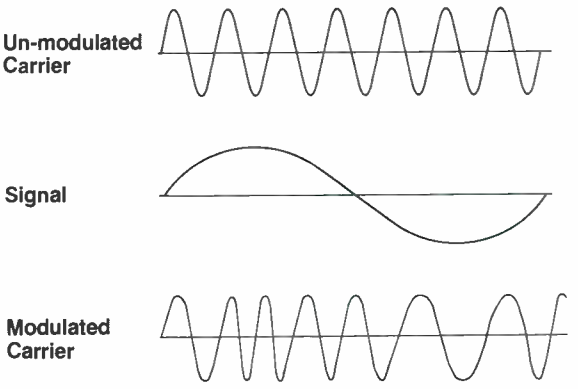


Fig. 7. The principle of frequency modulation (FM).

Error correction techniques make possible the use of very high densities in digital recording, provided that the heads and media can operate with the required resolution.

Another mode of magnetic recording that does not require linear waveform reproduction is frequency-modulation (FM). This is primarily used in video recording[7], but can also be applied to audio recording and is in fact used to give high-fidelity sound in some video cassette recorders. The principle of FM is that a carrier wave is generated whose *frequency* varies with the *value* of the signal to be transmitted (Fig. 7). It is this frequency-modulated carrier that is recorded on the magnetic medium. As in digital recording, the information is contained in the intervals between the zero-crossings of the recorded waveform; its amplitude is not significant as long as the signal-to-noise ratio is adequate for reliable detection. Unlike digital recording, FM recording contains an analog relationship between frequency and the value being transmitted. The benefits of FM, as compared to direct analog recording, are two-fold. One is the insensitivity to amplitude variations in the recorded waveform. The second, which is crucial to magnetic video recording, is that FM reduces the ratio of the highest to the lowest frequencies that need to be recorded; this is shown schematically in Fig. 8. Suppose that it is desired to record a video luminance (brightness) signal that contains frequencies from 30 Hz to 4.5 MHz. The upper and lower frequency limits have a ratio of 150,000 or 17 octaves. (By comparison, a full-fidelity audio system is required only to reproduce frequencies from 20 Hz to 20 kHz, a ratio of 1000, or 10 octaves.) A frequency span of 17 octaves (ratio of 150,000) is impractical in magnetic recording. First, the ratio of highest to lowest frequencies cannot exceed the ratio of the physical length of the playback head pole-pieces to that of the gap (reference 1, pp. 99-119). This ratio cannot in practice be as great

as 150,000. Even if it could, the 6 dB per octave frequency dependence (Fig. 2) would require a dynamic range of more than 100 dB for direct video recording, too much for successful equalization. Frequency modulation, as indicated in Fig. 8, reduces the ratio of highest to lowest frequency; this ratio after modulation is as low as 1 octave in some video recording systems.

The frequencies involved in video reproduction are much higher than those in audio. Since there are practical lower limits on the recorded wavelength, this means that much higher head-to-tape speeds are needed. To attain these speeds, all video systems use heads mounted on a spinning drum. The tape is transported around part of this drum at a speed much lower than that at which the heads are moving across the tape surface. The various systems in current use employ different FM carrier frequencies as well as different schemes for conveying the color information, which in practice has a lower resolution and therefore requires a smaller bandwidth than that of the luminance information. In all systems the hue and saturation information is conveyed by amplitude and phase modulation of a special color sub-carrier (at 3.58 MHz in the U.S.A.). In the one-inch, open-reel tape format commonly used in broadcasting, the modulated color sub-carrier is simply added to the luminance signal and the resulting sum is the signal used to frequency-modulate the video carrier. In 3/4-inch U-matic systems and in non-professional one-half-inch cassette systems, the color sub-carrier (with its amplitude and phase information) is heterodyned down to a lower frequency (about 0.6 MHz) which is then recorded directly, using the frequency-modulated luminance carrier for ac-bias. Some recently developed one-half-inch cassette systems for professional applications utilize FM recording of both luminance and color information with a separate head, tape track, and carrier frequency for each. This achieves broadcast-quality reproduction using the same cassettes used in consumer systems, but at the cost of much lower recording densities (higher tape consumption).

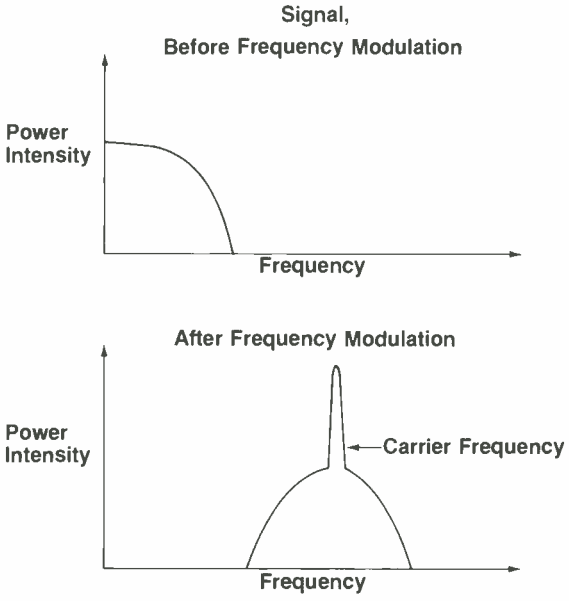


Fig. 8. In frequency-modulation (FM) the information is shifted to higher frequencies, but the ratio between highest and lowest frequencies is greatly reduced. FM schemes actually used in video recording do not use all of the sideband frequencies; see pp. 396-401 of reference 2.

MAGNETIC RECORDING MEDIA

Most magnetic recording media in use today are made by dispersing small magnetic particles in an organic binder and coating the resulting "paint" on a support material. See Fig. 9A. Each particle remains uniformly magnetized; its magnetization can change its direction but not its magnitude (this is a result of the very small size). The particles are sufficiently small that there are many of them in each magnetized region of the recorded pattern; this provides the needed resolution and signal-to-noise ratio. The particles can be of various types, according to the intended application[8,9]. In addition to the magnetic particles, the coating contains polymers for strength, lubricants to reduce friction and wear, and surfactants to aid in dispersing the particles. An additional particulate component is usually added to impart a controlled amount of abrasivity for head-cleaning purposes.

Another possible construction for a magnetic recording medium is shown in Fig. 9B. Like the dispersion-coated type, it also uses a non-magnetic base. The magnetic substance is in the form of a thin metallic film. Thin films offer magnetization intensities far surpassing those available in the coatings of dispersed particles, which compensates for the films' much lesser thickness. The thinness of the films is in itself an advantage in that the magnetic material is all in very close proximity to the record or playback head. This intimate contact with the head is extremely important to high-density recording and is further enhanced by the great smoothness possible in the thin films. These attractive features make thin-film recording media an exciting area of research and development and possible candidates for future products. At present, their major commercial applications are in video instant-replay memories and in advanced computer disks.

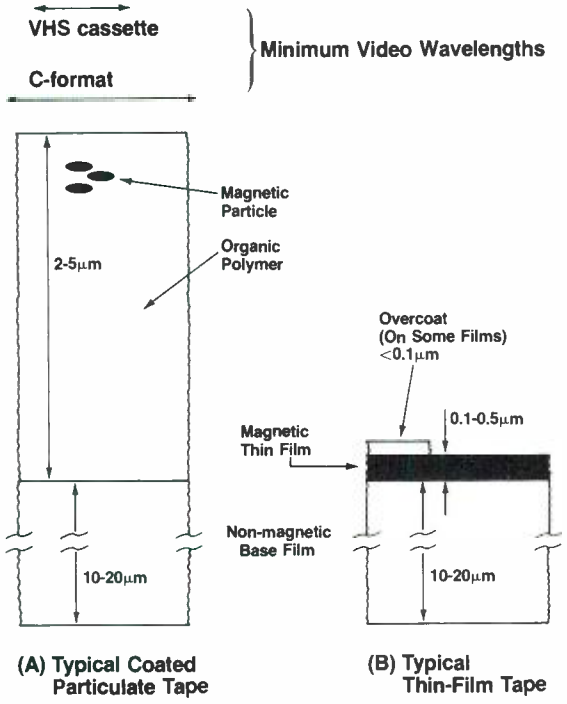


Fig. 9. Cross sections of a coated particulate recording tape and a thin-film tape. The particles are drawn approximately to scale but their spacing and uniformity have been exaggerated. Only a few have been drawn, although they actually fill the magnetic coating layer, occupying about 40% of its volume.

On the negative side, metallic thin films are subject to some concerns regarding their chemical stability, durability, and economical manufacture. Many of them are coated with a thin nonmagnetic overlayer for protection and lubrication. This layer, of course, tends to diminish the closeness of contact with the head. Metallic thin films are made by chemical plating or by some form of vacuum deposition and usually contain cobalt as a major constituent. The need for the special equipment used to carry out these processes is an additional barrier to the widespread commercial use of thin films in recording media. Futhermore, the thin-film products must compete with a particulate technology that not only benefits from more than 30 years of experience in manufacturing and application but is also evolving toward greater capability.

For the foreseeable future, economic and practical considerations dictate that coatings of dispersed particles will be predominant in audio and video tapes. The earliest comercially available audio tapes, made in the late 1940's, used iron oxide particles. The most important oxide, $\gamma - Fe_2O_3$, has been greatly improved as to particle shape and size since its introduction, and it retains an important role in audio, video and data-recording tapes today. It is also the most commonly used material for the disks, both flexible and rigid, used in digital data storage for computers. The relatively low coercivities (250-400 Oe) of pure iron oxides, however, proved to be a serious limitation as recording densities increased. An explanation for this is found in the self-demagnetization effect that exists in magnetized materials. Every magnet generates an internal field, which tends to oppose the magnetization that gives rise to it. This effect becomes stronger as the magnet is made shorter along its direction of magnetization (Fig. 10), and will be enhanced by the presence of nearby magnets if similar poles are placed together. The result of these phenomena is that magnetic recording, conventionally visualized as having the magnetization parallel or antiparallel to the direction of motion of the head with respect to the tape or disk (Fig. 1), suffers from a demagnetization effect that becomes more severe as the recording density becomes higher (that is, as the recorded wavelength becomes shorter). The ability of a magnetic material to resist demagnetization is expressed by its coercivity.

The requirement for higher coercivities was first met in the mid-1960's with the introduction of chromium dioxide (CrO_2). Like iron oxide, this material derives its coercivity and squareness properties, and therefore its ability to retain magnetization, from the needle-like shape of the particles. Chromium dioxide was first introduced for digital computer tapes. It was soon applied in audio cassettes and is today used in some video cassettes.

At the present time, the most widely used materials for applications requiring coercivities in excess of 400 Oe are iron oxide particles modified by the addition of cobalt. The interaction of the cobalt ions with the iron oxide structure provides additional resistance to the switching of the magnetization direction, and thus increases the coercivity. Values in the range of 500-600 Oe for audio cassette tapes, 600-700 Oe

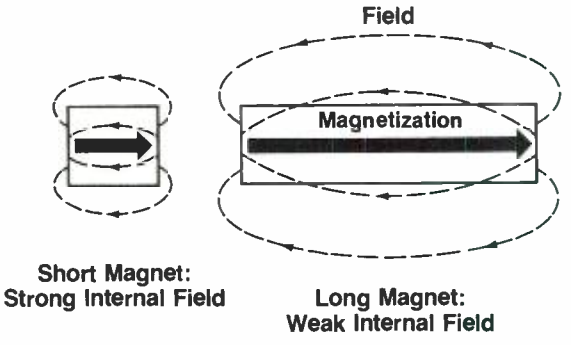


Fig. 10. Internal demagnetization fields for magnets of different shapes.

for video tapes, and 800 Oe or above for future applications are readily achieved. Many processes exist for adding the cobalt to the particles. Most in use today leave the cobalt segregated near the surface of the particles. Such particles, called "cobalt-surface-doped", "cobalt-adsorbed", "cobalt-epitaxial", or "cobalt-ferrite epitaxial" are now the predominant materials used in video cassettes and open-reel video tapes and are finding increased use in high-density data diskettes. Like undoped oxides and chromium dioxide, they retain magnetization along the particle axis. The manufacturing processes of tapes are usually designed to orient the particles along the tape length in order to increase the maximum remanent magnetization in this direction.

Tapes made with particles of metal (iron or iron alloys) have much higher remanent magnetization values than are possible in tapes that use oxide particles, and accordingly give much higher signal levels. This property is especially valuable in very compact formats, and metal particles are used in some audio cassette tapes and also in 8-mm consumer video tapes. These products have generally had coercivity values in excess of 1000 Oe, requiring much higher head fields for recording and erasure than those needed for oxide tapes. Recently, however, metal particles have become available with coercivities near 700 Oe, similar to those of cobalt-modified oxides.

Another particulate material currently being studied for recording applications is barium ferrite. The particles are formed in the shape of small hexagonal plates, each of which has its easiest axis of magnetization perpendicular to its flat faces. If these plates are incorporated into a tape coating so as to lie roughly in the plane of the tape surface, recording can be done primarily with perpendicular magnetization.

Fig. 11 shows the properties of various particulate magnetic recording materials.

Whatever the composition of the particles in a recording tape or disk, their size is extremely important, since it determines the number of particles contained in each magnetized region of the recorded signal. The greater this number, the greater will be the maximum signal-to-noise ratio that the recording medium can provide, since each particle contributes a pulse of magnetization to the playback head[10]. A great many small pulses clearly will combine to make a more accurate, less noisy signal than a smaller number of large pulses (even though the total density of magnetic material present may be the same), and the effect of random fluctuations in particle size or placement will be less.

One of the most important and difficult arts in the manufacture of magnetic recording media is the dispersion of particles in the coating. If ap-

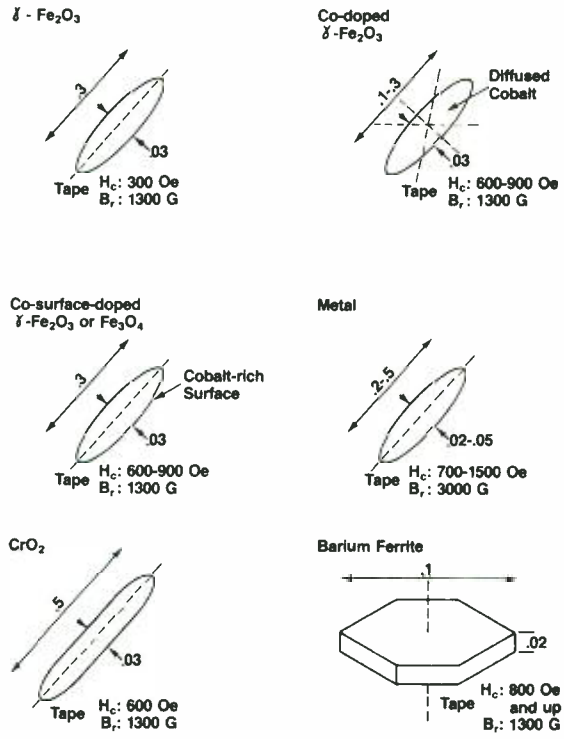


Fig. 11. Various particles used in magnetic recording. The preferred axes of magnetization are shown by broken lines. Some typical, approximate dimensions (in μm) and magnetic parameters are indicated.

preciable amounts of the particles are clumped together, the recording performance will suffer. The noise properties of the signal will be dominated to some extent by the clusters of particles, which are of course much larger than the individual particles themselves. A great deal of attention must therefore be paid to the formulation and milling of the dispersion, and to its coating and drying.

In the search for magnetic materials that give higher performance, care must be taken to avoid various undesirable features. For example, the trend to reduce particle size, and thus enhance signal-to-noise ratios, must not be carried to the point where the particles are so small that they begin to show the effects of thermal instability. In particular, the presence of excessively small particles can lead to the unwanted acquiring of a signal in one layer of tape on a reel as a result of the fields due to a strong signal on an adjacent layer. This phenomenon is often referred to as "print-through" or "pre- and post-echo", and is important only in (ac-bias) audio recording. In some applications, especially audio, thorough erasure is an important concern and one that places an upper limit on the coercivity of the recording medium. Efficient recording and erasure also require that the material's switching-

field distribution (Fig. 4) be relatively narrow. This means that the fields required to reverse the magnetization of the individual particles should be tightly clustered around the coercivity (which is essentially the median switching field).

Although this discussion has focussed on magnetic properties, one must not underestimate the importance of the non-magnetic components of recording media. The base film, the binder polymer, and the various lubricants and other additives in the coating are crucial to strength, durability, and freedom from undesirable levels of friction. The manufacture of recording media requires at least as much capability in organic chemistry as in magnetic materials. The ability to reliably produce coatings with smooth surfaces, substantially free of defects, is also an absolute necessity.

PROGRESS TOWARD HIGHER RECORDING DENSITIES

The state of the art in magnetic recording has clearly advanced in recent years. Fig. 12 shows

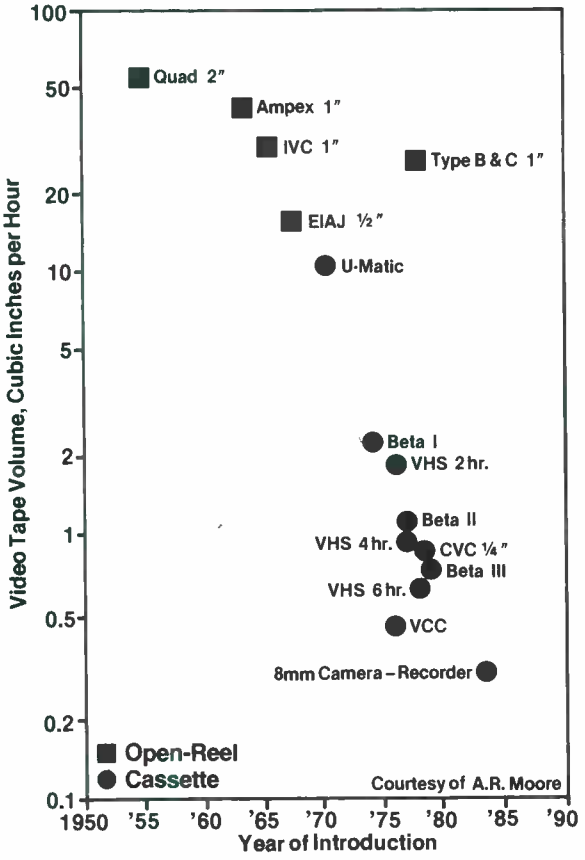


Fig. 12. Tape volume required per hour of playback, plotted against year of introduction, for various video formats. This plot was supplied by A.R. Moore, of 3M.

the great gains in practical recording density that have occurred in the video area. Intensive research and development is today aimed at continuing this trend. Two major driving forces are the desire for more compact consumer video products, especially cameras, and the trend toward digital recording of both audio and video signals. A brief survey of current developments will be given here, with emphasis on digital video.

As was mentioned earlier, the use of digital techniques requires a frequency bandwidth that is much increased over that needed for analog representation. Consider, for example, a broadcast-quality video signal that requires a bandwidth of roughly 10 MHz for adequate analog (FM) transmission. The analog recording system must handle 2×10^7 magnetic transitions per second. A digital system designed to transmit this same signal adequately would require nearly 3×10^8 bits per second[5]. Assuming that one bit of information corresponds to one magnetic transition (although this ratio varies somewhat with the digital code used), the digital recording system must handle nearly 3×10^8 magnetic transitions per second, a fifteen-fold increase over the analog rate. Clearly, if the use of digital rather than analog technology is not to entail a large increase in tape consumption, the digital recorder must use a higher density of magnetic transitions per square inch of tape. This density is the product of track density and the linear transition density along a track. Table I gives the values of these parameters in some practical and hypothetical video systems. The projected increases of recording density require the achievement of adequate signal strength and signal-to-noise ratios despite the use of much smaller magnetized regions in the recording medium. The difficulty presented by self-demagnetization at high densities was described earlier, as an explanation for the need to increase coercivities. However, a limit exists as to how much high-density performance can be bought by simply increasing the coercivity, since available heads must still be able to record, and also to erase or over-write, the material. Another route to avoiding or relaxing the density restrictions imposed by demagnetization is to avoid the head-to-head arrangement of magnetized regions. This can be done by using, to a greater or lesser extent, the perpendicular (sometimes called vertical) component of magnetization[11,12]. See Fig. 13. The relative merits of the various recording patterns, and of various head designs for creating and reading them, are currently under intensive study in many academic and industrial laboratories. It is likely that recording at relatively high densities has always used some degree of perpendicular magnetization, but new materials, including barium ferrite particles and some metallic thin films, are designed to accentuate this com-

TABLE I

System	Current C-format, one-inch open-reel video	Current six-hour VHS video	Projected digital video[a]
Magnetic Transitions per second (maximum)	2×10^7	10^7	3×10^8
Transitions per inch along track (maximum)	2×10^4	4×10^4	10^5
Tracks per inch	1.4×10^2	1.3×10^3	10^3
Transitions per square inch (maximum)	3×10^6	5×10^7	10^8
Tape consumption, in square inches per second	10[b]	0.2[b]	3

[a]This system embodies recording densities achieved in the laboratory. Digital systems closer to practical realization use somewhat smaller densities and achieve a tape usage closer to that of the analog C-format.[5]
[b]Includes tape area not devoted to video information.

ponent. The multiaxial cobalt-doped oxide particles (see Fig. 11) can be used to implement mixed-mode recording (Fig. 13) in a more or less isotropic medium.

Output losses at high densities can result from a number of causes other than demagnetization. Some are related to head design, and it is very clear that development of heads and recording media must proceed together in the search for higher-density recording. Fig. 14 shows some head designs under current consideration. The critical dimension of the head used for playback, the gap width of a conventional ring head or the pole width of a perpendicular-recording head, must be smaller than the shortest wavelength to be reproduced. The head used to record the waveform can have larger dimensions; indeed, this may be advantageous.

Whatever the head design and the recording medium composition, the closeness of the contact between the head and the surface of the medium is a factor of major importance in determining the achievable recording density. This

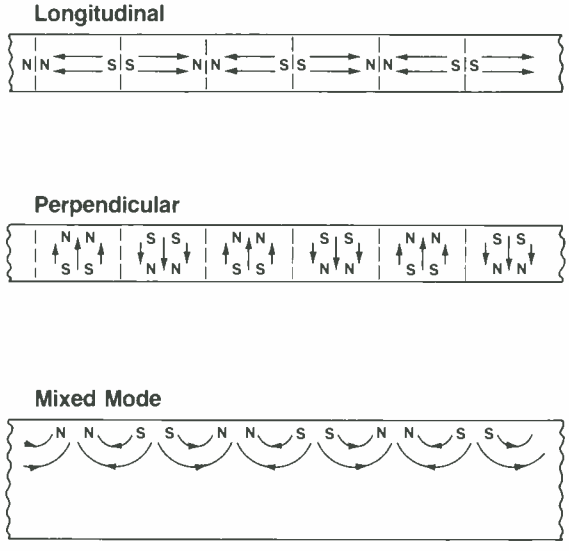


Fig. 13. Possible magnetization patterns in recording media. For the perpendicular component, increasing the recording density may actually decrease the demagnetization fields; see Fig. 10.

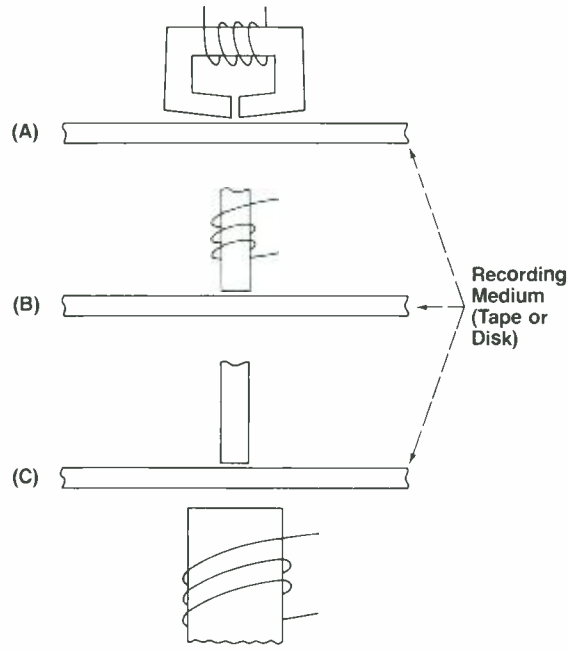


Fig. 14. (A) Conventional ring-type head, useful for both longitudinal and perpendicular recording. (B) Single-pole head, for perpendicular recording. (C) Single-pole head, driven by auxiliary pole, for perpendicular recording[11]. All heads can, if made with suitable dimensions, be used for reading as well as for writing. (B) and (C) are largely in the research and development stages at present.

follows from the fact that the resolution with which the head can record and read back deteriorates rapidly as spacing increases. The effect on the recording process has been estimated as a loss of 44 dB per wavelength of spacing, for a sinusoidal signal[13], and that on the playback process as a loss of 55 dB per wavelength[14]. This total of nearly 100 dB per wavelength means, for instance, that for sinusoidal recording at 50,000 transitions per inch (corresponding to a wavelength of 40 microinches or about one micrometer) every microinch of spacing will cause about 2.5 dB of overall loss in the reproduced signal. Obviously, variations in the spacing will amplitude-modulate the signal with the same sensitivity, and therefore add noise components to the signal. Thus, media surface smoothness may well be the ultimate limiting factor of magnetic recording density, although further development of heads and media are needed in order to reach this limit[15]. In addition to smoothness, the freedom from flaws and contaminants is crucial, if information "drop-outs", or momentary losses of signal, are to be minimized. As mentioned earlier, techniques of error detection and correction (or concealment) allow satisfactory performance even if imperfections exist in the recording medium. Even a highly sophisticated error-correction system, however, can be overwhelmed by defects that are excessive in number or size. As the recording density increases, the size of the flaw needed to cause a given system failure (visible video defect, audible audio defect) decreases. Thus, the development of advanced magnetic recording media entails the search for the means of producing highly perfect surfaces, as well as ideal magnetic properties.

ACKNOWLEDGEMENT

The author wishes to thank J. T. McKinney, A. R. Moore and N. C. Ritter for helpful information and discussion; also L. J. Nelson, C. A. Newman, and R.J. Spangenberg for help in preparing the manuscript and illustrations.

REFERENCES

1. C. D. Mee, *The Physics of Magnetic Recording,* North-Holland Publishing Company, Amsterdam, 1964.
2. F. Jorgensen, *The Complete Handbook of Magnetic Recording,* TAB BOOKS, Inc., Blue Ridge Summit, Pennsylvania, 1981.
3. P. Vogelgesang, "Another Look at Recording Bias," *Modern Recording & Music,* pp. 36-43, December 1980.
4. B. Blesser, "Digital Recording", *db, The Sound Engineering Magazine,* a series beginning with July, 1980. (The July, August, and September issues give good introduction to the basics.)
5. J. P. Watney, "Technical Choices for a Video Recorder", in *Television Image Quality,* J. B. Friedman, Ed., Society of Motion Picture and Television Engineers, Scarsdale, New York, 1984, pp. 127-136.
6. J. R. Watkinson, "Error Correction Techniques in Digital Audio," Fifth International Conference on Video and Data Recording, Inst. of Elect. and Radio Eng., Proc. No. 59, 1984.
7. H. Kybett, "Video Tape Recorders," Howard W. Sams & Co., Inc., Indianapolis, 1978.
8. G. Bate, "Recent Developments in Magnetic Recording Materials," *Journal of Applied Physics,* 52, pps. 2447-2452, March 1981.
9. M. P. Sharrock and R. E. Bodnar, "Magnetic Materials for Recording: An Overview with Special Emphasis on Particles", 30th Annual Conference on Magnetism and Magnetic Materials, to be published in the *Journal of Applied Physics,* 1985.
10. J. C. Mallinson, "Maximum Signal-to-Noise Ratio of a Tape Recorder," IEEE Trans. Magn., MAG-5, pp. 182-186, September 1969.
11. S. Iwasaki, "Perpendicular Magnetic Recording", IEEE Trans. Magn., MAG-16, pp. 71-76, January 1980.
12. J. U. Lemke, "An Isotropic Particulate Medium with Additive Hilbert and Fourier Field Components," *Journal of Applied Physics,* 53, pp. 2561-2566, March, 1982.
13. H. N. Bertram and R. Niedermeyer, "The Effect of Spacing on Demagnetization in Magnetic Recording," IEEE Trans. Magn., MAG-18, pp. 1206-1208, November 1982.
14. R. L. Wallace, Jr., "The Reproduction of Magnetically Recorded Signals," Bell System Tech. Journal, 30, pp. 1145-1173, October 1951.
15. M. P. Sharrock and D. P. Stubbs, "Perpendicular Magnetic Recording Technology," in *Television Image Quality,* J. B. Friedman, Ed., Society of Motion Picture and Television Engineers, Scarsdale, New York, 1984, pp. 137–151; and published in the *SMPTE Journal,* 93, pp. 1127–1133, December 1984.

5.8

Film for Television

Editor: Paul L. Gordon
Eastman Kodak Company
Rochester, New York

Technical Consultant: Rodger J. Ross
Cobourg, Ontario, Canada

Editorial Consultant: Robert G. Koch
University of Rochester, Rochester, New York

ATTRIBUTES OF FILM

Color motion picture film has three photosensitive layers coated on a plastic base. Exposure and processing produce dye images in these layers which, when projected on a large screen or scanned in a telecine, produce the color pictures.

Film in the 16mm width is the most common format for distribution of television programs. The 35mm width has been in general use for many years for large-screen picture projection in theatres, and for the production of prime-time television programs on film telecast by the major networks. Now this format is being used extensively in television postproduction houses, and for the production of television commercials. The newer generation of television film scanners has interchangeable optical blocks enabling either format to be reproduced in telecine equipment.

Professional motion pictures, most prime-time television programs and television commercials are made on color negative film. From these originals, prints can be made for distribution on either 35mm or 16mm materials. The newer generation telecines are capable of reproducing from either color positives or color negatives.

To show motion pictures on large screens, the projector advances the film one frame at a time, and a rotating shutter cuts off the light while the film is being moved. A claw or Geneva mechanism advances the film by engaging perforations along the edges. Film 35mm wide has perforations on both edges, but the 16mm material used to make prints has perforations on one edge only; the space on the other edge is taken up by the sound track.

In camera-type telecines the film is advanced intermittently, one frame at a time, by means of the perforations. But in the newer film scanners film movement is continuous, and the perforations are used only to drive a sprocket that generates framing pulses.

The film sound track may be either optical or magnetic. Telecine projectors and film scanners usually have interchangeable optical/magnetic sound playback heads. In the playback of an optical sound track, the lens imaging the exciter lamp filament at the film must be sharply focused on the emulsion side. Usually an adjustment is provided for this purpose, as the emulsion side in 16mm prints may be either towards the lens (preferred position) or towards the light source.

The standard motion picture frame rate around the world is 24 frames/second for both 35 and 16mm formats. The 35 format has 16 frames per foot; so at 24 frames/second the rate of film movement in a projector or scanner is 90 feet per minute (fpm). With 40 frames per foot in 16 mm the film passes through a projector or scanner at 36 fpm. The size of a 35mm film frame is 0.825 inch wide and 0.600 inch high, compared with a 16 mm frame, 0.380 inch wide and 0.284 inch high.

Fig. 1. EASTMAN Color Print Film 5384 (film can label) (courtesy Eastman Kodak Company)

With proper care film should have a long useful life, but the film surfaces can be scratched easily in faulty equipment or by careless handling. Also, the dyes used in producing the color images have been greatly improved over the years, not only in colorimetric characteristics, but in dye stability, or resistance to fading, as well. Useful life has been increased as much as several times over that of previously available print films. And, since fading of the three dye layers usually occurs at different rates, and causes changes in color balance that are difficult—if not impossible—to correct in telecine (with available electronic adjustments), a dye-stable print film should help to reduce the amount of dye fading so often seen in old movies. (See Fig. 1.)

ADVANTAGES OF LOW CONTRAST PRINT FILMS

When color television broadcasting started in the mid 1950s, the motion picture industry was the only source of pre-recorded program materials. It was soon recognized that significant picture quality losses occurred in telecasting films made for large-screen projection in theatres because of the inability of the television system to transmit the range of gray scale values needed to create acceptable pictures on motion picture screens. Committees of the Society of Motion Picture and Television Engineers (SMPTE) tackled this problem and published a report recommending that the density range in films for television should be limited by adjustments in staging and lighting rather than in the making of the color prints. In this way prints could be produced with a range of density values that the television system could reproduce.

For various reasons it has not always been possible to adhere to these recommendations. For example, on location, lighting ratios cannot be held to 2:1 as recommended, nor can the reflectivity of the lightest scene areas be held below 60 percent. An even more compelling reason is that market requirements make necessary the production of motion pictures for both purposes—theatre projection as well as television display.

At the start of color television broadcasting in Europe, engineers from the British Broadcasting Corporation, members of a working group in the European Broadcasting Union, defined the preferred luminance characteristics of films for television presentations as a density range of approximately 0.20 to 2.50. C. B. B. Wood of the BBC, writing in the Journal of the Royal Photographic Society pointed out that the contrast handling capacity of a color television system in ordinary home viewing conditions is likely to be somewhere between 20:1 and 30:1, whereas the contrast in typical theatre projection is about 160:1. Because of ambient light on the television screen, it seems better to compress the lighter rather than the dark tones. The ideal arrangement would be a single color negative printed either on conventional print film or on a special print film for television.

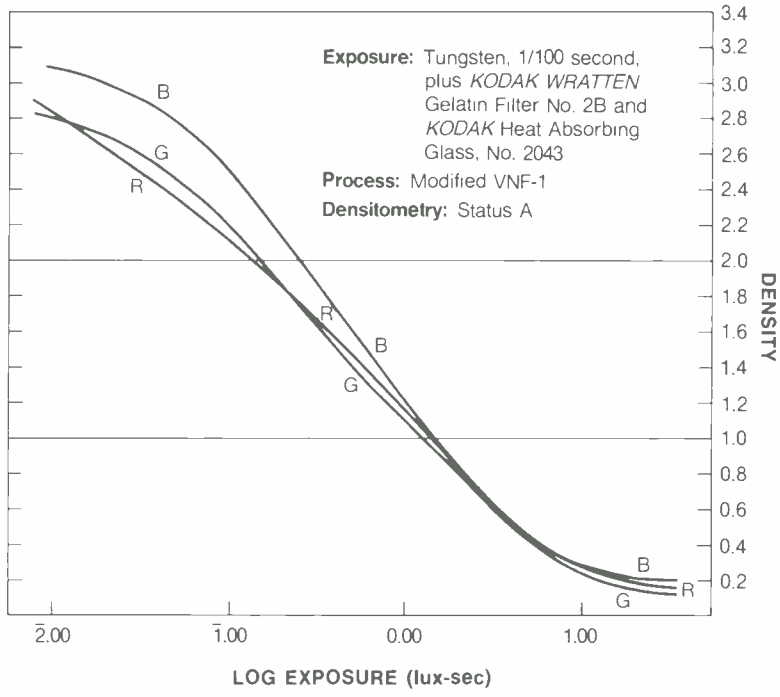
In response to these initiatives, Kodak Ltd. in the United Kingdom introduced a new Eastman color print film Type 5744. This film was designed with reduced upper scale contrast compared with print films for projection on theatre screens. This original attempt to conform with television density requirements has resulted, after numerous modifications, in a reduced contrast product in the Eastman color LC print Film 5380/7380.

The transfer characteristics of these new low contrast print films is a compromise among several considerations. The contrast has to be low as possible for good telecine performance, yet high enough to provide acceptable screen images in direct projection in review rooms, and the film must have enough color saturation to keep chroma gain at a fairly low level.

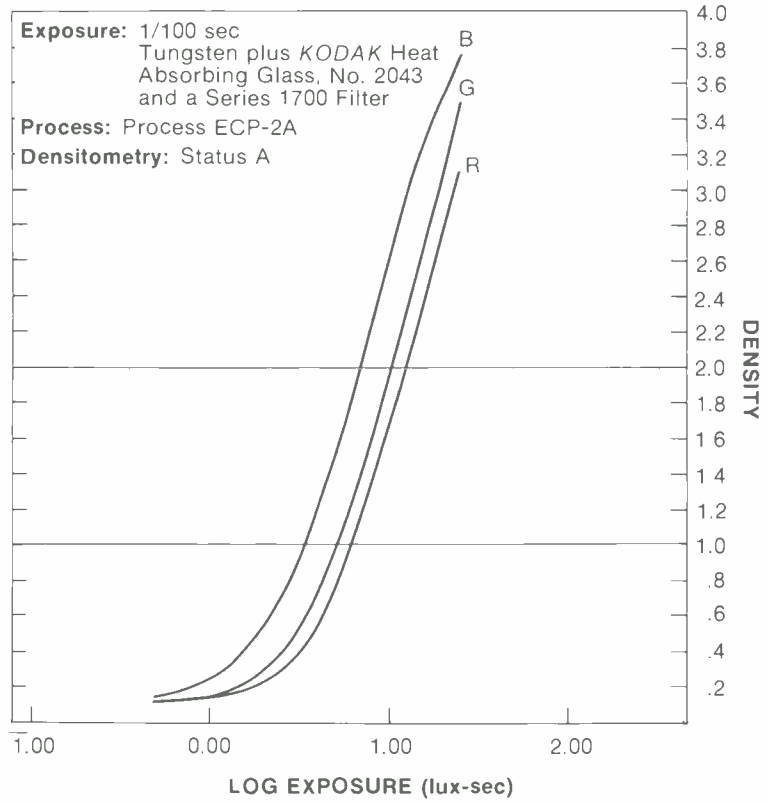
When a film with a contrast range of 160:1 is being squeezed into the television system, the shadow areas in the pictures are compressed and much of the shadow detail is lost. Some improvement can be achieved through the use of black stretch circuitry in the telecine, but little can be done with films made deliberately dark in shadow areas to make the story on the screen in theatres more convincing. No doubt television reproduction of these old motion pictures could be improved considerably by printing on low contrast print film.

FILM DENSITY TO ELECTRONIC OUTPUT

The term "density" as used in photography and motion pictures refers to the light-absorbing properties of film images. Density is defined as



(Positive print film)



(Negative print film)

Fig. 2. Characteristic curves for typical negative and positive print films.

the logarithm of the reciprocal of the transmittance, and transmittance is the ratio of the transmitted to incident light. The response of a film material is usually illustrated graphically in the form of a characteristic curve, produced by plotting density against the logarithm of the exposure.

In the negative-positive motion picture process it is customary to use a relatively low contrast negative film in the camera, and then print the negative on a relatively high contrast positive film. Fig. 2 shows the characteristic curves plotted on graph paper. Photographic gamma is the slope of the straight line portion of the characteristic curve.

The range of light values reflected from different parts of a scene can be placed anywhere on the negative characteristic curve by adjusting exposure level, but good practice is to place the darkest area of the scene at about 0.10 above base and fog level. This is accomplished by making use of a photoelectric exposure meter set for the exposure index of the negative film.

When a print is being made from the negative, printer exposure is adjusted to place the range of scene brightnesses on the positive characteristic curve in such a way that the lightest scene area is close to clear base so as to retain bright highlights on the screen. Surveys have shown that good quality motion picture prints are likely to have a minimum density of 0.25 to 0.40, with maximum densities from 2.30 to 2.70.

SMPTE Recommended Practice RP46-1972 specifies that the density corresponding to white level for television reproduction should be 0.30 to 0.40, while dark areas may have densities as high as 2.50.

However, image details and color in these areas may be lost or distorted. The Kodak gray scale test slide for setting up camera telecines has minimum and maximum densities of 0.30 and 2.35, and in a properly adjusted telecine these densities should produce video waveform levels of 100 and 7.5 IRE units.

From the foregoing brief description of the correlation between the motion picture and television imaging systems, it can be seen that in the production of a program on film, important scene elements can be placed at any desired levels on the television waveform monitor and in the brightness range of a television picture by adjusting the reflectances of these scene elements with the aid of supplementary lighting.

However, with a conventional high contrast print material, there is almost always a problem with preserving detail in the darker areas of the television pictures.

For anyone interested in how the coordination between film and television is achieved, a paper by DeMarsh "Optimum Telecine Transfer Characteristics" in the October 1972 of SMPTE Journal has much useful information.

OPTIMUM TELEVISION PICTURES FROM FILM

Two distinctly different methods of operating telecine equipment have been in general use for many years. One method is to allow the telecine to run unattended, signal level being maintained within permissible limits by automatic signal level control. This is the normal method of operation in television stations around the country. The other method, employed mainly in film and video postproduction is manual control, a skilled video operator being employed to adjust the telecine camera controls as necessary to compensate electronically for color, hue and saturation variations in the films being telecast.

More Than Just Acceptable

Automatic signal level control is an economically efficient operating method, and for the most part acceptable television pictures can be produced in this manner. Of course, films made to conform with published recommended practices for television should give equally good pictures whether the automatic signal level control is turned on or off. But in practice, the densities and colors in some films vary to a much greater extent than the recommended practices specify. Designers of television equipment have always claimed that automatic signal level control reacts much more quickly to scene-to-scene density shifts than even the most skillful video operator. However, the automatic control circuitry cannot distinguish between a good or a poor picture, something that an operator can immediately detect and then make appropriate adjustments in the settings of the camera controls.

In the large network centers where costly program materials are being assembled and reproduced, personal attention to signal levels, color balance and general picture quality is essential, especially in dealing with film commercials. For the sponsors of these products, color and texture must be preserved in the television pictures, and perhaps even enhanced. Even with the old vidicon color telecines, the changes that can be made in the appearance of the television pictures are usually quite surprising.

Scanners

Much more striking is the performance of the flying-spot scanner in reproducing color films. Its potential was recognized early. For example, as

soon as the Rank Cintel scanner became available in North America, television postproduction companies were the first to install these telecines. By 1984 over 130 were in use in these centers.

The capabilities of the flying-spot scanner have been greatly extended with Digiscan, a digital storage and processing unit; Amigo, a telecine programmer, allowing speed control scene-by-scene, and many other functions including frame-by-frame color correction. After making appropriate adjustments in gain, gamma, pedestal, enhancement and so on, to produce the best possible television pictures as seen on the telecine picture monitor, the operator presses a data entry button to enter the corrections plus the scene timecode into a memory. With a secondary color correction unit, hue and saturation of any of the three primary and three secondary colors can be altered in any desired manner. These changes and corrections can be recalled from memory automatically when the film is being transferred to videotape.

Color Correction

Corporate Communications Consultants of Holbrook, New York, is a pioneer in the development of highly sophisticated color correction equipment for use in the transfer of films to video tape. Among several models of color correction equipment available from the company, The System 60XL is perhaps the most versatile. The digitized analog variable control panel contains 40 or more high resolution digital shaft encoders, one for each variable, organized in three major subsections—color or balance (pedestal, gamma and gain for red, green, and blue); color derivatives (hue and saturation for red, green, and blue); and a luminance section. The digital entry panel and floppy disk system form the main command console. Interfaces are available for the Rank Cintel Mark IIIC flying-spot scanner and the Bosch and Marconi CCD scanners. These interfaces, connected to a color correction system, can be switched by actuating a push button.

To create a color cross fade or dissolve, for example, the computer requires only that the first frame be displayed on the color monitor and the film jogged to the closing frame. The computer automatically adjusts the values for the frames in between and produces an aesthetically pleasing picture with a gradual fade that is smooth to the eye.

An important advantage of using this color correction equipment with the flying-spot and CCD scanners is that the film drive uses tension, not sprockets; therefore, valuable film originals can be run forwards or backwards with little danger of damage.

When The System 60XL is used with CCD scanners, the differential or RGB signal outputs of the digital store produce equivalent signals with the color corrections incorporated. All the critical color parameters can be corrected while the scanner is in the freeze mode. In most cases three frames have to be scanned before the optimum result can be achieved.

American Cinematographer Magazine has published a booklet, "Electronic Production Techniques," in which one chapter, "Electronic Color Control," describes the operation of The System 60XL, with four pages of color photographs showing the range of color modifications that can be achieved with this equipment, starting with a color negative.

Film/Video Colorist

Video operators working on electronic color correction equipment are known sometimes as *colorists*. These highly skilled technicians can quickly assess a film scene on the telecine picture monitor and decide on the nature and extent of the corrections needed to produce the best possible or most attractive television pictures, or to portray commercial products more accurately. To perform these operations efficiently, the telecine and its picture monitor must be carefully set up with a suitable test film and a monitor calibrator.

Video colorists need to have a good understanding of colorimetry and the way in which color images are formed in motion picture film. This knowledge enables them to predict with confidence the effect of a particular correction on the color picture. For example, if the picture on the color monitor has a reddish tinge, one might want to adjust the setting of the red control. But the color unbalance actually may be in the magenta direction, requiring a green adjustment to correct the reddish color. The video colorist has the advantage that the color monitor can be switched back and forth between the corrected and uncorrected pictures to determine whether or not the predicted change in the picture has been achieved. But with a lot of people waiting, the colorist who can make the right adjustment every time is soon in great demand.

ADVANTAGES OF CHOICES

Only a few years ago, broadcasters in the United States and Canada were limited to the use of camera-type telecines for reproducing films. Now there are several choices of systems and makes of equipment with different characteristics, as well as many new opportunities for using film more effectively as a source of television programs.

Camera-Type Telecines

Camera-type telecines equipped with automatic signal level control offer the advantages of easy frame rate conversion, economical unattended operation, simplified fault-free switching, optical multiplexing of films and slides for continuous on-air operation, and rugged, long-life, relatively trouble-free equipment installations.

The storage-type vidicon tubes used in most of these telecines give surprisingly good television pictures from film, considering the way in which the signals are generated. However, these camera tubes suffer from lag, which adversely affects resolution. Another major problem with these telecines is the difficulty of maintaining registration of the separate elements of the color pictures. The multiplexed telecine has a complicated optical path for the projected film, with numerous glass-to-air surfaces, requiring frequent cleaning to reduce flare.

Projection of the film into the camera requires an intermittent mechanism, advancing the film frame-by-frame at the rate of 24 per second. Some telecine projectors can run either backwards or forwards, but there is always the risk of damage to the film surfaces and the perforations. A major problem in all intermittent projectors is maintaining acceptable image steadiness as the picture frames are registered successively at a rapid rate in the projector gate.

Flying-Spot Scanner

In the flying-spot scanner, film motion is continuous and the light source is the rapidly moving spot of light in the raster on the face of a cathode ray tube. This type of scanner has been in use in Europe since the start of television broadcasting. The essential 1:1 relationship between film and television frame rates was easy to achieve in the 625-line, 50-field television system by speeding up the film frame rate slightly to 25 per second. This method could not be used in North America, however, because of the much greater difference in frame rates—24:30 for the 525-line, 60-field system.

In 1980, Rank Cintel, an English company, demonstrated the Mark IIIC flying-spot scanner designed for the North American television service. In this scanner, frame rate conversion was accomplished by sequentially scanning the continuously moving film, writing the scanned lines into a store and then reading out the lines into complete, interlaced television frames.

This development has had a profound effect on the use of film in television in the United States and Canada. Pictures from color film reproduced in the flying-spot scanner have a sharper appearance, with brighter and more saturated colors. There is complete freedom from registration errors in the scanner since color separation takes place after the film has been scanned. Interchangeable plug-in gate options are available for 35mm and 16mm films as well as 2 × 2 inch slides, with a single film transport.

The objectionable effects of storage and lag associated with camera-type telecines are eliminated in the flying-spot scanner. The scanner also produces a very clean black level, and flare is reduced to a minimum.

These features make the flying-spot scanner particularly attractive in the post-production of television programs where best possible picture quality and flexible, versatile user control over the transfer process are essential.

For the television station concerned mainly with on-air telecasting of 16 mm films, the flying-spot scanner with its extensive array of sophisticated features may not be an economically viable alternative to the continued use of existing camera-type telecines. Instead, a much simpler and more cost- effective telecine design—the CCD scanner, now available from several equipment makers—is likely to be a better choice.

The CCD Line Array Film Scanner

The main advantage of the CCD scanner is its simplicity. As the film is advanced continuously, an optical system focuses a narrow slit of light across the surface of the film. Light passing through the film, after color separation, falls on single line arrays of image sensing elements (CCDs) where the signals are generated. The signals emerge from the sensors in sequential scans of the film frames and are then converted into interlaced television frames by a 3, 2, 3 utilization of stored fields.

Another advantage of CCD film scanning is operating economy. Barring accidents, the line sensors have a virtually unlimited life, compared with costly, expendable flying-spot CRTs or camera tubes. The scanner requires no electrical registration—its performance is predictable and drift-free. No routine lineup procedures are needed.

CCD scanners are limited to a fixed form of scanning related to the CCD array so that many of the parameters of film-to-video transfer are predetermined, adjustable only by subsequent electronic processing. It is worth noting that the lens used in the scanner only has to form a narrow slit of light across the film, eliminating many of the problems encountered in camera-type telecines.

Basically the CCD scanner is a stand-alone, self-contained apparatus incorporating the film transport, image sensing and color separation mechanisms, and an electronics module with monitoring and control facilities. The old camera-

type multiplexer has been abandoned in favor of what is now known as "electronic multiplexing." Several film transports, each with its own servo and a switchable 35/16mm optical block, can be operated from a central film deck control panel. panel.

The first CCD telecine designed specifically for broadcast use is the Rank Cintel ADS 1 digital scanner. A vertical transport orientation brings the film transport within easy reach of the operator. Another feature is a built-in automatic sequencer allowing direct entry of start, stop and on cues for three transports. An even more important innovation is automatic electronic cancellation of dirt and scratches on the film. This is accomplished by taking advantage of the sensitivity of the CCDs to infrared radiation. Color film dyes are transparent to infrared while dirt shows up distinctly. By utilizing a fourth CCD array, the telecine can be made to detect defects automatically; then image processing techniques are employed to cancel the defects.

The Marconi B3410 line array scanner is claimed to be the world's first telecine with full digital processing, a major move towards the goal of eliminating time-consuming adjustments. This scanner has full logarithmic masking and true power law gamma correction, as well as aperture correction. The telecine can be operated by automatic control or with a preprogramming system called PREFIX, controlled from a dedicated panel or a keyboard, with operating data recorded on a floppy disk. This system can be used also as a search-and-find method to give quick turnaround in running film segments.

The Bosch FLD 60 scanner has been designed for multipurpose telecine use—that is, for direct on-air broadcasting of film as well as for the much more demanding requirements of program post-production. An optional A/B interface allows two scanners to be operated from one film deck control panel. A wet gate has been developed for the scanner to hide scratches on the film surfaces, similar to the equipment used in motion picture printing machines. By means of a secondary color processor, hue, saturation and luminance can be varied in six sectors independently. A film grain reducer compares film frames for uncorrelated content and grain is cancelled out electronically.

A film reproduction programmer is also available for use with this telecine. The programmer is a microcomputer-controlled color correction system in which the controlled values for color correction can be recorded on a floppy disk for later use.

Color operation with the CCD film scanner was first introduced in the early 1980s, for use in the European television system. Subsequently, digital picture storage enabled store conversion of sequentially scanned signals from the arrays into 625-line, 50-field or 525-line, 60-field.

Further development of solid-state scanning technology can be confidently expected, taking into account the simplicity of the signal-generating system in comparison with other methods employed in the past. No doubt existing camera-type telecines will continue to be used for some years to come, and it will be difficult to displace the flying-spot scanner in the most demanding applications, but the solid-state scanner in improved and expanded versions may eventually replace all other methods for making television pictures from film.

SETUP
(PROCEDURES AND ALIGNMENT)

In the earlier days of television broadcasting there was a great deal of controversy over the reasons why the television pictures from film compared unfavorably with the pictures from live studio cameras. Then a gray scale on film, mounted in a 2 × 2 inch slide, was produced and projected into the cameras of multiplexed telecines. In this way it was found that the video waveforms varied considerably from one telecine to another, and everyone involved in the tests agreed that a standard telecine setup procedure would eliminate a major cause of unsatisfactory film performance.

A test slide with cross-step gray scales, 3¼ x 4 inches in size, for use at the field lens position in multiplex telecines, was produced by Eastman Kodak Company and made available to television stations. This slide was made by depositing metal on glass; the gray scales had seven steps increasing in density from 0.30 to 2.35, in the center of a uniform gray background. The densities of the intermediate steps in the gray scales were so arranged that in a properly adjusted telecine a linear stair-step display would be obtained on the waveform monitor, with the lightest step set at 100 IRE units and the steps with highest density at black level (normally 7.5 units).

Subsequently, the Society of Motion Picture and Television Engineers submitted to the Standards Committee a Recommended Practice RP27.7— 1972, "Specifications for Gray Scale Operational Alignment Test Pattern for Telecine Cameras," which was adopted. The Kodak test slide currently available conforms with this recommended practice.

An appendix to the recommended practice describes the use of the test slide in setting up telecines. Gamma correction circuitry can be adjusted with the aid of the slide by setting the steps at predetermined signal levels on the waveform monitor. In a color telecine the transfer characteristics of the three color channels can be com-

pared and adjusted for neutral color balance. The test slide also enables correction circuits to be adjusted for minimum shading.

Television stations were slow to adopt the standard telecine setup procedure using the test slide and the accompanying recommended practice mainly because of the variability in light-transmitting characteristics of motion picture films supplied to the stations for broadcasting.

Designers of telecine equipment proposed that video signal levels could be maintained automatically by electronic controls but surveys showed that the control devices would have to provide a range of about 100:1 in peak signal level. It would be much easier for everyone, they suggested, if films could be made with greater uniformity in minimum and maximum densities.

The concept that films being produced for television should be made deliberately with highlight and shadow densities matching the steps of the cross-step gray scale tests slide started a trend that resulted in an entirely new approach to film making and telecasting. By making sure that each scene had some light areas to generate peak white signal levels in telecine, film makers found that it was much easier to achieve the desired artistic effects, and these effects would then be preserved in the television pictures.

The change-over to color broadcasting greatly accelerated this trend. At the same time, the telecine setup procedure had to be extended to include the color picture monitor. This proved to be much more difficult. Many different methods and types of measuring equipment have been tried, but it seems that none of these has given entirely satisfactory results. A survey by the Eastman Kodak Company showed an evident lack of consistency in the primarily subjective methods used to adjust picture monitors.

In the drive to improve film performance in television, a group of television engineers at the Canadian Broadcasting Corporation in Montreal proposed that the television pictures obtained from film in telecine should match the directly projected pictures as seen in a specially constructed television viewing room, simulating typical television viewing conditions. Practical demonstrations of this concept used two identical copies of the SMPTE Subjective Reference Test Film, one in a projector with a high-intensity light source and the other in a telecine with appropriately modified colorimetry, set up with a gray scale test slide. Comparison showed that a good match could be obtained between the optical and electronic displays.

The European Broadcasting Union (EBU) has published recommendations in a document, Tech 3096, giving specification for viewing conditions for the appraisal by means of optical projection of color films intended for television presentations. Para. 2 of this document states that "broadcasting authorities should aim to provide a standard of telecine performance such that any film which appears to be of good technical quality when evaluated under the special optical viewing conditions can also be expected to be of good technical quality when transmitted by color television."

In a statement by the vice-president for television affairs of SMPTE, in the same issue of the Journal, the position of telecine color balance was that American practice relied upon a standardized neutral balance adjustment using a neutral gray scale in the telecine camera field lens and placed the prime responsibility for color uniformity upon the film producer and the processing laboratory. This meant, in effect, that telecines were expected to operate unattended, with automatic signal level control, after having been set up with the standard cross-step gray scale test slide.

Most of the older models of multiplexed vidicon telecines still in use have a means for inserting the gray scale slide in a holder at the field lens position. To set up the telecine, it is necessary only to move the slide into the light path from one of the projectors and then make appropriate adjustments of camera controls to obtain the desired waveform display. The automatic signal level controls can then be turned on for normal operations.

In these conditions the pictures from old, faded motion pictures may not be entirely satisfactory, but if station operating conditions permit, manual adjustment of camera controls usually will result in significantly better television pictures. Later on, during a short break, the telecine neutral balance can be restored by reinserting the test slide in the projector light beam and resetting the camera controls to their original positions.

New RCA Camera-Type Telecines

New models of telecine cameras available from RCA—TK29 B and C, and TK 290—include automatic features for control of white level, black level, color balance, gamma balance, and flare corrections. In addition the TK 290 electronics can be set up automatically by a touch of a button, utilizing the same setup terminal as the TK 47 studio camera. All of these new telecine cameras have sealed non-telecentric optical systems with a field lens in two sections, and a holder which allows the test slide to be inserted into the air gap.

This arrangement allows the optical systems in these new camera type telecines to be set up with the cross-step gray scale test slide in accordance with the SMPTE recommended practice for neutral color balance in preparation for unattended operation.

CCD Line Array Telecines

The CCD line array film scanners available from Rank Cintel (ADS 1); RCA (TKS 100); Marconi (B3401), and Robert Bosch (FDL60), are far simpler in design and operation than the older multiplexed camera-type telecines. A central electronics module can be used to control the operation of two or three film scanners, while continuous video output is maintained by electronic multiplexing. Interchangeable optical blocks allow either 16 or 35mm film to be reproduced in the scanners. A condenser lens forms a narrow slit of light across the width of the film, and sequential scanning of film frames takes place as the film moves continuously through the gate.

The standard 3¼ x 4 inch cross-step gray scale test slide cannot be reproduced in the optical system of a CCD scanner, nor is there any way for handling 2 x 2 inch slides, even if the gray scale pattern could be made available in this format.

All of the CCD scanners are designed for unattended operation with automatic control of video levels, automatic color correction and automatic correction of optical shading. Matrixing, film masking and gamma correction are usually performed digitally, with the goal of eliminating time-consuming adjustments.

SURVEY OF NEW GENERATION TELECINES

Eastman Kodak Company has made a survey of 20 production facilities to evaluate the picture quality from color film through the new generation CCD and flying-spot scanners. In preparation of the survey a telecine analysis film (TAF) was developed, including an eight-bar color test pattern, a neutral density scale and a constant density surround. The gray scale was intended to be used to adjust subcarrier balance and black-and-white levels, while the color bars help to evaluate system colorimetry and other factors affecting hue and saturation, using a vectorscope. Along with the TAF, Kodak supplied subjective picture test films consisting of scenes on Eastman color negative film and a color print from the negative.

Several different methods were being used to adjust telecines in these production facilities, including open gate, "China Girl," film D-min, black-and-white test film and test materials fabricated in-house. Acceptable picture quality was being obtained from the telecines, but considerable differences in gray scale rendition and color quality were noted. The biggest differences were in the shadow areas of scenes. The TAF color bars as displayed on a vectorscope showed that the red bar was reproduced in a fairly consistent manner, but striking differences were observed in the phase angles of the green and blue bars.

This survey showed that there is a need for a telecine analysis film; the TAF film should fill that need. Very evident in the survey was a lack of consistency in setting up color picture monitors. Most of the methods being used were subjective.

CORLEY TELECINE TEST FILM (TP2)

A new 16mm test film for evaluating telecine performance is available from DSC Laboratories in Rexdale, Ontario. This test film was produced in cooperation with the Development Department of the Canadian Broadcasting Corporation in Montreal. The methods used to make the film are described in a paper in SMPTE Journal, April 1982, page 361.

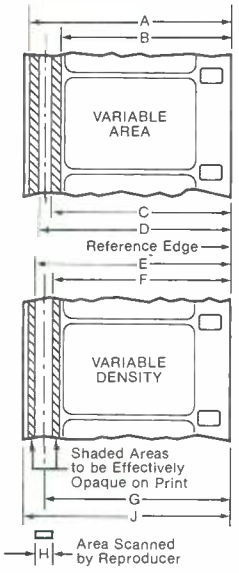
This test film has a series of patterns in two categories. The first includes colorimetry tests—white levels, gamma and black levels, and color tests of the six vector colors. The second category consists of optical and dimensional tests for shading, flare, lag, framing, focus, resolution and automatic black-and-white level tests.

The test film was designed to place the six colors—yellow, red, magenta, blue, cyan and green—in the appropriate boxes in the vectorscope display when the test film is being reproduced in a properly adjusted telecine. It should be noted that if the color-reproducing conditions, color analysis, masking, and matrixing are different than those for which the test film was developed, the test colors will not fall in the vectorscope boxes.

COLOR BARS FOR SETTING UP TELECINES

In a paper with this title in the Feb. 1978 issue of SMPTE Journal, Dr. R. W. G. Hunt of Kodak Ltd., proposed that carefully exposed strips of film arranged in sequence to produce the familiar color bar pattern on picture monitors should be used to determine optimum values of electronic masking. This proposal was based on the premise that the telecine should be considered as a complete transfer unit with the settings being done against the only relevant standard, the human eye.

In the research project by Canadian Broadcasting Corporation reported in the SMPTE Journal, March 1969, "An Engineering Approach to Color Telecine," it was proposed that the reproduction of color film in telecine should match visually the directly projected pictures as seen in a review room simulating television view-



Dimensions	Inches	Millimeters
A	0.611 max	15.52 max
B	0.513 ref	13.03 ref
C	0.540 ± 0.002	13.72 ± 0.05
D	0.600 ± 0.002	15.24 ± 0.05
E	0.610 ± 0.002	15.49 ± 0.05
F	0.530 ± 0.002	13.46 ± 0.05
G	0.570 ref	14.48 ref
H	0.071 ref	1.80 ref
J	0.628 ref	15.95 ref

Fig. 3. Standard location and dimensions of 16mm sound tracks.

ing conditions. The colorimetry of the vidicon camera telecine used for this project was modified to enable a near-perfect match to be obtained.

Another paper in the March 1984 issue of the Journal of the British Kinematograph, Sound and Television Society (BKSTS) by A. M. Harcourt of Kodak Ltd., "Film and Electronics Interface," shows (in Fig. 2 of the article) typical spectral response curves for flying-spot and CCD telecine sensors. When the spectral response curves for the typical CCD scanner are superimposed on the curves for the vidicon telecine used in the CCD research project (March 1969 SMPTE Journal), it can be seen that the red and green curves match fairly well, but the blue curve for the CCD scanner is displaced towards the green.

Research by BBC on color operation of line array CCD telecines (see SMPTE Journal, Feb. 1980, page 100) showed that chromaticity shifts in the reproduction of a series of nine test colors could be almost completely corrected by suitable matrixing.

As one writer on this fascinating subject of color reproduction in the television system has said, "The aim should be for trouble-free transference of images from one excellent medium—film—to another image maker—television—in such a way that the eye brain 'sees' it as real."

FILM SOUND

By far the most common film format in television stations is 16mm. Many of the television programs coming into the stations from distributors are in the form of 16mm prints with optical sound tracks along one edge.

An optical sound track usually consists of a kind of recorded waveform with a high density envelope, varying in area with the amplitude and frequency of the sound. Sometimes a film may have a sound track made up of transverse striations, known as variable density track.

Generally speaking, the quality of the sound from optical tracks on 16mm film is quite good. But sound quality can be adversely affected by a variety of faults in playback. The standard location and dimensions of the sound track on 16mm film is shown in Fig. 3.

Sound Track Playback in Camera Type Telecines

In the film projectors used in camera-type telecines, the sound reproducer is located just below the picture gate. An optical system focuses a slit of light from the exciter lamp on the film. Usually this lens is adjustable to accommodate films with the emulsion side—and the sound track—either towards the light source of the projector or towards the lens.

A system of damping rollers smoothes out the movement of the film over the sound scanning drum, following the intermittent frame-by-frame movement of the film in the picture gate. The sound in the film track is located 26 frames ahead (in the direction of film travel) of the corresponding picture frame.

Variations in the light-transmitting properties of the sound track modulate the light beam as it passes through the film, and the light falls on a photocell generating an output which, after suitable amplification, becomes the audio signal.

The optical system in the sound reproducer must be sharply focused (Fig. 4) on the emulsion side of the film where the sound track is located for best high-frequency response. This is a critical adjustment because the focal length of the lens is quite short; a change of only one or two thousandths of an inch can cause a noticeable high-frequency loss. Usually the lens has only two positions—either for the back or the front of the film—but the focus should be checked routinely by maintenance.

If the intensity of the scanning beam across the width of the sound track is not uniform, the

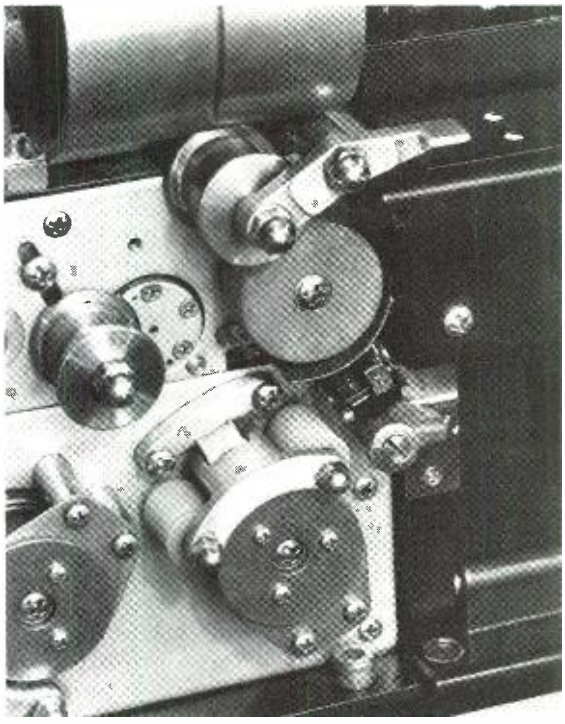


Fig. 4. A 16mm sound track scanner assembly.

reproduced sound may be distorted or low in level. Lack of uniformity is usually caused by dirt accumulating in the slit of the optical system. Incorrect adjustment of the exciter lamp filament will also adversely affect sound quality.

Many 16mm films in circulation have magnetic sound tracks. The stripe of iron oxide is coated on the side of the film facing the projector lamp. The playback head in the projector is located 28 frames ahead of the corresponding picture frame. Projectors for television service usually have selectable optical and magnetic sound playback.

The azimuth of the magnetic playback head must be properly aligned. Ideally the gap in the head should be positioned at exactly 90° to the direction of film movement. An incorrect azimuth setting results in loss of high frequencies. Head-to-film contact is vitally important in maintaining high frequency response. Periodic cleaning is essential to remove buildups of oxide or film emulsions that prevent good contact.

Sound Playback in Film Scanners

Continuous film motion in flying-spot and CCD scanners makes sound reproduction much easier, since there is no need for a system of damping rollers at the sound drum as in intermittent projectors used in camera type telecines. Fig. 5 shows the optical/magnetic sound reproducing module in the Bosch FDL60 CCD telecine.

The Bosch FDL telecine scans optical and magnetic sound tracks directly at the capstan. A roller is mounted between the capstan and picture gate to obtain the necessary picture/sound separation for 16 and 35mm film.

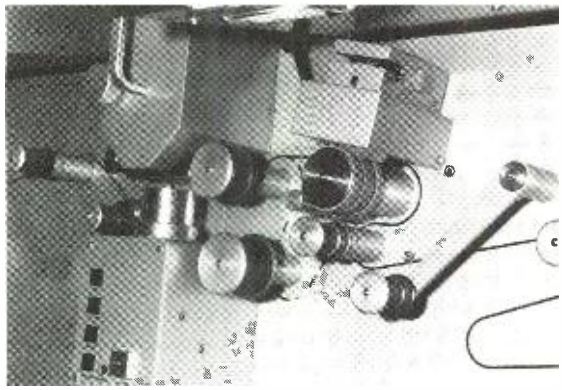
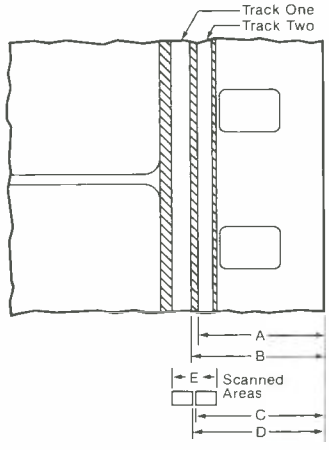


Fig. 5. Optical/magnetic sound reproducing module (Bosch FDL-60 CCD telecine). (Photo courtesy Robert Bosch GmbH, West Germany)

Sound Tracks on 35mm Film

In some applications, such as program packaging and post-production, and high-quality film-to-video transfer operations, 35mm color film is the preferred format. In many of these operations the original color negatives are reproduced in telecine, instead of making prints from the negatives.

Film prints in the 35mm format normally have optical sound tracks (Fig. 6). Flying-spot and CCD film scanners are usually fitted with interchangeable picture and sound units for 35/16mm films. While the wider film may not be en-



Dimensions	Inches	Millimeters
A	0.238 ± 0.002	6.05 ± 0.05
B	0.248 ± 0.002	6.30 ± 0.05
C	0.242 ± 0.001	6.15 ± 0.03
D	0.244 ± 0.001	6.20 ± 0.03
E	0.084 ref	2.13 ref

Fig. 6. Sound track location in 35mm print.

countered to any great extent in television stations, the new generation telecines are used increasingly in operations where these two film formats may have to be intermixed.

In postproduction operations 35mm picture negatives give the best television picture quality. Normally the negatives do not have sound tracks; if sound accompanies the pictures, it will be on a separate magnetic film.

Special equipment is needed to interlock sound playback from a magnetic film with the corresponding negative or positive picture film in telecine.

Optical and Magnetic Test Films for 35mm and 16mm Sound Reproducers

The Society of Motion Picture and Television Engineers can supply a considerable number of test films for checking and adjusting telecine sound reproducing equipment. Among these are:

16 and 35mm Optical Tracks

Buzz Track—300 and 1000 Hz tracks on opposite sides of a central strip for checking lateral positioning of the scanning beam.

Flutter—A sound recording which should reproduce at 3150 ±25 Hz.

Scanning Beam Uniformity—A 1000 Hz recording moving laterally across the track.

Sound Focus—A 5000 Hz recording for 16 mm and 7000 Hz for 35mm for focusing scanning beams.

16mm and 35mm Magnetic Tracks

Azimuth—A sound recording at 7000 Hz for 16 mm and 8000 Hz for 35 mm for checking and adjusting azimuth setting of playback head.

Flutter—A sound recording which should reproduce at 3150 Hz ± 25 Hz.

Multifrequency (16mm only)—Recordings at 15 different frequencies from 15,000 to 50 Hz, with a 400 Hz reference section.

SMPTE Test Materials for Motion Pictures and Television, a catalog listing these and many other test films is available without charge by writing to: Society of Motion Picture and Television Engineers, 862 Scarsdale Avenue, Scarsdale, New York 10583

STILLS

Broadcasters have always made extensive use of 2 x 2 inch (35mm) slides in television programming. Multiplexed camera type telecines usually include a slide projector. One popular type of projector has a dual-channel optical system and two slide drums, by which a transition from one slide to the next takes place in the form of a very quick dissolve, by remote control from the telecine operating console. With this projector, lettering can be superimposed over a television picture, and slides can be used as a simple, inexpensive method for commercial advertising, with a series of slides being shown, one after the other, at any desired rate, supplemented by audio and video, if necessary, from another source.

Making slides on color film is the easiest and least costly method for obtaining color television pictures. For television service, registering slide mounts ensure uniform positioning of lettering in the television pictures.

Storage and Retrieval

In addition to 2 x 2 inch slides, television stations make extensive use of graphics and still pictures reproduced by live television cameras. Storing, searching, and retrieving slides and graphics are time-consuming, tedious operations; yet some stations stock thousands of slides and graphics.

Methods have been devised for the electronic recording, storage, retrieval, and broadcast of slides and graphics (stills, as these picture sources are known). For this purpose, digital recording techniques are used. The digital store may be a multi-surface disk pack drive and interchangeable disk packs.

At the same time, methods have been developed for generating graphics electronically, and these electronic stills can be stored in the disk packs as well.

Computer graphics have replaced much of the work being done by artists at the drawing board, but the creativity and dexterity of the artist are irreplaceable elements in producing illustrative materials. Similarly, there is no really practical alternative to the use of the easy-to-operate, inexpensive 35mm single lens reflex film camera for obtaining sharp, colorful still pictures. These pictures can be in the form of 2 x 2 inch slides, used as is, enlarged to produce color prints, or combined with other illustrative materials and transferred into an electronic still store.

Reproducing 2 x 2 inch Slides

By far, the best way to generate electronic pictures from 2 x 2 inch slides is in a telecine. The slide projectors in the old multiplexed camera-type telecines are so versatile and easy to use that this is still the preferred transfer method in many stations.

The Rank Cintel flying-spot telecine has a programmable slide-scanning facility in which the slides are held stationary in the interchangeable slide gate. Although not quite as easy to use as

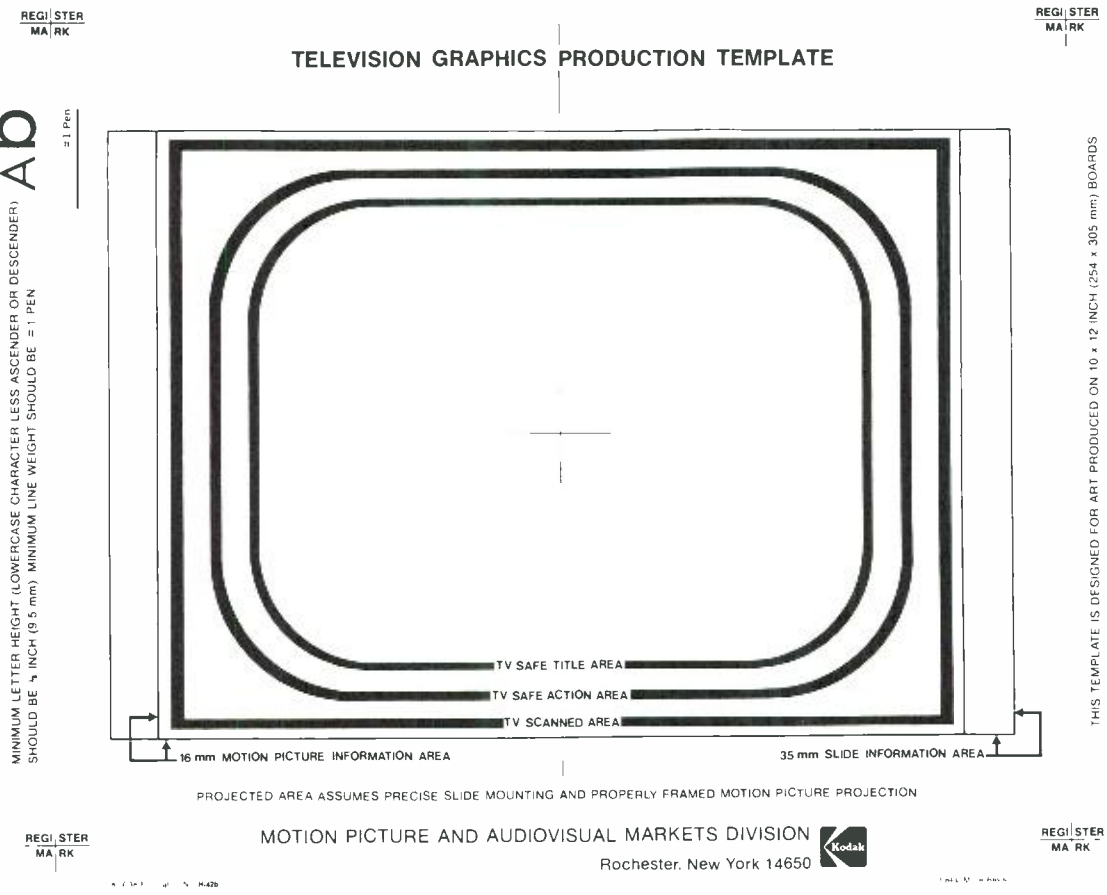


Fig. 7. TV Safe Title Area.

a camera-type telecine projector, it is capable of generating greatly enhanced color television pictures. The company also has developed an electronic slide file that can be programmed with their Amigo scene-by-scene telecine control system.

So far as is known, none of the currently available CCD line array telecines has the capability for reproducing still pictures. In these telecines single-line scanning is utilized and continuous movement of the film is needed to trace out complete television picture frames. To reproduce a 2 x 2 inch slide, the slide would have to be moved in the picture gate at the same rate as normal film movement while scanning is taking place.

Safe Title Area for Television

In the production of 2 x 2 inch slides for television, important picture information such as lettering and commercial messages should be held within the area of the television picture that will be reproduced by the majority of home receivers.

Fig. 7 shows the safe title area specified in SMPTE Recommended Practice RP9-1977.

This diagram shows the areas of the slide frame cut off at each stage between the original exposure of the film in the camera to the reproduction of the picture on the average home receiver. Unless these area losses are taken into account in making the original slides, parts of objects, letters, titles or numbers may be lost beyond the edges of the mask in home receivers.

RECOMMENDED PRACTICES FOR TELEVISION FILMS AND SLIDES

Many papers have appeared in the *SMPTE Journal* with proposals for improving film reproduction in the television system. Of particular concern have been some means for ensuring uniform film reproducing conditions in telecines. This work was started long before the introduction of the new generation of film scanners, in response to complaints by motion picture makers that they were being asked to make films with different light-transmitting characteristics to conform with different telecine reproducing characteristics.

Surveys by Eastman Kodak Company indicated there was a need for an operational gray scale slide with known transmission values for use at

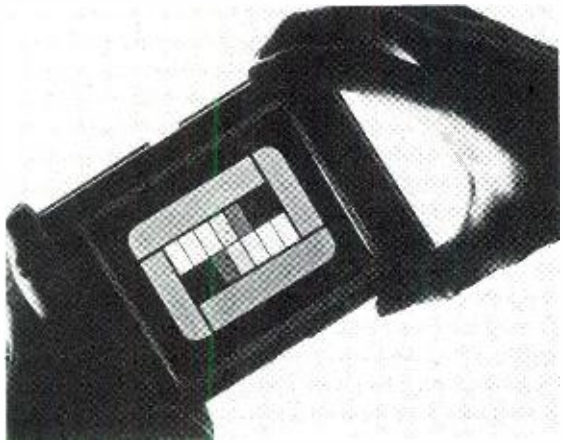


Fig. 8. Cross-Step Gray-Scale Slide (Photo courtesy of Eastman Kodak Company.)

the field lens position in multiplexed telecines, to enable balancing and shading adjustments to be made in each of the projector inputs. It should be possible also to make use of the slide for adjusting tracking and gamma.

In response to these requests, a test slide was produced (Fig. 8) and made available to television broadcasters using a metal alloy evaporated on glass. It is stable, achromatic, and non-scattering. This slide has seven steps in two rows, increasing in density in opposite directions, in the center of a uniform density surround.

In a properly adjusted vidicon telecine this slide should produce a cross-step waveform display as shown in Fig. 9.

With the aid of this slide the gain control of the camera can be set to display the minimum density step at 100 IRE units on the waveform monitor, while the maximum density step is placed at blanking level, normally 7.5 units, by adjusting the black level control.

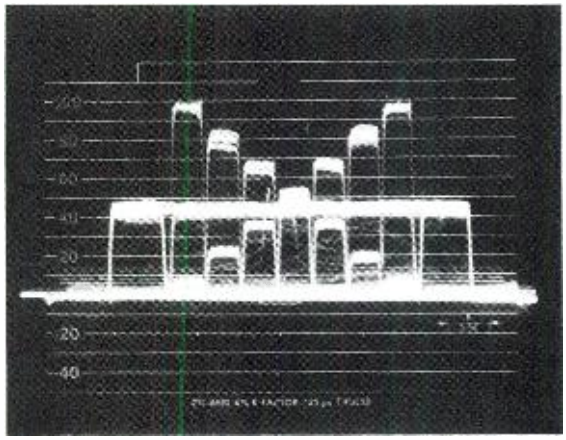


Fig. 9. Video waveform showing correctly set up cross-step gray-scale slide.

Faults in the setup and operation of the telecine show up in the waveform display from the slide as departures from the optimum waveform, as shown in the above illustration. For example, a nonlinear diffuse display of the uniform density surround indicates there is a shading problem, while blurred waveform steps are the result of poor tracking in the three color channels. In telecines where the waveforms from the three color channels can be displayed simultaneously side-by-side, tracking and gamma adjustments can be made easily.

This slide, designed to produce a linear waveform display, is an invaluable aid in setting up telecines in a precisely reproducible manner day after day. When the settings of the telecine camera controls have to be changed, as in making manual corrections of reproducing conditions for films that do not conform with density and color specifications, it is quite easy to restore the telecine to its normalized operating condition by inserting the test slide in the projector light path and re-adjusting the camera controls to obtain the normal waveform display, as shown in the illustration above.

One of the most interesting and useful side effects of using the gray scale slide for telecine alignment is that, if a normal waveform display cannot be obtained by varying the camera controls, this would indicate the existence of a serious maintenance problem. The slide can also be utilized very effectively to evaluate the effects of maintenance adjustments.

SMPTE Recommended Practice RP27.7-1972

As a direct result of this work by Eastman Kodak Company, the Society of Motion Picture and Television Engineers published Recommended Practice RP27.7-1972—"Specifications for Gray Scale Operational Alignment Test Pattern for Telecine Cameras." This recommended practice states that the purpose of the test pattern is to check:

(a) Light signal transfer characteristics of a television camera,

(b) Signal compression or clipping in the video signal channel,

(c) Operation of gamma correction circuitry,

(d) Operational setup and balance of gain and black level controls,

(e) Amplitude tracking among the video signal channels of a color television camera.

Broadcasters too became involved in devising methods for telecine alignment that would ensure uniformity of film reproducing conditions. The outcome of one of these undertakings was a telecine test slide produced by D & S Corley Ltd.

on color film material, also for use at the field lens position in multiplexed telecines. This slide has cross-step patterns similar to the Kodak slide, but with only five steps in each direction. The objective in making this slide on color film was to produce a test object with characteristics similar to the film materials being used to produce television programs.

Recently D & S Corley has produced a telecine test film TP2, designed to verify the accuracy of telecine alignment and the uniformity of film reproduction through the television system. This test film is produced on 16mm color print stock and contains several test sections.

Densities of Color Films and Slides For Television

As a guide for the makers of films for use in television, SMPTE published another Recommended Practice RP46-1972, "Density of Color Films and Slides for Television." This recommended practice specifies that the density of television white level should be 0.30 to 0.40, corresponding to fully lighted objects of a scene with a reflectance of about 60 percent. This will result in the reproduction of fully lighted human faces with reflectances of 35 to 15 percent at densities of 0.20 to 0.50 greater than television white.

At the other end of the scale, dark or black areas in which detail is not essential may have densities in the order of 2.50.

Subjective Reference Test Film

SMPTE has also produced a color television subjective reference test film, available in both 35 and 16mm formats. This film is intended for two separate purposes. First, it should serve as a subjective reference print in the motion picture laboratory for the subjective evaluation of color balance and density of prints being made for color television transmission, enabling the color timer to correct the overall balance of prints for a good subjective match with the test film. This use of the test film should result in more consistent balance of color prints for color television. Second, the test film should be used by broadcasters for the subjective evaluation of the performance of a color television film transmission system after the system has been properly set up.

The test film has a running time of about 4 minutes and contains a series of interior scenes including samples of day and night lighting.

Television Film Review Room

Another particularly interesting development has been the design of a review room for color television film evaluation, complementing the steps taken by motion picture makers and television broadcasters to improve film performance as a source of television pictures. A Recommended Practice published by SMPTE, RP41-1974, "Evaluation of Color Films Intended for Television," represents a major advance in this direction.

Recommended Practice RP41 specifies conditions that provide a standard correlate of the ambient field of view of the television screen which affects apparent picture contrast, and a constant adaptation field against which the color balance of the projected picture can be referred when making color balance judgments.

Setup of Color Picture Monitors

The setup of color monitors used for evaluation of color television pictures was another area in which improvements in uniformity were urgently needed. SMPTE Recommended Practice RP71-1977, "Setting Chromaticity and Luminance of White for Color Television Monitors using Shadow Mask Picture Tubes," specifies adjustment procedures using either a visual comparator or a light measuring instrument.

Alignment of Flying-Spot and CCD Line Array Scanners

The introduction into North American television of flying-spot and CCD scanners has raised once again the questions of how these telecines should be set up and operated to produce the best possible television pictures from film. A survey by Eastman Kodak Company has shown that good quality pictures are being produced, but there is a considerable amount of variability in gray scale and color reproduction. At the same time, users of these telecines indicated that there is a need for a test film for telecine analysis.

COLOR TELEVISION TEST FILMS AND SLIDES

Over the years, many different test films and slides have been used in adjusting and setting up television film reproducing equipment. Of these, two gray scale slides are still available, and two new telecine test films have been produced.

Cross-Step Gray-Scale Slide For Telecine

The cross-step gray-scale slide for telecine alignment developed by Eastman Kodak Company, as described in SMPTE Recommended Practice RP.7-1972, has seven steps increasing in transmission over a 40:1 range, following a 2.5 power law related directly to the gamma of the

television picture tube. A value of 50 percent transmission ($D = 0.30$) was selected for the lightest steps of the two wedges, corresponding to the recommended density for film picture highlights (see RP46-1972). Step seven, the darkest step, has a light transmission of 0.45 percent ($D = 2.35$).

The progression of transmission values for steps one through six follows the 2.5 power law over a contrast range of 40:1, appearing as a smooth step-by-step progression from near black level to reference white level. The transmission of step seven was chosen to fall half an increment below step six on a 2.5 power law curve. This provides an additional contrast range relative to step one of slightly more than 100:1, but tonal gradations (picture details) between steps six and seven may not be reproduced properly due to black compression and gamma correction circuit limitations.

The slide was designed to produce a crossed staircase display on the telecine waveform monitor. This enables gamma correction to be adjusted by setting the steps at predetermined levels. The test slide can be used also to compare the transfer characteristics of the three channels in a color camera for neutral color balance, an essential condition in telecine setup. Another use for the test slide is to check black clipping on step seven as the blanking controls are adjusted. Normally step seven should be set at blanking level. Shading correction can also be set with the test slide, using the neutral density background in the slide as a reference.

Corley Telecine Alignment Slide

The original Corley telecine alignment slide was designed to transmit essentially equal energy RGB, and its neutrality was tested in a color telecine that had been set up to neutral by perforated metal attenuators to give equal red, green and blue signal levels. The objective in making the slide on color film stock was to produce a test object with characteristics similar to the film materials being reproduced in telecines.

In a properly adjusted telecine the five staircase steps of the slide should appear at 20, 40, 60, 80 and 100 IRE units on the waveform monitor in the red, green, and blue camera channels.

These slides were numbered and dated before delivery to users, with a recommendation for periodic replacement to avoid the effects of fading or deterioration.

Later on, in 1981, Corley produced a new series of test objects for the alignment and evaluation of telecine colorimetry. This series consists of Corley's TA2 gray scale slide, a CB2 color bar slide, an MT multitest, and a flare slide, size 3¼ x 4 inches, designed for use in the optical system of multiplexed telecines and a set of six 2 x 2 inch slides including all of the above patterns, plus a depth-of-modulation slide and a TC test chart.

Eastman Kodak Company's Telecine Analysis Film (TAF)

The telecine analysis film produced by Eastman Kodak Company in preparation for a survey of new generation telecines consists of an eight-bar color test pattern, a neutral density scale, and a constant density surround. To produce the TAF a special target transparency was photographed on Eastman color negative film. Sequential red, green and blue separation exposures of the tungsten-illuminated target were made through Kodak Wratten gelatin filters (R:29, G:99, B:98) using a pin-registered camera. The gray surround of the target is 0.75 in density, and overall film exposure is adjusted to obtain specified laboratory aim density values in that area of the processed negative. The target white is clear, the black is opaque, and the intermediate gray scale steps range in density from 0.30 to 1.8 in six 0.30 increments. Each color bar is produced by appropriate combinations of either 0.30 or 1.20 density silver neutral-density filters during the separation exposures. For example, the red bar is produced with a 0.30 density filter during the red exposure, and a 1.20 density filter during the green and blue exposures.

The TAF color bars are not intended to match electronically generated color bars, but may be used to evaluate system colorimetry and other factors affecting hue and saturation using the vectorscope.

To assist in obtaining optimum television picture quality from film, TAF is being made available on 16 and 35mm Eastman color negative film; prints from these negatives on Eastman color print film and Eastman Ektachrome video news film.

Corley 16mm Test Film for the Evaluation of Telecine Performance

The Corley 16mm test film, TP2, was designed to test the accuracy of film reproduction through the television system. The first section of the film includes tests of gray scale and color reproduction (colorimetry test); the second section includes all of the other optical and dimensional tests such as shading, flare, lag, framing, focus and resolution, and automatic white and black level tests.

Included in the colorimetry tests are white levels, gamma and black levels, as well as color tests of the six vector colors. To produce the test film a mathematical model of the ideal telecine was created, and the model was used to design

the test colors, producing outputs that could be easily evaluated.

In the section containing optical and dimensional tests, the shading test consists of a 70 IRE uniform gray field; the flare test has a 100 IRE background with five black squares; the lag test has 10 diagonal traverses of a 100 IRE rectangle on a black background, and the framing, focus and resolution test chart has five bull's eyes, one in the center and one at each corner. The automatic white and black level test consists of five split field patterns in which the telecine's automatic adjusters should raise or lower white and black levels in a minimum time.

Television Film Review Room

The purpose of the television film review room is to create a viewing ambient where films intended for television can be evaluated by optical projection; that is, the directly projected pictures in the review room should match the appearance of the electronic pictures from a telecine and its associated picture monitor that have been set up in accordance with the specifications in applicable recommended practices.

SMPTE Recommended Practice RP41-1974 specifies that screen chromaticity and spectral distribution of the open gate screen in the review room should be approximately 5400°K, while the luminance of the screen should be about 40 foot lamberts. In these conditions a film conforming with Recommended Practice RP46-1972 should produce a white luminance of about 20 foot lamberts, corresponding approximately to peak white luminance of color television picture monitors at that time.

The viewing screen in the review room should have a uniformly illuminated surround at about 1/10 open gate screen illumination, and approximately eight times the viewing screen area.

FILM CLEANING AND HANDLING PRACTICES

In the normal operation of a television station it is not easy to ensure that all films are spotlessly clean and free from physical defects. The methods of film handling adopted by television stations and the degree of tolerance for image imperfections that broadcasters allow sometimes aggravate these conditions.

Film Cleaning

When film and slides are being reproduced in the television system, any particles of dust and dirt as well as scratches and abrasions on the film surfaces produce most unpleasant effects in the television pictures. And electronic image enhancement invariably enhances the picture defects as well.

The large network centers rarely broadcast a scratched or dirty print. Few stations seem to have the time, however, to clean every film prior to telecast, and replacements for defective prints are seldom readily available.

The preparation of film programs for on-air release or transfer to videotape usually involves much handling and rewinding, often at a high rate of speed. If the film reels are bent or damaged, the plastic base and emulsion may be scraped off the edges of the film and trapped between the layers on the take-up reel.

Even when the greatest care is exercised, film has the tendency to attract dirt particles. Smoking in film handling areas should be discouraged (perhaps forbidden is a better word here) because ashes and smoke residues soon become widely dispersed on floors, work surfaces, and eventually on the films.

Cleaning film to remove dust and dirt particles is not a difficult or time-consuming task. All that is necessary is a pair of film rewinds, already available in just about every station, along with a plush pad and a bottle of cleaning fluid (Fig. 10). The roll of film to be cleaned is placed on the left-hand rewind, and an empty take-up reel on the other. Put a few drops of cleaning fluid (Kodak movie film cleaner with lubricant or one of several other commercial products) on the plush pad, fold the pad over the film strand, and then by turning the crank for the take-up reel, pull the film slowly through the pad, exerting only light pressure on the film. Winding should be stopped several times through a 1200-ft. (½ hr.)

Fig. 10. Cleaning a film using a plush pad and a pair of rewinds.

roll, to shake out the collected dirt from the pad, and to add a little more cleaning solution. Don't forget to go back a few feet when cleaning is restarted, to remove any dirt buildup at the point where the film was stopped.

Avoid putting too much cleaning fluid on the plush pad, for if the surfaces of the film are left in a wet condition as the roll is being wound up, drying marks may appear on the film surfaces later on. Cleaning pads can be made up from pieces of plush velvet 12 x 16 inches in size, folded over once and sewn around the sides with the edges turned inwards.

The amount of time needed to clean a ½ hr. roll of 16mm film, winding the film slowly and changing the pad a few times, should take no more than about 5 minutes. Machines are available for large scale film cleaning operations. (For complete information on various aspects of manual or machine film cleaning, see "The Book of Film Care," KODAK Publication No. H-23, especially pages 78-83.)

Film Handling

Motion picture film will stand a considerable amount of abuse, but sooner or later a valuable color print may begin to show signs of damage. The most common forms of damage are scratches and abrasions on one or both film surfaces. Film can be scratched in any piece of equipment where it is drawn over metal surfaces. A tiny nick in the gate of a telecine projector can put a severe scratch on the film from one end to the other. Constant attention is needed to make sure that scratches are not being caused by faulty equipment.

Metal surfaces that come in contact with moving film are usually undercut in the central picture area, with slightly raised rails to support the edges of the film. Sometimes small particles of grit or dirt become lodged in these surfaces. Particles of film emulsion can also build up on these metal surfaces and cause scratches.

Abrasions are usually caused by careless handling, such as excessive rewinding speed or pulling on the end of a film to tighten up a loose roll. As a film is being rewound, one hand should be placed lightly on the edge of the feed reel to provide a little hold-back tension. Jerky or erratic winding is a common cause of abrasions. A particularly bad practice, often seen in television stations, is to start winding at high speed and then allowing the film reels to coast.

An alert telecine operator, noting scratches or abrasions on a film being telecast, can usually check quickly to determine whether the film has already been damaged, or if the damage is occurring in the station's equipment. As the film is running off the feed reel of the telecine projector, pick up the edges of the film lightly between two fingers and turn it towards a bright light. Even slight damage will show up as disturbances in the light reflected from the film surfaces.

With a little practice the probable cause of a film scratch can be identified by noting the nature of the damage. A straight, uninterrupted scratch parallel to the film edges is most likely caused in a machine where the film moves continuously. Projector scratches may show some discontinuities caused by the intermittent action of the claw and gate mechanism. Wavy scratches are usually caused by careless cleaning practices.

Another common source of damage is nicked or deformed perforations, usually caused by a faulty projector. Damaged perforations likely will give rise to unsteadiness in the television pictures. (Again, KODAK Publication No. H-23, "The Book of Film Care," is an authoritative guide on these and other aspects of film handling. See especially, pages 51-83 for tips on film handling.)

FILM SPLICING

Many different methods can be used to prepare films for on-air release or transfer to video tape. For example, a film program and all the short commercials, promos, etc., to fill a full half-hour broadcast period can be spliced together into a single, complete roll ready to run in a telecine projector or scanner.

Another method is to splice together all the commercials and promos on one reel, with short sections of leader between these items, and run this reel on one telecine projector or scanner while the main program is running on another. A complete on-air program or a video tape transfer can be produced by switching from one projector or scanner to the other.

Still another method is to transfer the film program and all the commercials, promos, etc. to video tape and package a complete program by electronic editing.

Whatever method is used in a station, some film splicing will always be needed. Each of the splices should be considered as a potential hazard in the telecasting of a program or in its transfer to tape. If a splice comes apart in the telecine, operating schedules will be disrupted, with accompanying losses of time and money.

Splicing film is not a difficult or complicated procedure. Good splices that will stand up to normal handling and repeated projections, running backwards or forwards if necessary, can be made in two different ways—either by joining with cement or by applying adhesive tape to the two sec-

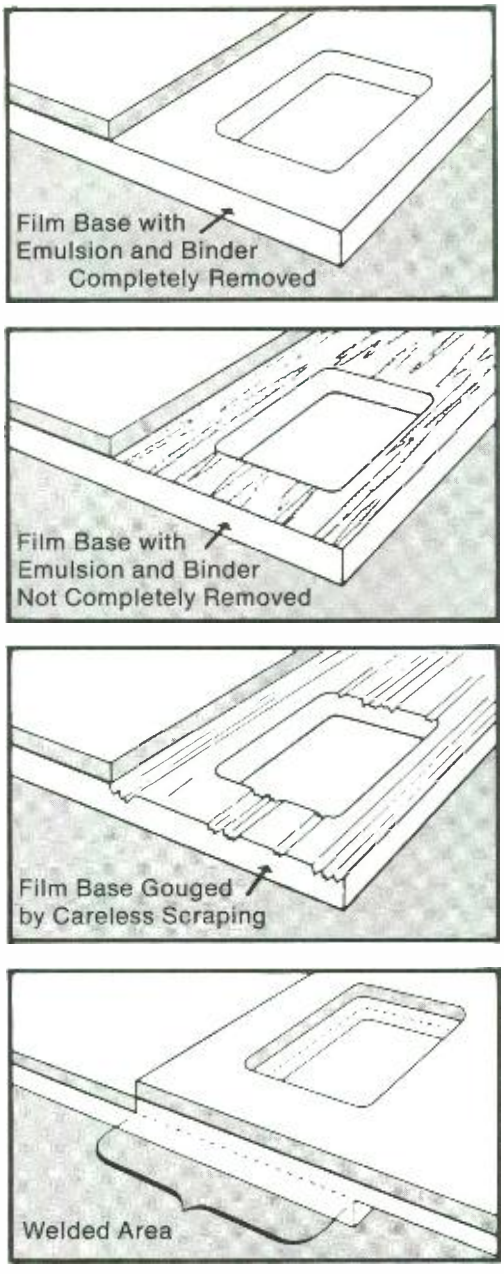


Fig. 11. Making a splice in 35mm film showing the full-hole overlap area.

tions of film at the join. (KODAK Publication H-23, "The Book of Film Care," deals with film splicing, pages 60-67.)

Cement Splices

When a cement splice is being made, the ends of the two pieces of film to be joined are overlapped (Fig. 11) in the splice area and the emulsion is removed from the lower section of film. Then a little cement is applied to the scraped area, and the base side of the other piece of film is placed over it and pressure is applied till the cement dries.

Film cement is a solvent capable of dissolving the film base.* Usually films are spliced in a small hand-operated machine, which has two hinged platens, registering pins to accurately position the two film ends by the perforations, a scraper for removing the emulsion in a narrow strip in the splice area, a knife to cut off the two ends neatly, and a hinged pressure block to hold the two ends in contact after cement has been applied. The film cement is stored in a small bottle, with a tiny brush to apply the cement sparingly in a narrow area of the film at the splice. A good splice has sufficient strength after about 20 seconds to be removed from the splicer and wound up on a reel.

Tape Splices

Tape splices are easier to make, are less likely to come apart or break during projection than cement splices, and can be made on any film base. The tape used for making splices is clear, with an adhesive backing. Many different types of film splicing tape are available.

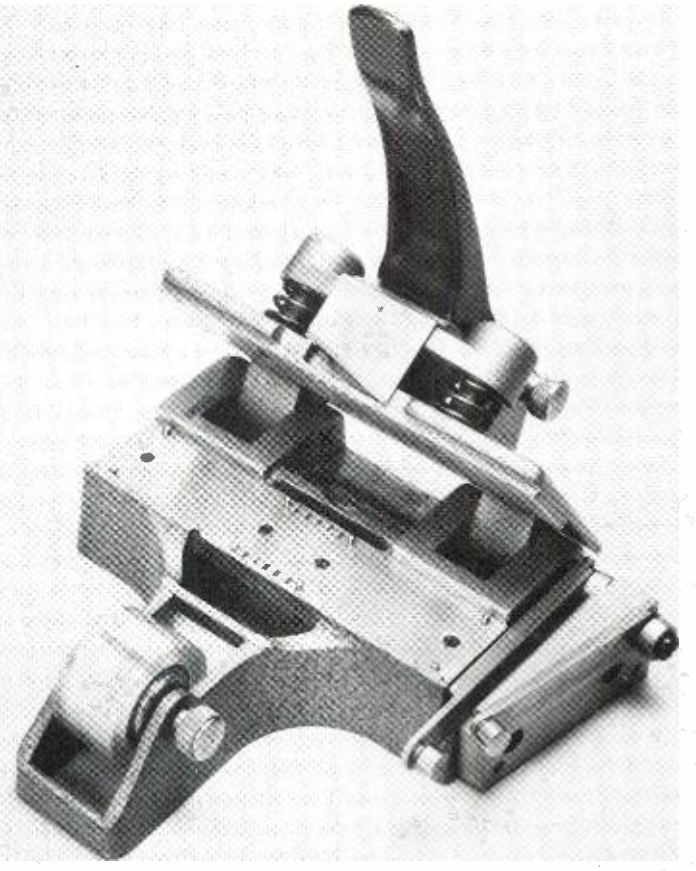
Tape splicing machines (Fig. 12), readily available, make application of the tape and finishing of the splice very easy. An important advantage of tape splices in a television station is that no frames are lost when two film are being joined together. The film ends are simply butted in the space between frames and the splicing tape applied. Another big advantage is that tape splices can be taken apart easily later on, with no damage to the film frames, by simply peeling off the tape.

STORAGE OF FILMS AND SLIDES

In a television station there is seldom any need for long-term film storage, since most of the program films coming into the station every day must be returned promptly or passed on to another station.

Film commercials, promos and the like may accumulate in a station until storage and retrieval becomes a real problem. Some stations solve this problem by transferring these short lengths of film onto video tape reels. Slides, too, require cataloging and filing unless the station has an electronic still store.

*Since no stable, commercially available solvent exists for polyester film base, cement splices cannot be made on polyester base films.



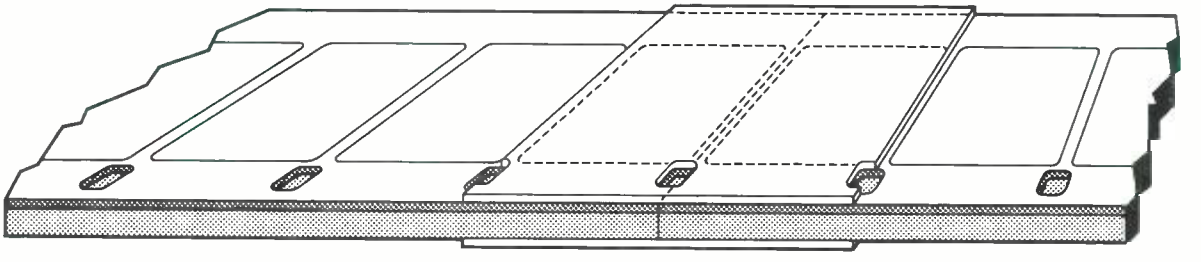


Fig. 12. Tape splicer and tape splice (perspective drawing).

Fig. 13. Film storage area in a television station. (Photo courtesy WXXI-TV, Rochester, NY.)

For those stations that must provide storage space for films and slides, a separate small room should be provided, with shelving suitably spaced for film reels, and a few drawers for slides. Metal shelving that can be assembled on the spot is easier and less expensive to install. Perhaps the best plan is to set up separate shelves or sections (Fig. 13) for 1200 ft. (½ hr.) film cans, and make use of this space for all incoming and outgoing film programs. Then, depending on the volume to be handled, a number of narrower shelves can be set up for commercials and promos. Usually these are placed in small individual 100-ft. film cans, numbered and identified for easy retrieval.

The easiest way to store slides is in cardboard or metal boxes or trays; but if a large number have to be handled, a good filing and identification system is a must to enable any one slide to be located in a hurry out of several hundred.

When Kodachrome film is sent to a central station for processing, the film can be returned uncut if desired, or the individual frames can be placed in folder-type card mounts. These mounts leave both surfaces of the film exposed and likely to pick up dust and dirt even in storage boxes. Metal slide mounts are available with the film protected on both sides by thin glass plates.

Large (1200 ft.) reels of 16mm film should be placed in cans to keep out dust and dirt and stored on the shelves upright, on the edges. Commercials and promos can be stored in any convenient manner to show the identification number. The storage area should be dry (that is, not damp) because the film emulsion absorbs moisture easily. The room should not be allowed to become too hot, as this would dry out the emulsion layer and lead to deformation. Air conditioning is needed only for long-term storage to prevent the film from becoming brittle.

The most important factor in short term storage is cleanliness of the storage area. Keeping the room clean will help to keep the film clean too and improve the station's image with the viewing public.*

*For more information on all aspects of film storage see "The Book of Film Care," Kodak publication No. H-23, especially pages 26-35.

KODAK, EASTMAN, EKTACHROME, KODACHROME, and WRATTEN are trademarks.

5.9

3/4″ and 1/2″ Video Recording Systems

Stanley N. Baron,
Eric F. Pohl,
Peter Smith, Ph.D.
National Broadcasting Company
New York, New York

3/4″ FORMAT TAPE SYSTEMS

Introduction

The U-format video tape system was developed in the late 1960's as a joint effort of the Matsushita Electric Industrial Co. (U-Vision), Victor Company of Japan (U-Tape), and Sony Corporation (U-matic). The system employs a 3/4″ cassette and records the video information using an analog component recording format known as color-under recording.

The U-format system bandwidth characteristics are less than the full-bandwidth of the NTSC system, but the U-format systems ease of use and equipment size and weight characteristics make it a desirable system for most electronic news gathering (ENG) applications and many electronic field production (EFP) applications.

Basic Definitions

The following basic definitions apply to the 3/4″ U-format helical-scan technology. They are helpful in understanding the technology employed and are adapted from SMPTE V16-861 Appendix C.

DRUM: A cylindrical column around which the tape is at least partially wrapped in such a manner as to permit rotating pole tips protruding radially from the column to form the head-to-tape interface of a video tape recording system.

SCANNER: A mechanical assembly containing a drum, rotating pole tips, and tape-guiding elements used to record and reproduce video tape recordings.

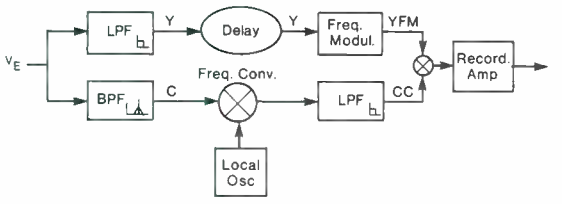
LOWER DRUM: That part of the drum in a helical-scan video tape recording system which contacts the reference edge of the tape and usually includes tape-guiding elements.

EFFECTIVE DRUM DIAMETER: A value of drum diameter which, when used in theoretical calculations, will correspond to the actual video recording produced in a helical-scan video tape recording system. The effective value is equal to or greater than the actual drum diameter.

HELIX ANGLE: The angle formed between the path of the rotating pole tips and the tape reference edge-guiding system on the scanner of a helical-scan video tape recording system.

TRACK ANGLE: The angle of a video record with respect to the reference edge of the tape in a helical-scan video tape recording system.

WRAP ANGLE: An angle that is positioned with its apex on the center of drum rotation and subtended by the line of contact between the drum and the reference edge of the tape.



V_E = encoded, composite video
Y = Luminance signal
C = Chrominance Signal
YFM = Frequency Modulated Luminance signal
CC = Converted Chrominance signal

Fig. 1. Color-under recording system.

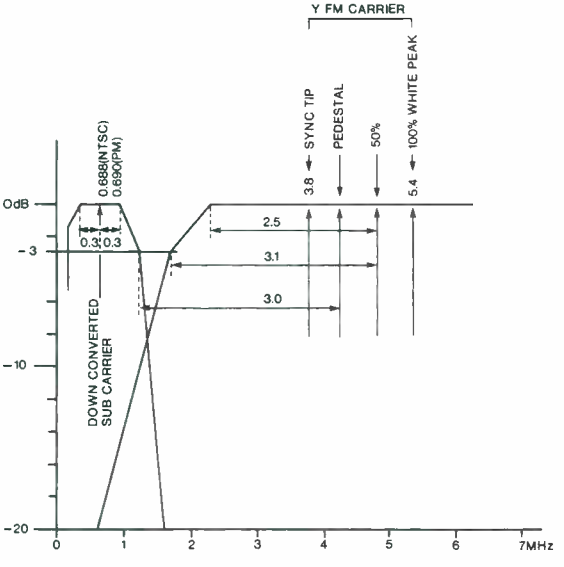


Fig. 2. Color-under frequency assignment.

Color-Under Recording

In the color-under record system, the composite color video signal is first separated into its *luminance* (Y) and *chrominance* (C) components.

The luminance (Y) component is frequency-modulated for recording.

The chrominance (C) component is heterodyned with a fixed frequency continuous signal and down-converted to a region of 600 to 800 kHz depending upon the system used. The frequency selected for the down-conversion is chosen to minimize the color-dot-crawl effects. The down-converted subcarrier (f_s) is related to the line rate (f_h) in the following manner:

$$f_s = \tfrac{1}{4}\,(2n + 1)\,f_h.$$

For U-format systems,

f_s = 688.374 kHz, n = 87.

After down conversion, the chrominance signal is superimposed on the Y-FM signal with the Y-FM carrier acting as a bias (Figs. 1 and 2). The Y-FM signal is recorded at an optimum level and the C signal is recorded at a level designed to obtain maximum linearity. This is generally 10 to 15 dB below the level of the FM carrier.

High frequency non-linear pre-emphasis is applied in the Y-channel to increase detail information prior to recording. A de-emphasis noise reducing circuit is applied during playback.

During playback the chrominance signal is extracted via a low pass filter and the Y-FM signal is demodulated. The chrominance subcarrier signal is up-converted to 3.58 MHz by a process that compensates for time-base error; it is then mixed with the luminance signal to produce an NTSC composite video signal.

Principles And Characteristics

A "helical-scan" architecture is used in the 3/4" format machines, in that tape unspools from the supply reel and is presented to the drum in such a manner that the heads slant across the tape to form part of a helix.

Two sets of video heads are placed 180 degrees apart on the scanner and the tape is wrapped around the scanner for slightly more than 180 degrees (Fig. 3). Each set of video heads consists of two heads, one for the channel record/playback and one for the channel erase. The scanner rotates at exactly 29.97 revolutions per second (approx. 1800 rpm) recording one TV frame per revolution and one TV field per 180 degree scan.

The 3/4" format provides, in addition to the two video channels, four longitudinal tracks, two for audio, one for control track and one for the address track (Fig. 4). The video tracks do not interfere with the address track and can be independently edited.

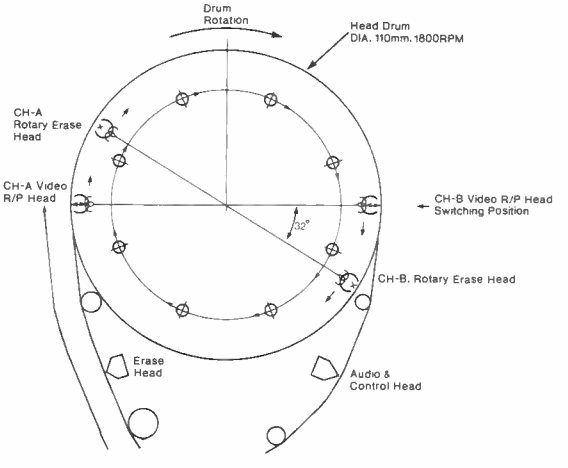


Fig. 3. U-format.

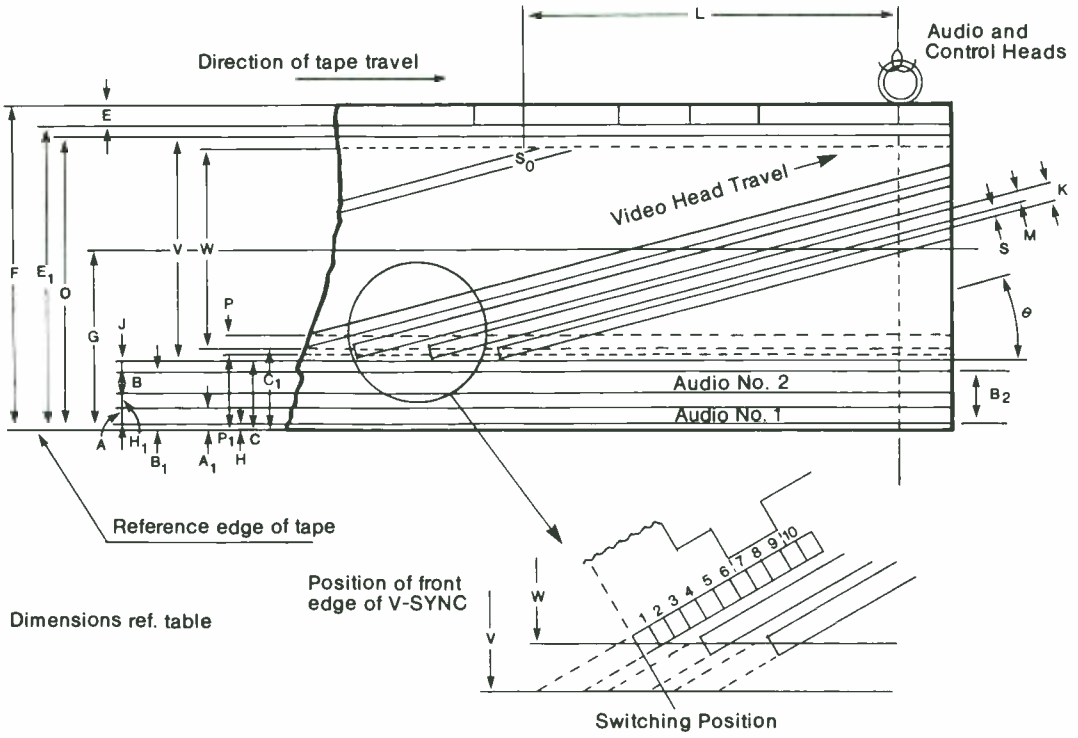


Fig. 4. Track configuration and dimensions from magneto-sensitive side.

	Dimensions	Millimeters		Inches	
A	Audio No. 1 width	0.80	± 0.05	0.0315	±0.0020
A_1	Audio No. 1 reference	1.00	nom	0.0394	nom
B	Audio No. 2 width	0.80	± 0.05	0.0315	±0.0020
B_1	Audio No. 2 reference	2.50	nom	0.0984	nom
B_2	Audio track total width	2.30	± 0.08	0.0906	±0.0031
C	Video area lower limit	2.70	min	0.1063	min
C_1	Video effective area lower limit	3.05	min	0.1201	min
D	Video area upper limit	18.20	max	0.7165	max
E	Control track width	0.60	nom	0.0236	nom
E_1	Control track reference	18.40	+ 0.28 — 0.18	0.7244	+ 0.0110 — 0.0071
F	Tape width	19.00	± 0.03	0.7480	±0.0012
G	Video track center from reference edge	10.45	± 0.05	0.4114	±0.0020
H	Audio guard band to tape edge	0.2	± 0.1	0.008	±0.004
H_1	Audio-to-audio guard band	0.7	nom	0.028	nom
J	Audio-to-video guard band	0.2	nom	0.008	nom
K	Video track pitch (calculated)	0.137	nom	0.00539	nom
L	Audio and control head position from end of 180° scan	74.0	± 0.5	2.913	±0.020
M	Video track width	0.085	± 0.007	0.00335	±0.00028
P*	Address track width	0.50	± 0.05	0.0197	±0.0020
P_1	Address track lower limit	2.90	± 0.15	0.1142	±0.0059
S	Video guard band width	0.052	nom	0.00205	nom
V	Video width	15.5	nom	0.610	nom
W	Video effective width	14.80	± 0.01	0.5827	±0.0004
θ	Video track angle, moving tape	4° 57′ 33.2″			
	stationary tape	4° 54′ 49.1″			

TABLE 1. Recorded Magnetic tape records.

The U-format system provides an overlap period during which the same information is recorded by the head preparing to leave the tape and the head which is initiating its pass. This overlap also exists in playback. Electronic switching is used to control the changeover to produce a continuous TV signal.

The switching position takes place in the vertical interval before the leading edge of vertical sync. The RF output extends past the switching point by approximately three horizontal lines to provide three horizontal lines of overlap.

Typical Performance Specifications

Video

Input Signal: NTSC Composite, 1.0 V p-p
Dubbing Input/Output:
  Luminance: 1.7 V p-p
  Chrominance: 0.9 V p-p
Signal-to-Noise Ratio:
  47 dB (color mode)
  48 dB (monochrome mode)
Horizontal Resolution:
  260 lines (color mode)
    (approx. 3.2 MHz BW)
  340 lines (monochrome mode)
    (approx. 4.2 MHZ BW)

Audio

Frequency Response: 50 Hz to 15 kHz
Signal-to-Noise Ratio: 48 dB (ref. 3% distortion level)
Distortion: 2.0% (1 kHz at reference level)

System Features

Use of the U-format system since its introduction has caused evolutionary changes in system capability. Various features and functions are available although many may be options depending upon system application and manufacturer and model. These features include:

Shuttle and Jog Search Functions

The search functions enable quick location of edit points. In the shuttle mode a recognizable picture is obtained at speeds from 1/30 to 10 times normal speed in both forward and reverse direction. In the jog mode the picture moves in one field increments according to the motion search control dial.

Dynamic Tracking

Playback head position is servo-controlled to maintain optimum tracking in still frame and other nonstandard-speed modes.

Editing

Equipment which provides edit mode capabilities, in general, permits preroll, assemble, insert mixed audio channel editing, preview, entry in/out, and trim field-by-field capabilities.

Dubbing

Dub mode provides the capability of directly recording the separated luminance and chrominance channels without the need to up-convert and reassemble and then decode and down-convert.

Time-Code Generator: internal automatic time-code generator and reading per SMPTE Time Code

Time-Base Correctors: normal color-under processing corrects time-base error sufficiently for viewing video playback directly on a color monitor or receiver. However, to meet broadcast specifications, additional time-base correction is required. Time-base correction is also required to provide proper signal timing in the stop motion or enhanced motion modes.

Drop-out Compensation (DOC): A playback carrier drop-out detector and compensator replaces the missing RF information with a delayed signal.

Summary

The 3/4″ U-format system was conceived originally as a non-broadcast system due to its low cost and limited bandwidth. The heterodyned signal was sufficiently stable to lock a monitor but was not broadcastable.

With the advent of low cost TBCs and portable recorders, 3/4″ became used in broadcast news operations because of its obvious advantages over film with respect to turn around time, program length and general adaptability to news gathering. It thus became the defacto ENG standard.

As technology has improved, 3/4″ continues to be improved to its limits. But there are definite constraints of the format itself. The color-under technique allowed slower tape and drum speeds by mixing the color information to a lower frequency, and bandlimiting the luminance information. The restricted luminance bandwidth limits detail and can cause ringing on abrupt transitions. Because the chroma is recorded as an AM signal, it is susceptible to off-tape amplitude variations (unlike FM). Because the color signal is separately filtered and processed, chrominance-to-luminance delay can be difficult to maintain, and the resulting bandlimiting can cause ringing on large color transitions. However, recent developments have overcome some of these limitations.

The 3/4″ U-format continues to fulfill a need. Full-bandwidth recording provided by Quad or

Type C was not cost efficient. Low cost TBCs allow heterodyned U-format video to be broadcast and 3/4" has found a comfortable niche in ENG and EFP recording despite its limitations.

MAINTENANCE

Introduction

The key to maintaining any piece of equipment is a systematic approach for both attacking an unknown problem and preventing recurring problems. A systematic preventative approach maintains performance and reduces out-of-service time.

One can break down the maintenance of U-format machines into two areas. One area is the routine procedures for prevention and upkeep. Troubleshooting and problem analysis can be divided into functional subgroups to aid in problem determination.

There are a few items discussed herein that pertain to the Sony BVU-800, but for the most part, all items are generally applicable to all 3/4 inch equipment.

Routine Activity

The following should be performed on a regular basis, starting with that which should be done most frequently.

1. Operational Check

An operational check should be performed before each extended operational session. This is merely a quick verification of all functions of the machine, from tape threading to editing.

All button lamps should be checked because they burn out regularly. The lamps which illuminate the cassette area should also be checked.

2. Cleaning

Cleaning of video heads

Cleaning of the video heads should be performed with a non-residue producing evaporative solvent such as freon, and a non-lint producing cloth wipe. (There are commercial products available for this application.) When the drum is cleaned, one must take care in gently cleaning heads in a direction parallel to head travel only, otherwise the heads can be damaged. The best technique is to turn the drum slowly while holding the cloth against it.

Cleaning of the tape path

All surfaces that are in contact with the tape should be cleaned, including the fixed heads (time code, audio/control track, erase) and all tape guides.

Cleaning and inspection of pinch roller

It is very important for the pinch roller to stay clean. It easily collects oxide residue, and loses its ability to grab the tape. The roller should be inspected for aging or deformation, and changed if necessary. The roller can dry out and not grab effectively.

Head Degaussing

Both the rotary heads and the fixed heads should be degaussed. The degausser is placed as close to the head as possible, turned on, and drawn away before it is turned off. This removes residual magnetization from the heads. (This procedure does not have to be done as often as cleaning but is easily done at the same time.)

Cleaning of head drum slip rings

This need only be done when necessary but is included for completeness. The slip rings should be cleaned with a soft brush to remove built-up dirt. If necessary, freon can be used.

3. Tension Detector Adjustment

The BVU-800 has two tension detectors which control tape tension by regulating power supplies to the take-up and supply reels (Fig. 5). The detector is an electromechanical device which consists of an LED which shines through a slit onto a special photoresistive cell. The slit is on a plate which is in contact with the tape and moves according to how much tension is present. When the slit moves, a varying control voltage results. This control voltage is used to vary the reel motor torque.

The tension detectors are replaceable and should be checked and adjusted as needed, on a regular basis (manufacturer recommends 500 hrs.). Both physical alignment and calibration should be checked.

4. Head Replacement and Optimization

The rotary video heads are not replaced individually, the whole upper drum assembly is replaced when any one head fails. The upper drum is easily changed, but it must be carefully aligned. The manufacturer supplies an eccentricity gauge which is used to align the drum. The gauge assembly is attached to the chassis adjacent to the drum so that the tip of the gauge is in contact with the rim of the drum. If the drum is not centered on the flange the gauge indicates its deviation. The position of the drum on the flange is adjusted until the gauge indicates a deviation of less than 5 microns during a revolution.

After replacement of the head assembly, adjustments should be to optimize performance for the characteristics of the new head. The following adjustments, should be made (check with manufacturer's manual).

- Equalization
- Playback RF Levels and Balance
- Record Currents (Y, Chroma, Erase)

It is also desirable to perform these adjustments several times throughout the life of a set of heads, because their characteristics change as they wear. Manufacturer's recommendations are for replacement after 1000 hours and optimization at 200, 500 and 750 hours.

Functional Divisions for Troubleshooting

1. Threading

The cassette loading process involves sensors, solenoids and motors, which detect and control the loading process. If a sensor becomes misaligned, the process will halt. If a solenoid or motor cycle is out of specification a mechanical jam could occur. The manufacturer's manual should be consulted for the mechanical adjustments.

A good understanding of the control logic associated with the loading cycle will ease in troubleshooting. Often the manufacturer outlines a logic timing diagram which displays when each event is supposed to occur. Also, the control logic, is often designed to put the machine into a safe state (one that will not result in tape or machine damage) when it detects that certain cycles have not occurred. Understanding the possible conditions that result in the machine entering this state, will help.

2. Control System

The control system interprets all input from the buttons and sensors, and for actuating events in the sequence required. Most problems with the control system "hanging up" are due to a cycle that was not completed. This is unlikely to be a control system problem but a problem with a signal that the control system is supposed to see. Therefore it is important for all the sensors to operate properly.

3. Tension and Tape Run

If the cassette successfully loads, but jams still occur, or if portions of the picture appear consistently noisier—implying a nonlinear RF envelope, the tension and tape run should be checked.

Tension

As previously mentioned, the tension detectors feedback a control voltage which in turn regulates the take-up and supply reel tension (Fig. 5). Other adjustments that affect tension are calibration of the brake and motor sensitivity.

Tape Run

After the tension adjustments have been made, the tape guides should be checked. The manufacturer's manual should be consulted for this. But the objective is to be able to play an alignment tape, and observe a uniform RF envelope, implying that the video heads are successfully staying within the recorded tracks on the alignment tape. If the entrance or exit guides are not properly aligned, the beginning or the end of the RF envelope will have a lower amount of detected RF. The many other tape guides are responsible for aligning the tape properly as it passes by the stationary heads, and maintaining a uniform edge to edge tension as the tape turns and changes height. These all must be checked and adjusted per manufacturers specifications.

Notes on use of Alignment Tape

For both audio and video systems alignment, procedures regarding the use of alignment tape should be understood. The alignment tape should be handled very carefully, and stored under good conditions. One should make sure the machine is running with correct tension, and that the tape path is clean and degaussed, before the alignment tape is played on the machine. It is best to run the tape all the way through without stopping because starting and stopping may stretch the tape and destroy its accuracy.

4. Servo System

Elements of a Servo System

There are 4 elements to a basic servo system:

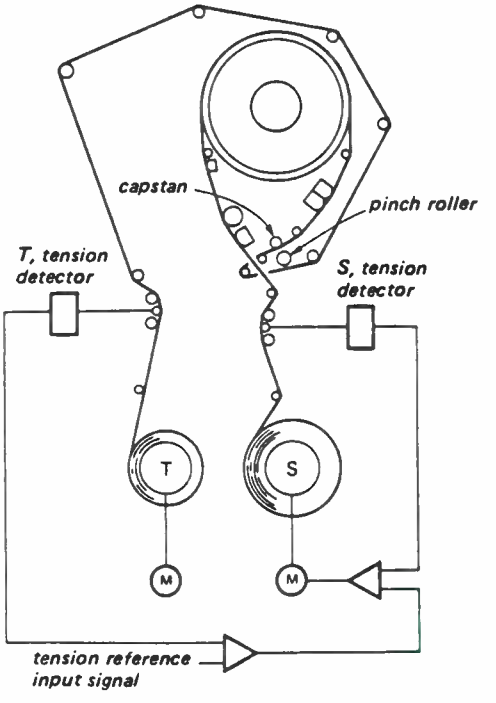


Fig. 5. Tension controlled by regulating power supply.

1. Input Reference
2. Motor or some other device to provide movement
3. Feedback detector of output position
4. Comparator to determine difference between desired and achieved output

Adjustments to the many servo systems in a machine (such as that in Fig. 5) include calibration of references and calibration of open loop responses. The manufacturer's manual should be consulted for these adjustments.

5. Audio System

Alignment of the audio system is similar to an audio recorder, except that there is a combined record/play head. Physical alignment should be checked, then an alignment tape played back to verify playback bias, equalization and levels should be adjusted to result in comparable playback through the set up playback electronics. The erase current also should be checked.

6. Video System

Alignment of the video system should be performed in the same manner as that described for audio, in that playback electronics are aligned first according to alignment tape, followed by record adjustments to optimize playback through the previously adjusted playback electronics.

Functional Divisions

1. Playback amplifier optimization (as previously described)
2. Demodulator adjustments (both luminance and chroma)
   ACC adjustment
   DOC adjustment
   Playback color oscillator
3. Modulator adjustments
   Color separation filter
   Local oscillator for chroma modulator
   Record equalization

The manufacture should provide procedures to perform the above adjustments.

7. Power Supply

The power supplies can be checked and adjusted if they are suspected of causing a problem.

Things to look for:

1. Purity of dc
2. Regulation under varying loads
3. Regulation over the specified range of input voltages.

Summary

This section, in conjunction with the theory section, is intended to provide an understanding and an organized approach towards maintenance of 3/4 inch equipment. The two most important items being an effective preventative maintenance schedule and a thorough functional understanding of the machine to enable quick isolation.

1/2" FORMAT VIDEO TAPE SYSTEMS

Principles And Current State Of The Art

Introduction

The introduction of the 1/2" VHS and Beta cassette tape formats was directed at the consumer market and featured long playing times at the sacrifice of professional performance levels. Subsequent improvements in tape technology offered an opportunity to provide 1/2" tape formats meeting various levels of performance for specific professional applications.

Three different 1/2" formats were introduced in the 1982-1985 time period. The three systems, in the order of introduction, are the M-Format, Betacam format and MII-Format.

All three are based on a helical-scan video tape recording system using 1/2" tape cassettes. All three employ component recording in that they record the luminance (Y) and baseband chrominance (C) signals for one television field on separate tracks with each pass of the recording head. Assigning separate tracks for the luminance and chrominance-video permits the system to have a wider baseband recording capability, but with a sacrifice in tape usage.

Among other factors, differences in the record locations and dimensions, tape speed, and the method of encoding the chrominance channel produce various levels of performance among the three systems.

These differences in implementation and the resulting differences in performance are described in following sections.

Component recording offers the following advantages over composite recording:

- editing without being constrained by color framing considerations,
- no color misregistration from envelope delay problems inherent in composite systems,
- lack of sub-carrier caused moire.

The disadvantages are:

- the need to maintain signals in component format throughout the editing process, or subject video to degradation due to continual encoding and decoding

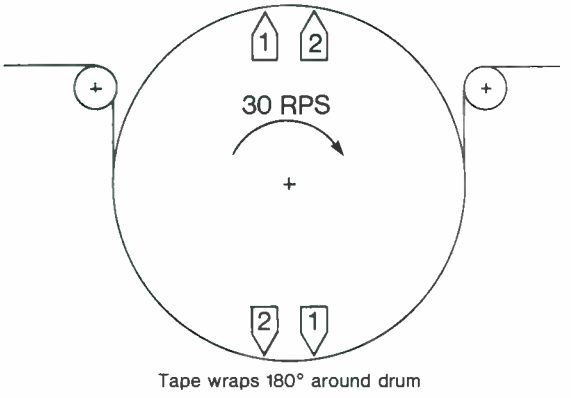


Fig. 6. Half-inch tape format.

- chrominance/luminance delay variations
- less efficient use of tape

Basic Definitions

The basic terms, such as *drum* or *wrap angle*, are essentially the same for 3/4″ and 1/2″ recorders. Please see page 5.9-159 of this chapter for a brief glossary.

Principles And Characteristics

A "helical-scan" architecture is used in all three 1/2″ format machines, in that tape unspools from the supply reel and is presented to the drum in such a manner that the heads slant across the tape to form part of a helix.

Two sets of video heads are placed 180 degrees apart on the scanner and the tape is wrapped around the scanner for slightly more than 180 degrees (Fig. 6). Each set of video heads consists of two heads, one for the luminance (Y) channel and one for the chrominance (C) baseband channel with the two channels (Y and C) recorded simultaneously. An additional set of heads is employed for "flying erase." The scanner rotates at exactly 29.97 revolutions per second (approx. 1800 rpm) recording one TV frame per revolution and one TV field per 180 degree scan.

All three systems provide, in addition to the two video channels, four longitudinal tracks, two for audio, one for control track and one for time code (Fig. 7). The video tracks do not interfere with the time code track and can be independently edited.

The differences in performance are attributable to, among other factors, the variations in implementation such as drum diameter, frequency spectrum, chrominance coding, writing speed and tape speed, the details of which are provided in Tables 2 and 3 and Fig. 8.

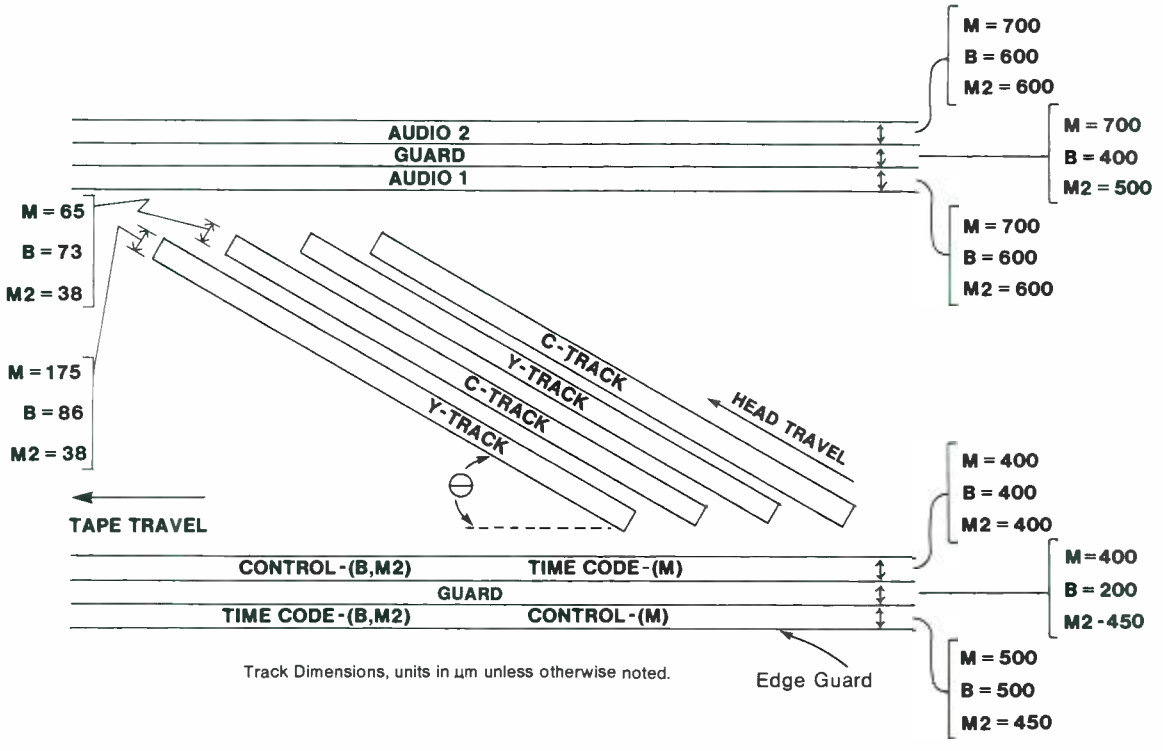


Fig. 7. Tape format comparison.

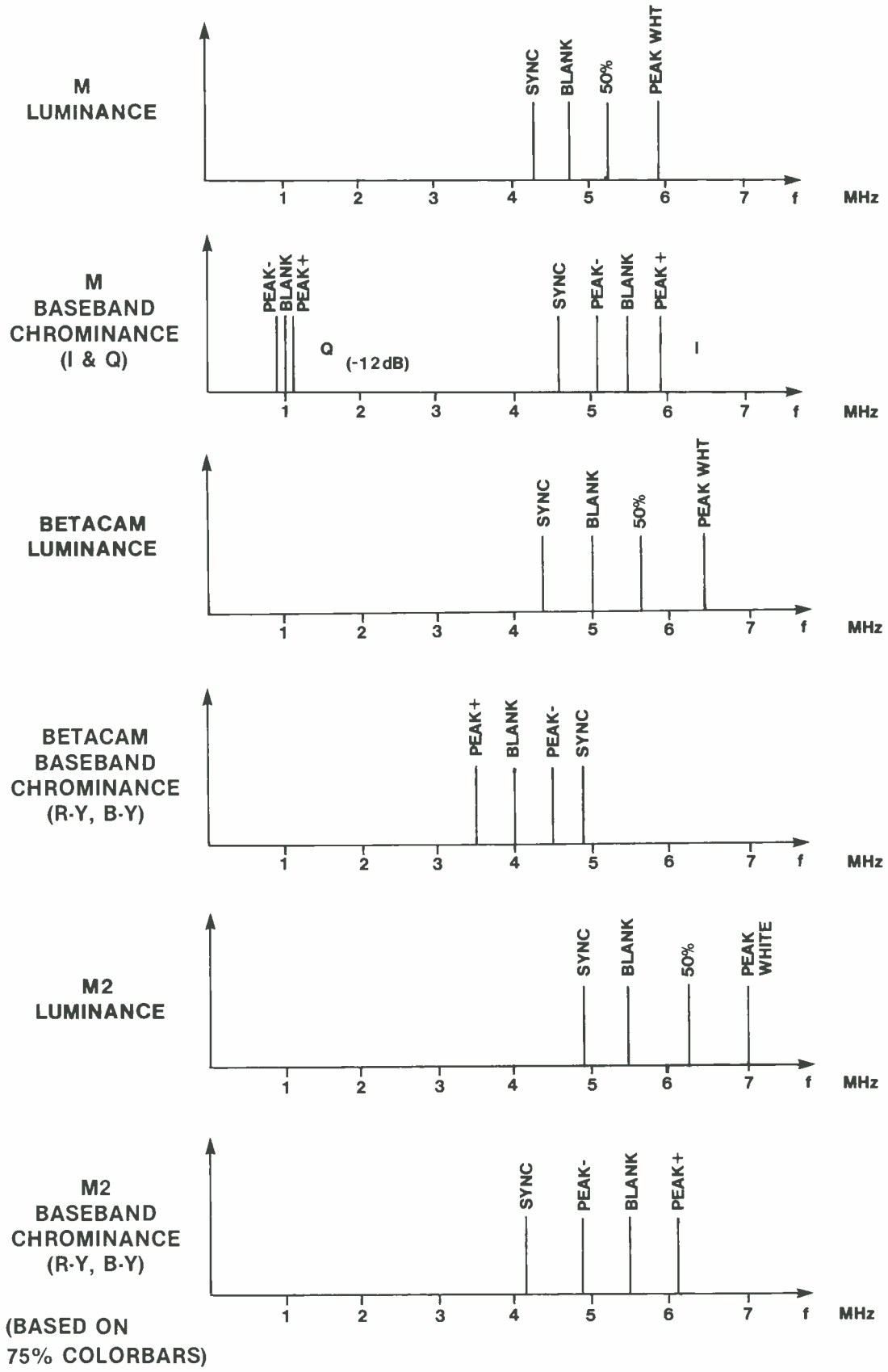


Fig. 8. Frequency spectrum of formats.

TABLE 2. Format implementation comparison.

	M	BETACAM	MII
DRUM DIAMETER	62.0 mm	74.487 mm	76.0 mm
R.P.M.	1800	1800	1800
WRITING SPEED	5.63 m/s	6.89 m/s	7.09 m/s
LINEAR TAPE SPEED.	204.5 mm/s	118.52 mm/s	67.65 mm/s
CASSETTE LENGTH (standard)	246 m	150 m	391 m
PLAY LENGTH (standard)	20.0 min.	21.1 min.	96.3 min.

In all three systems, the luminance (Y) and baseband chrominance (C) channels are pre-emphasized by two methods before modulation.

Luminance And Chrominance

In all three systems the luminance signal is converted to an FM signal and is recorded on the Y track. The three systems differ in the method of encoding chrominance and the FM deviation used as shown in Table 4.

The M system carries the color information encoded in the I and Q format defined for the NTSC system. These are converted to a 5.0 to 6.0 MHz deviation FM signal for I and a 0.75 to 1.25 MHz deviation FM signal for Q. The FM signals are then summed (frequency multiplexed) and recorded on the color track as shown in Figs. 3 and 4. The Q signal is linearly recorded with the I level increased to provide the high-frequency bias needed for linear recording.

The Betacam and MII systems carry the color information encoded as R-Y and B-Y. These are time compressed 2:1 so that each of the R-Y and B-Y components are contained in a period equivalent to ½ active horizontal picture interval (Fig. 10). An additional delay of approximately ½ H is applied to the B-Y component to place the compressed B-Y information in the last half of the line. The information is then FM modulated as described in Fig. 8.

During playback the decompressed R-Y and B-Y information is demultiplexed, and any system processing delay differences between the three channels (Y, R-Y, B-Y) are corrected.

TABLE 4.

M	
Luminance	(deviation 1.6 MHz)
Chrominance	I and Q frequency division multiplexed (Q deviation 0.36 MHz, I deviation 1.25 MHz)
BETACAM	
Luminance	(Deviation 2.0 MHz)
Chrominance	Time division multiplexing of compressed R-Y signals (deviation 1.4 MHz)
MII	
Luminance	(deviation 2.1 MHz)
Chrominance	Time division multiplexing of compressed R-Y and B-Y signals (deviation 2.0 MHz)

System Features

All three systems offer the following features, some of which may be optional on specific models:

Control track: The control track provides a constant flux level, alternating in polarity, and completing one cycle per frame. The polarity of the track-control record is such that the south pole of the magnetic domains points in the direction of tape travel when channel 1 (field 1) is recording.

TABLE 3. Manufacturers' specifications.

Technical Performance

Parameter	M – (1)	Beta(2)	MII(3)	
Luminance Bandwidth (–3 dB)	4.1	4.1(–6 dB)	4.5	MHz
Luminance SNR	50	48	49	dB
K factor (2T)	2	2	<2	%
Chroma Coding	I,Q	R-Y,B-Y	R-Y,B-Y	
Chroma Bandwidth	1.3	1.5	1.5	MHz
Chroma SNR	52	50	50	dB
Diff Gain	<3%	<3%	<2%	%
Diff Phase	<3°	<3°	<2°	degrees
Y-C Delay	<30	<20	<20	ns
Audio Bandwidth (±3 dB)	40-15k	50-15k	50-15k	Hz
Response	±2	±3	±1.5, –3	dB
Audio SNR (3% distortion)	53	50	56	dB
Audio Distortion	1.0	2.0	1.0	%
Wow & Flutter	.15	.15	.1	%
Track Width	Y175, C65	2 × 73 Y86, C73	2 ×38	um

(1) Per AU 300 Specification
(2) Per BVW 40 Specification
(3) Per AU600 Specification

One Piece Recorder/Camera: Each of the systems offers a one-piece recorder/camera featuring a recorder time of 20 to 30 minutes depending on the system. Power consumption is less than 12 watts and weight of less than 4 kg (sans lens) depending upon the model.

Studio Recorder: Each of the systems offers a studio player or recorder/player with built-in TBC, jog/shuttle functions, built-in time-code generator, dynamic tracking and/or editing functions depending upon the model.

Field (Portable) Recorder/Player: Each of the systems offers a field unit with various options with power consumptions less than 24 W and weight less than 7 kg depending upon the model.

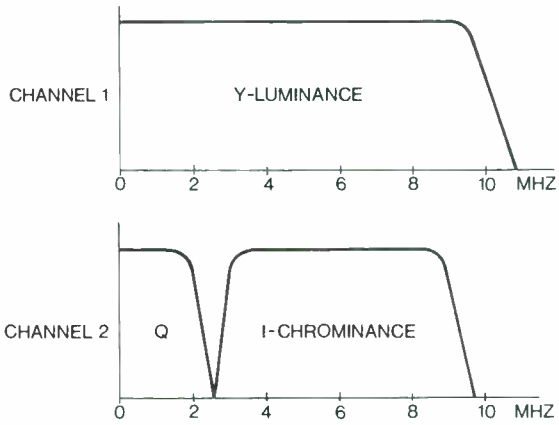


Fig. 9. M system two-channel FM multiplexed spectrum allocation.

Time-Code Generator: SMPTE/EBU Time Code is automatically recorded on the dedicated time-code track.

Audio Noise Reduction: Dolby C ™ is included on most models.

Additional audio tracks: some systems offer additional audio channels recorded in portions of the video tracks using FM or PCM techniques, offering better quality than the analog tracks.

High Speed shuttle: between 5x and 32x depending upon the manufacturer and model.

Camera/Recorder Playback: viewfinder playback with various performance indications is provided in most models.

Back-space edit: on camera/recorders, provides sequential recording without picture break-up at transition points.

Editing features: include frame-by-frame forward or reverse trim, selectable pre-roll time, auto edit in/out functions, dub interconnections, audio mixing, built-in TBC's, and most features found on professional broadcast VTRs.

Summary

Pursuit of full bandwidth recording, such as Quad or Type C, resulted in a push for higher FM carrier frequencies (Low-band to High-band

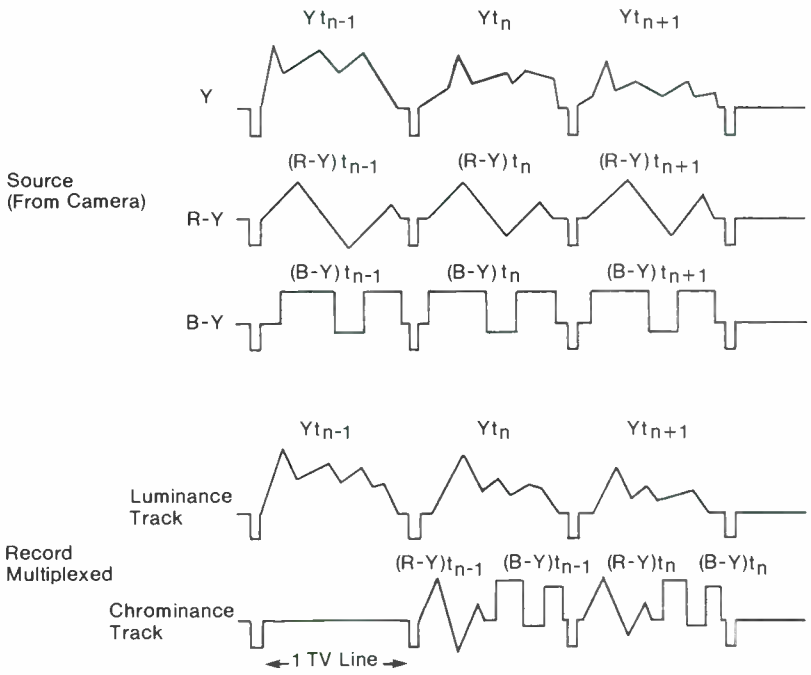


Fig. 10. Betacam, MII two-channel time domain multiplexed allocation.

etc.) This resulted in shorter recording wavelengths. The problems associated with using shorter wavelengths are a poorer carrier-to-noise ratio due to smaller, longitudinal magnetic components and an increased chance of drop-outs.

By separating luminance and chrominance information prior to recording, and recording on two tracks in one scan, one can utilize longer recording wavelengths. Also, if source material is from a camera, the information can remain in component form to the recorder, preserving chroma bandwidth.

These 1/2″ formats apply these techniques to enable a smaller tape and a smaller scanner with only a 180 degree wrap (as opposed to Type C <360 degree). Near full bandwidth can be achieved as opposed to color-under systems which sacrifice bandwidth.

MAINTENANCE

Introduction

Although at first glance, 1/2″ component format machines may appear similar to 3/4″ U-format counterparts, the similarity ends there. The video signal system is significantly different and requires additional test equipment. Also, the circuit board construction techniques applied in camera recorders require a significant change in repair procedures. Both new equipment and techniques are required for repair work to be done on the boards. In this section we will discuss maintenance of 1/2″ component equipment.

Routine Activity

The following should be performed on a regular basis.

1. Operational Check

An operational check should be performed before each extended operational session. This is merely a quick verification of all functions of the machine, from tape threading to editing.

2. Cleaning

Cleaning of video heads

The following applies to essentially all helical video tape recorders.

Cleaning of the video heads should be performed with a non-residue producing evaporative solvent such as freon, and a non-lint producing cloth wipe. (There are commercial products available for this application.) When the drum is cleaned, one must take care in gently cleaning heads in a direction parallel to head travel only, otherwise the heads can be damaged. The best technique is to turn the drum slowly while holding the cloth against it. For 1/2″ equipment there are 2 sets of opposed heads, for 1/2″ machines with Slo-mo, there are 3 sets of opposed heads.

Cleaning of the tape path

All surfaces that are in contact with the tape should be cleaned, including the fixed heads (time code, audio/control track, erase) and all tape guides.

Cleaning and inspection of pinch roller

It is very important for the pinch roller to stay clean. It easily collects oxide residue, and loses its ability to grab the tape. The roller should be inspected for aging or deformation, and changed if necessary. The roller can dry out and not grab effectively.

Head Degaussing

Both the rotary heads and the fixed heads should be degaussed. The degausser is placed as close to the head as possible, turned on, and drawn away before it is turned off. This removes residual magnetization from the heads. (This procedure does not have to be done as often as cleaning but is easily done at the same time).

Cleaning of head drum slip rings

This need only be done when necessary but is included for completeness. The slip rings should be cleaned with a soft brush to remove built up dirt. If necessary, freon can be used.

3. Tension Check

It is advisable to check tape tension in all modes of operation. Improper tape tension can cause tape or head damage, yet tension can be checked quickly.

4. Head Replacement and Optimization

As with U-format equipment, the upper drum assembly is replaced when any one video head fails. The upper drum is then aligned using an eccentricity gauge. The gauge, which must be attached to the chassis, is used to verify that the drum is centered on the flange. The drum is rotated slowly and the gauge is observed. Adjustments are then made, and the process is repeated until the drum is centered.

After replacement of the head assembly, adjustments should be made to optimize performance for the characteristics of the new head. And because these systems are component systems, there are two sets of record and playback electronics to be optimized. The following adjustments should be made for both chroma and luminance channels:

- Equalization (Playback and Record)
- Playback RF Levels
- Record Currents (also for erase heads)

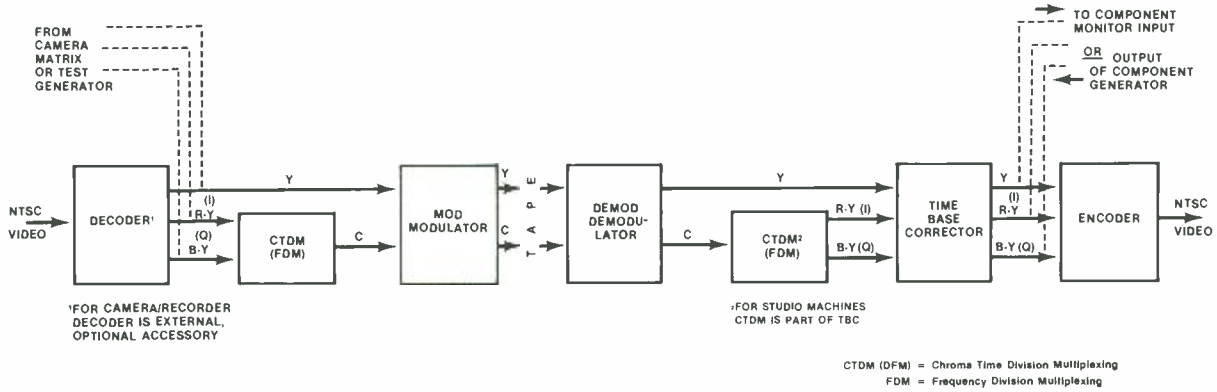


Fig. 11. Component video recorder player: functional divisions.

In addition to performing these adjustments after head replacement, it is also desirable to perform these adjustments several times throughout the life of a set of heads. This is because their characteristics change as they wear. Manufacturers recommended interval for replacement should be checked. If you maintain consistent selection of tape and operating conditions, you may be able to determine your own head life projection, and base your replacement schedule on that.

Tools and Test Equipment

1. Component Test Equipment

At this point it is appropriate to discuss the important differences in a component machine. The video signal system has two separate paths (Fig. 11).

It becomes important to have component test equipment available to facilitate isolation of problems. With component test signals available, it is easier to set up the encoder accurately. With component monitors the record/playback system performance can be scrutinized without considering encoder effects. Using both, one can concentrate on the record/play system by itself.

2. Soldering Stations

The introduction of camera recorders, brought with it a new circuit board construction that requires new techniques for component replacement. Surface mount components require special tools, such as different soldering tools. The stations are different in that they have suction and regulated heat as well as special tips that are designed for use with specific components. Use of these tools requires training. Component replacement is dramatically different from regular printed circuit board work, but given the time, one can become proficient.

Functional Divisions for Troubleshooting

1. Threading

The cassette loading process involves sensors, solenoids and motors, which detect and control the loading process. If a sensor becomes misaligned, the process will halt. If a solenoid or motor's cycle is out of specification a mechanical jam could occur. The manufacturer's manual should be consulted for the mechanical adjustments.

2. Control System

The control system interprets all input from the buttons and sensors, and for actuating events in the sequence required. Most problems with the control system "hanging" are due to a cycle that was not completed. This is unlikely to be a control system problem but a problem with a signal that the control system is supposed to see. Therefore it is important for all the sensors to operate properly.

3. Tension and Tape Run

If the cassette successfully loads, but jams still occur, or if portions of the picture appear consistently noisier—implying a non-linear RF envelope, the tension and tape run should be checked.

Tension

As previously mentioned, the tension detectors feedback a control voltage which in turn regulates the take-up and supply reel tension (Fig 11). Other adjustments that affect tension, are calibration of the brake and motor sensitivity.

Tape run

After the tension adjustments have been made, the tape guides should be checked. The manufacturer's manual should be consulted for this. But the objective is to be able to play an alignment

tape, and observe a uniform RF envelope, implying that the video heads are successfully staying within the recorded tracks on the alignment tape. If the entrance or exit guides are not properly aligned, the beginning or the end of the RF envelope will have a lower mount of detected RF. The many other tape guides are responsible for aligning the tape properly as it passes by the stationary heads, and maintaining a uniform edge to edge tension as the tape turns and changes height. These all must be checked and adjusted per manufacturers specifications.

Notes on use of Alignment Tape

For both audio and video systems alignment, procedures regarding the use of alignment tape should be understood. The Alignment Tape should be handled very carefully, and stored under good conditions. One should make sure the machine is running with correct tension, and that the tape path is clean and degaussed, before the alignment tape is played on the machine. It is best to run the tape all the way through without stopping because starting and stopping may stretch the tape and destroy its accuracy.

4. Servo System

Elements of a Servo System

There are 4 elements to a basic servo system:

1. Input reference
2. Motor or some other device to provide movement
3. Feedback detector of output position
4. Comparator to determine difference between desired and achieved output

Adjustments to the many servo systems in a machine include calibration of references and calibration of open loop responses. The manufacturer's manual should be consulted for these adjustments.

5. Audio System

Alignment of the audio system is similar to an audio recorder, except that there is a combined record/play head. Physical alignment should be checked, then an alignment tape played back to verify playback bias, equalization and levels should be adjusted to result in comparable playback through the set up playback electronics. The erase current also should be checked.

6. Video Systems

Alignment of the video system is significantly different from either type C or U-format. Looking at the block diagram (Fig. 11) we see that we now have a decoder and an encoder to align (decoder for studio NTSC machines). Also there are two modulators and demodulators.

Alignment should be performed in the same manner as that described for audio, in that playback electronics are aligned first according to alignment tape, followed by record adjustments to optimize playback through the previously adjusted playback electronics.

Functional Divisions

I. Playback Electronics (done first)

- A. Demodulator Adjustments
  - Playback Equalization (de-emphasis)
  - —Non-Linear
  - —Non-linear, incremental
- B. Encoder Adjustments

II. Record Electronics

- A. Decoder Alignment (for NTSC studio machines
- B. Modulator Adjustments (for BOTH modulators)
  - Record Equalization (pre-emphasis)
  - —Non-Linear
  - —Non-linear, incremental

The manufacture should provide procedures to perform the above adjustments.

7. Power Supply

The power supplies can be checked and adjusted if they are suspected of causing a problem. Things to look for:

1. Purity of dc
2. Regulation under varying loads
3. Regulation over the specified range of input voltages.

Summary

This section, in conjunction with the theory section, is intended to provide an understanding and an organized approach toward maintenance of 1/2″ equipment. The two most important items being an effective preventative maintenance schedule and a thorough functional understanding of the machine to enable quick trouble isolation.

REFERENCES

1. N. Kihara, "Color Cassette System for the NTSC and Japanese Colour-Television Standards" *E.B.U. Review*, February 1971, pp.2-8.
2. ANSI C98.21M-1980, "American National Standard Dimensions and Location of Records for 3/4″ Type E Helical Scan Video

Tape Cassette Recording, *SMPTE Journal*, May 1980, pp.379-381.

3. SMPTE RP 87-1980 "Reference Carrier Frequencies, Pre-emphasis Characteristic and Audio Control Signals for 3/4″ Type E Helical-Scan Video Tape Cassette Recording" *SMPTE* Journal, May 1980, pp.337.
4. "BVU-820 Specifications," Sony Corporation of America, New York, NY.
5. "BVU-850 Specifications," Sony Corporation of America, New York, NY.
6. SMPTE Document V16-861, Appendix C.
7. Panasonic AU300 Brochure/Specification.
8. Sony BVW 40 Brochure/Specification.
9. Matsushita AU600 Brochure/Specification.
10. Sadashige, Koichi, "An Introduction to Analog Component Recording," *SMPTE Journal*, May, 1984, pp. 477-485.
11. Gurley, Thomas and Carl Haglett, "Development of a Prototype Studio – Quality Component Analog VTR," *SMPTE Journal,* October 1984, pp.904-910.
12. Morita, Tsuneo, "Recent Progress in Betacam System Technology," *Montreux 14th International Symposium Record*, June, 1985, pp. 5-20.
13. Norita Masaaki, Katsuhiko Yamamoto, Orojuro Yamamitsu, "Half-Inch ENG/EFP In-Camera VTR-M Format," *Montreux 14th International Symposium Record*, June 1985, pp. 21-35.

5.10

Video Tape Editing

Michael Keller
Systems Engineer
Landy Associates, Inc.
Waltham, Massachusetts

INTRODUCTION

The advent of Electronic News Gathering (ENG) brought high volume video tape editing into the average broadcast facility for the first time. Previous to ENG, news editing was usually done with film, and production video tape editing performed on a small scale using a pair of the "air" VTRs located in the video tape machine room.

The news edit suite of today has become almost a complete "out of the box" system, requiring minimal custom engineering. Once a satisfactory design has been achieved, additional suites are built to provide sufficient editing capacity. In total, a complete news editing assembly line can exist with excellent speed and efficiency in performing this specific task.

It should be with little surprise that the engineering manager, who so efficiently replaced the cantankerous film processor with the technology of ENG, should hear the request of his general manager to eliminate the cost and expense of utilizing out-of-house post production facilities. As the general manager sees it, nothing could be simpler than combining a more sophisticated editing controller with other pieces of studio equipment that sit idle between productions. The facility probably already owns a digital effects system, character generator and numerous VTRs that, according to the advertising brochures he has seen, can be "easily" integrated into an in-house post production system.

The purpose of this chapter is to provide a combination catalog and primer designed to fill in the gaps between the information found in glossy brochures and the experience gained from ENG editing.

HISTORY

The introduction of quadruplex video tape recorders provided the broadcaster with an early means of video mass storage. The new found ability to record and immediately play back the recording appeared to be such an obvious advantage over film that, soon after introduction, the future of film was predicted to be that of obsolescence. Today, more than a quarter of a century after the introduction of video tape recording, the predictions of the total demise of film have proven to be a bit premature.

One major reason that film has not been entirely pushed out of the editing room is that a frame of film can be directly observed. Using this ability, it is possible to mark a desired frame and mechanically or optically splice it to a different frame, thus producing an edit.

Video tape recording technology cannot easily duplicate the simplicity of direct observation editing. Video tape recording makes use of magnetic media to record electronic signals representing the visual information. The storage of visual information by a method that can not be directly observed eliminates the ability to edit using direct observation. Ever since encountering this prob-

lem, advances in video tape editing technology have been aimed at giving the video tape user the same or similar ability found in film editing, and the "real time" advantages of tape.

The initial approach to editing video tape attempted to directly emulate film techniques. The tape was played back, and the edit points marked on the tape with a grease pencil. In order to physically observe the magnetic track in the vicinity of an edit point, tapes were developed with fine particles of ferrous materials in a liquid suspension. These liquids provided the ability to visually locate, with the aid of a microscope, the frame pulse and associated video track near the edit marks. The actual edit was then performed by cutting and splicing the source and record tapes. A complete cut of the tape effectively divides both video and audio channels thus preventing individual channel editing.

The finality of each edit, the questionable durability of tape splices, and many other physical limitations of the mechanical techniques, produced a demand for an improved method of editing. About the only advantage of this type of editing was that it required only the original tape generation at a time in recording technology when generation loss was severe. The mechanical editing technique was replaced by the first generation of the electronic editors. VTRs equipped with electronic editors contained the systems necessary for correct record timing and servo switching to properly transition from the playback to the record mode while the tape continuously rolled. This switch occurred between the tracks before the vertical interval, and upon playback appeared as if the transition had been accomplished by the studio switcher.

To perform an edit, the operator would mark the tape at the pre-roll point, backspace each VTR by hand to allow enough time for lock-up and manually start them, as simultaneously as possible. If both VTRs locked-up before they reached the edit point, the operator would manually initiate the edit. If the pre-roll time had slipped between the source VTR and the record VTR, the edit point would be missed. If the editing operator's reactions were off slightly causing the desired edit point to be missed, there would not be a second chance. These problems produced the need to devise a method that would reduce the dependence on operator reaction time, and allow the testing of an edit without actually recording.

The Ampex Editec, see Fig. 1, approached these problems by allowing the operator to record a cuetone to make the edit point. This tone could be used to trigger the edit record timing circuitry of the electronic editor.

An edit could be previewed by using the cuetone to switch the record VTR input to the play VTR, without turning on the record amplifier and erase systems. The play VTR signals were then routed through the Electronics to Electronics (E to E) path of the record VTR instead of the record VTR Video. This cuetone technique became the common place method, but it still relied on manual per-rolling of the transports.

A complete description of the Ampex Editec can be found in the video tape recording chapter of the previous, 6th edition of this *Handbook*.

One of the difficulties encountered in quadruplex recording is the inability to examine edit points on a frame by frame basis. This problem was addressed by utilizing magnetic disc technology, as exemplified in the Ampex HS-200, see Fig. 2. Early magnetic disc technology offered the ability to examine video on a frame by frame basis. The HS-200 integrated the programmable control of the HS-100 video disc recorder and cuetone control of quad VTRs. This allowed the slow motion and still frame capability of the disc system to be initiated by edit marks. The ability to program switcher transitions and effects between the HS-100 and VTRs under control of the edit marks was also contained in the HS-200.

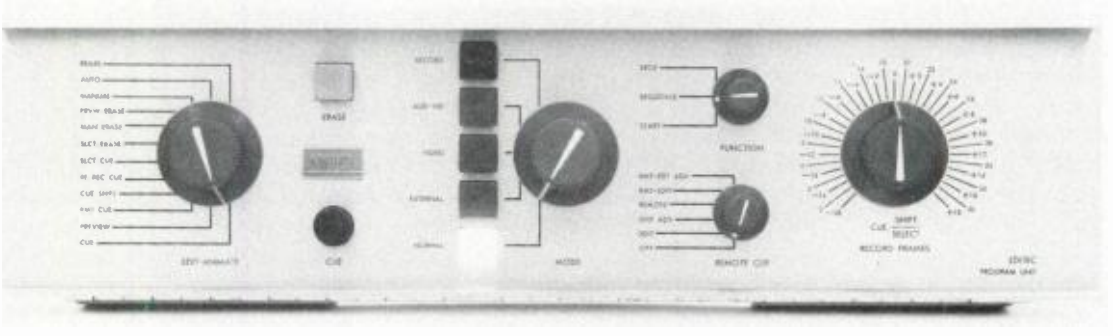


Fig. 1. Ampex Editec. (Courtesy Ampex)

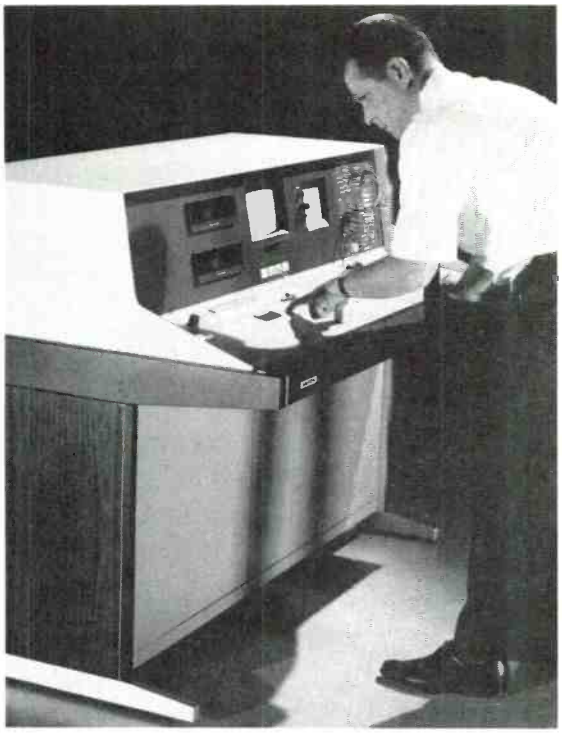


Fig. 2. Ampex HS-200 Operating Console. (Courtesy Ampex)

The problems of transport control for single and multiple VTR editing were addressed by the use of a frame code in the Ampex RA-4000, see Fig. 3. A unique address for each frame was laid down during recording on the cue track. This number stream provided references for transport control servo systems, allowing a desired frame to be searched for automatically.

The technique of multiple source VTR editing became feasible with the use of frame code. With the code as a common reference, the multiple play VTRs and the record VTR could be automatically synchronized by the RA-4000.

The use of disc technology to preview edit points, and time code to provide random access, was integrated into an on-line/off-line concept exemplified by the CMX 600 and 300 systems, see Fig. 4 and 5. In the 600 system, a total of 30 minutes storage capacity was attained when recording single monochrome fields with audio tracks encoded into the front and back porch of the video signal using six disc packs.

Off-line editing using the 600 disc system generated a list of time-code numbers defining edit decisions, that could be printed out or punched onto paper tape. The CMX 300 on-line system loads the paper tape into memory and runs a pro-

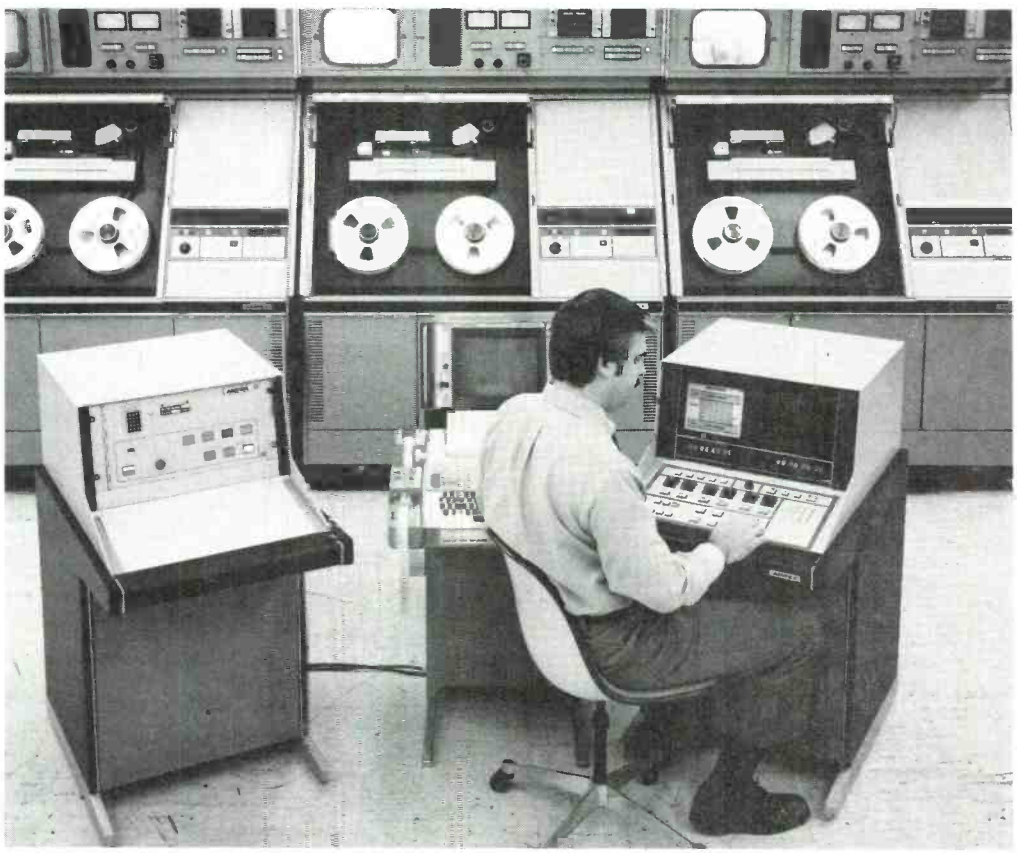


Fig. 3. Ampex RA-4000 Controlling AVR-1 VTR's. (Courtesy Ampex)

Fig. 4. CMX-300 Edipro.
(Courtesy CMX)

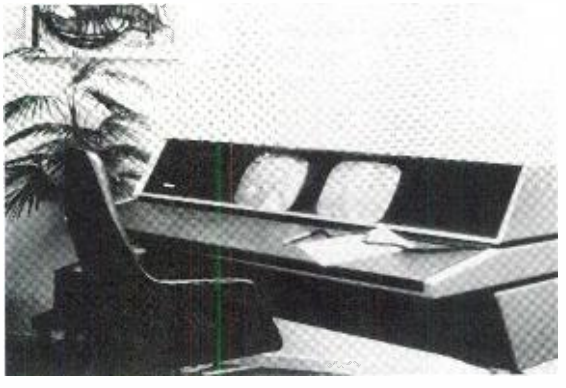


Fig. 5 CMX-600 Operating Console. (Courtesy CMX)

gram that uses the data to automatically assemble the master using quad tape.

The introduction of broadcast-quality, full field helical VTRs and their ability to view a still field produced the next major advance in editing technology. This removed the need to utilize disc technology to compensate for the quad VTRs shortcomings by providing three hours of recording time, viewable pictures while searching, and slow motion/still frame ability.

The current generation of editing controllers takes advantage of the helical scan recording technology and the increasing power of inexpensive microprocessor based computers. This combination has allowed video tape editing technology to come closer to combining the techniques of film editing with the advantages of magnetically stored video.

VTR EDIT TIMING

All external video tape editing control systems or edit controllers, rely on the record VTR to implement the edit electronic sequence. An operator command to the edit controller keyboard determines the place to perform the edit, the selection of tracks to be edited, the duration of the edit interval, and the editing mode, but the editing record VTR provides the internal systems necessary to switch servo references and sequence the erase heads and record/play electronics. These timing sequences are determined by the physical constraints of the tape format, involving the video and audio head positions and tape speed. The following example is based on the operation of the internal edit timing system of a type "C" one inch VTR.

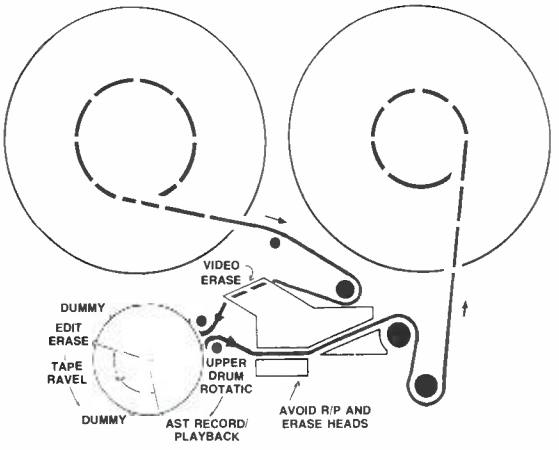


Fig. 6. Head position diagram Ampex VPR-80.

The reception of an edit record command starts a timer that results in the operation of the flying erase head. This head is located in the video scanning assembly, see Fig. 6, and provides erasure of video tracks that have travelled past the stationary video erase head prior to the start of the edit interval. The flying erase head traces the same path as the helical record/play head and therefore can erase only the video track.

The record/play relay switches to the record position after the second timer in the sequence expires, and is followed by another timer delay, that activates the record amplifier and the edit interval recording begins. At the end of the video edit interval the sequence is run in reverse. The flying erase head shuts down first, then the record/play relay switches back to play, and the record amplifier is turned off. To perform an audio edit, the edit timing systems control the audio erase current and the record switching for any or all channels. The audio erase current is applied to the erase head in advance of the edit point. This timing advance compensates for the distance between the audio erase head and the record/play head stack. Upon arrival of the erased segment at the record/play stack, the record amplifier is ramped-up by the completion

of its timer cycle, and the audio "edit-in" is performed. Conversely at the edit-out point the erase command is removed several frames before the edit-out point reaches the R/P head and the audio record amplifier is ramped down upon reaching the edit-out point. Attention should be paid to these ramping characteristics when moving a tape between recording VTRs of different manufacturers in order to avoid audible discontinuities at edit points.

The internal VTR editor can perform edits in two modes: *Insert* and *Assemble*.

Assemble mode editing is similar to non-edit recording in that the original control track is erased and a new one recorded. Upon arrival at the edit-in point, the new material is added onto the previous material in a building block fashion. The new material being recorded then becomes the "previous" material to which another segment may be added. Consequently, an edited tape is built by adding segment to segment to segment over previously blank tape. This assembly of new material onto previously recorded blank material typically occurs for all tracks. The typical VTR utilizes two full width erase heads thus precluding separate track editing.

In the *Insert* editing mode, the newly recorded material replaces previously recorded material for an edit interval duration shorter than the original recording length. The new material is sandwiched between previously recorded material at the edit-in and edit-out points. The full width erase head is disabled and erasures occur on a per track basis. The original control track pulses are maintained reducing servo instability caused by differences between the original and new recordings.

Basic Time-Code Editing Controller

The following discussion is an operational overview of a "general model" micro computer based time-code editing controller. It is used to illustrate the basic concept upon which larger systems are built, A/B roll or multisource editing. See Fig. 7.

In this example, the record VTR internal editor functions as before. Commands to the VTR internal editor are now generated by editing software, processing user commands from the editor keyboard. In the standby mode, the host computer running the operating system awaits a user command. Selecting a key on the editor keyboard sends a character to the keyboard port located in the computer system where the CPU initiates the program necessary to service the requested function. In the case of a play command for VTR-A, a play command is sent to the VTR-A

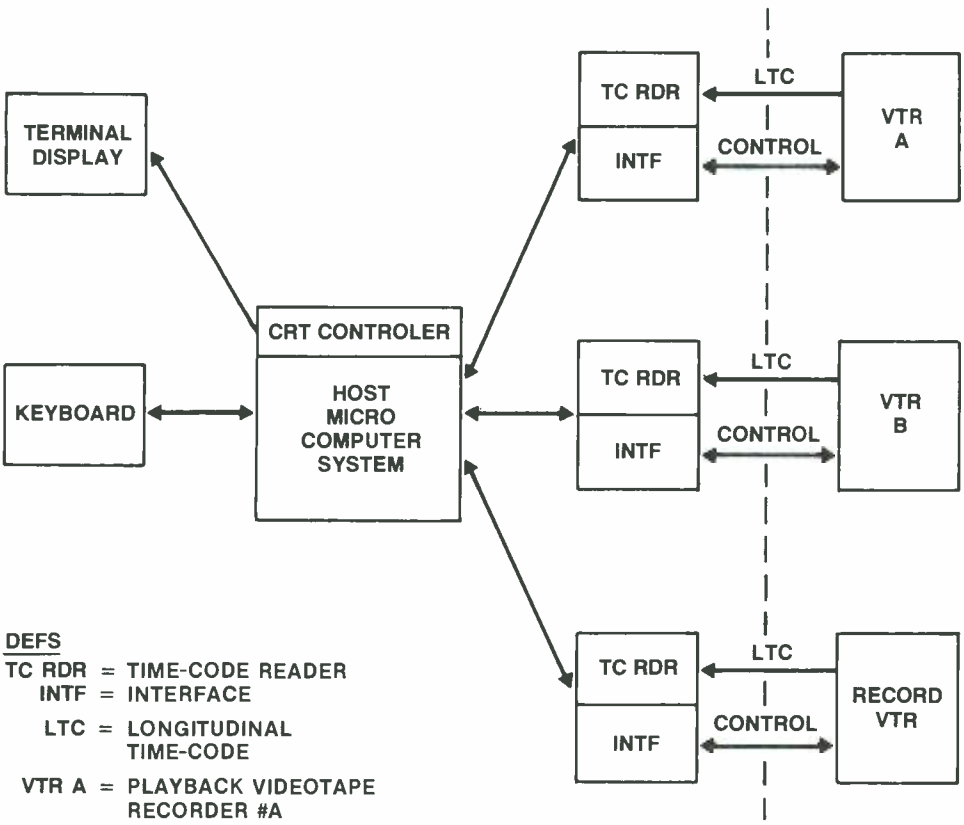


Fig. 7. Basic time code editing controller and A, B, record VTRs.

interface microcomputer subsystem. The micro-subsystem stores the command received from the host, initiates a local routine and produces a play function at the selected VTR. Since control methods vary widely between VTR manufacturers, the play command received requires format and protocol conversion. The interface runs a conversion program written to match the protocol characteristics of the dedicated VTR, and then the command signal is hardware converted to match the VTR port configuration. Confirmation or tally that the controlled VTR has received the desired command follows a reverse process back through the same chain to the keyboard, lighting a tally at the associated key. Concurrently with the initiation of the VTR mode, the corresponding time-code reader converts the SMPTE Time-Code bit stream into a suitable parallel form, making it available to the system buss where the CRT controller uses it to up-date the operator's time-code display. If the operator selects a certain location in tape as a desired edit-in point, that time-code number is transferred from the data buss to the system memory address defined as a VTR start time for the current event number. The same method applies to selecting a VTR edit-out point except for the memory address. Similarly, the record VTR is commanded into the Play or Shuttle mode until an edit point is located and matching time-code number is transferred to its particular memory address. If the operator elects to preview the edit, the host computer calculates the cuepoints by subtracting the preroll time from the edit-in point. The amount of preroll for each transport has been assigned by the operator via the keyboard or default values resident in the operating system. The interface computer runs a search program to determine the direction to the desired location and rapidly searches the VTRs, stepping down the shuttle speed as the cuepoint is approached. As this point is approached, the VTR is placed into the play mode and upon arrival, parked. As each VTR reaches the cuepoint its respective slave interface returns a cue status to the host computer. Upon receiving confirmation of cued status from all VTRs involved in the preroll, the host computer issues play commands to all machines. As the VTRs approach the edit-in point the host monitors the synchronization error between Play VTRs and the Record VTR. The difference between how far the Record VTR must go to reach the edit-in point and how far the Play VTR must go to reach the same point is termed *sync error*. The host sends this time difference sync error to the slave microcomputer where it is converted into the appropriate speed-up or slow-down command, thus enabling the Play VTRs to reach the edit-in point synchronized with the Record VTR.

If a VTR fails to arrive at the edit-in point by this synchronization loop, a sync error signal is displayed and the entire system retries the preroll. In order to insure that the VTR will arrive in synchronization during the next attempt, many systems will automatically add preroll time. If this attempt also fails, the system will try again with an even greater preroll interval. A non-sync condition after three attempts will cause a halt to the synchronization process, and operator intervention is required. If synchronization between transports is within the acceptable error prior to the edit-in point, the preview will continue. Prior to reaching the edit-in point, the host computer must also receive a servo locked response from the slave computer. The VTR interface slave monitors the horizontal and vertical servo lock signals from the VTR, and if both are satisfied before the edit-in point is reached a servo confirm tally is issued to the host and the preview continues. If failure of the VTR to achieve horizontal and vertical lock prior to entering the edit interval results in a preview abort, the system will re-try as for a sync roll failure. The Record VTR and the Play VTR time code are compared for color frame match. Color frame status is displayed and, if a match is achieved, the preview will be performed by switching from the Record VTR playback at the edit-in point, the "E to E" mode allowing the Play VTR to be displayed up to the edit-out point where switching reverts back to the Record VTR play video. If colorframing mismatch occurs, the operator is requested to offset the play VTR edit-in point one frame. This restores the four field color sequence described in EIA Proposed Standard RS-170A. See Fig. 2 on page 75, Section 5 Chapter 4 of this *Handbook*.

Edit recordings are performed essentially the same way as edit previews. The observable exception being that the Record VTR switches from playback mode to the record mode at the edit-in point.

Medium Scale Time-Code Editing Controller

The previous section described the operation of a relatively unsophisticated time-code based edit controller. It allowed the operator to remotely control the VTR functions, to select edit points using time-code numbering, and to synchronize multiple VTRs in order to preview and perform edits. The following description is based on one example of a moderately-priced microcomputer-based editing controller suitable for advanced broadcast production application, the Paltex Edit-Star ES-1, see Fig. 8. It may be considered representative of other editing controllers in this category, which operate in essentially the same

Fig. 8. Paltex Edit-Star ES-1.
(Courtesy Paltex)

manner. The first or "software" section is a condensed description of what such a system can be expected to accomplish and the parameters required. The second or "hardware" section describes the task of integrating the editing controller into real world equipment.

Upon turn-on of any sophisticated editing controller, various initial conditions must be entered. Set-up data is usually entered at the beginning of a new session and can be completely or partially up-dated as the session progresses. Typical parameters required by this initial dialogue are shown in the following list.

Preroll Time

The amount of time before the cuepoint that the system will backspace the VTR. This number is usually expressed in seconds or frames.

Postroll Time

The amount of time the VTR will continue to roll after the edit event has been completed. This allows editing continuity to be observed and is often expressed in seconds or in frames.

Reaction Time

This allows a system to compensate for the reaction time of the operator when marking edit points while tape is moving and is typically expressed in frames or seconds.

VTR Assignment

This identifies to the system the operational function to be assigned to the interfaced VTRs. Any VTR can be delegated as a player or recorder under software control in the ES-1.

Reel Number Assignments

In order to construct a useful edit decision list, the material edited must be traceable. Reel numbers are the only library key the system has.

Event Number

Provides the editing system the current event number assigned to the edit decision first completed after set-up. Edit events are numbered sequentially ascending from this base number.

Time Code

Assigns system Time Code operation to drop or non-drop frame. Automatically monitors the status of incoming time code from each VTR and will override an incorrect manual selection in order to provide proper calculations.

Record VTR Color Framing

Selects use of system or Record VTR color frame. A test edit is performed and color frame reference is selected to eliminate horizontal shifts if system color framer is used.

Time-Code User Bits

If present the system time-code reader will display the data read from the user bits in the space normally allotted to the SMPTE time-code values.

Edit Interval/Duration

Allows the selection of edit duration calculation method. Duration can be that of the Record VTR or the interval of the effective play source.

Display Out/Duration

Depending on operator preference, allows for the display in the edit decision list to record VTR out-times or the edit duration.

Once this initial information has been loaded into the operating system program, the editing operator is now ready to start an editing session using the editors VTR manual functions.

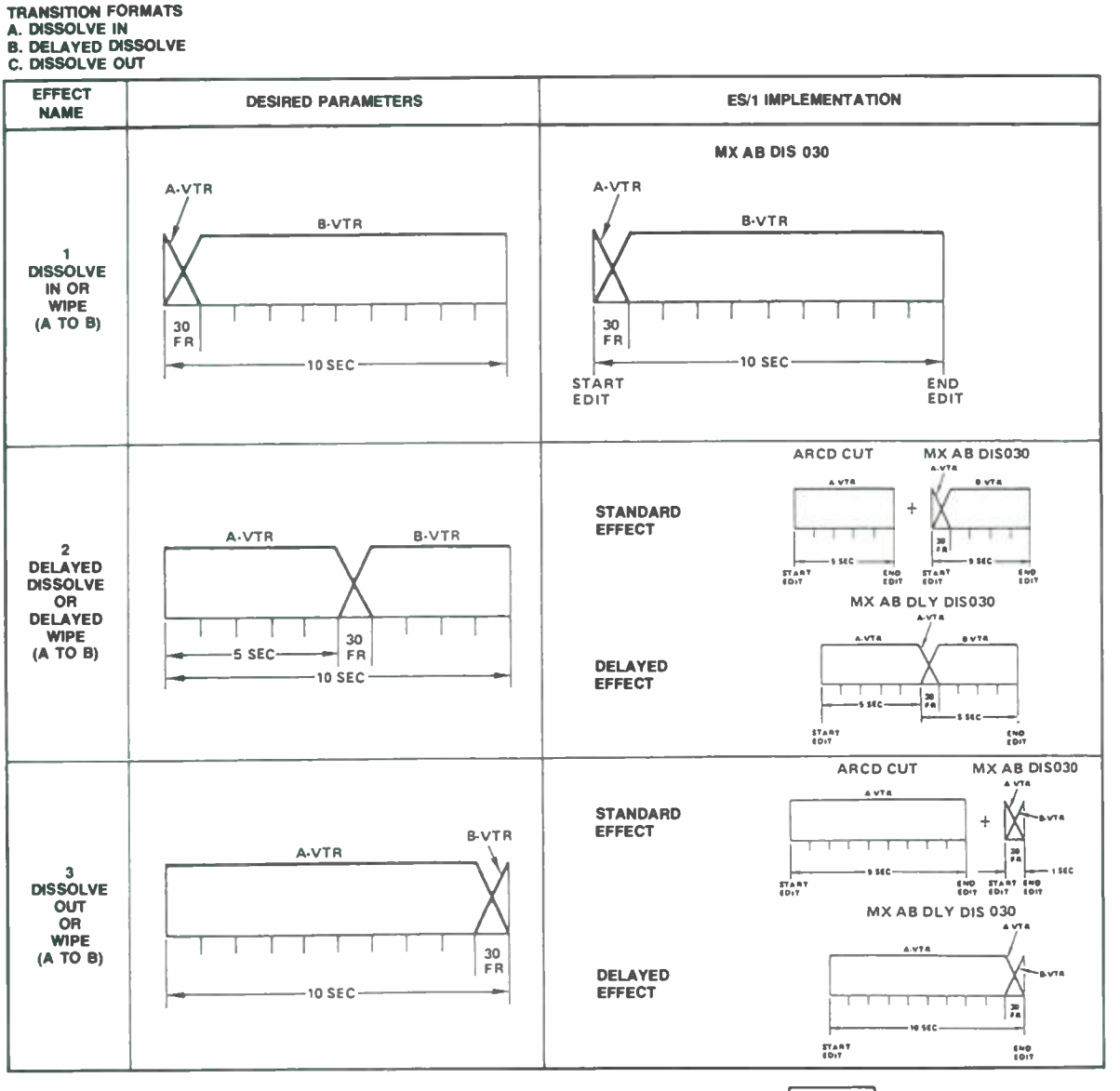
EDITOR VTR CONTROL

A manual function is a basic VTR command that has been remoted from the VTR front panel to the edit system control panel. The manual functions on an editing controller include Stop, Play, Record, Rewind, Fast Forward and Pause, along with the selection of which VTR they control. In the ES-1, controls defining each of these functions are used on a per key basis. A rotary control is used to simulate the shuttle/job knob found on helical VTRs.

An edit entrance point is selected in a variety of ways using editor manual controls. One method is entry of the time-code number via a calculator pad. In this method the operator shuttles or jogs tape to identify the correct edit point for each or all tracks, and enters the numerical data from the time code displayed by hand. This technique requires excessive operator intervention. A more efficient method for transferring this in-

formation is accomplished by the "on-the fly" or "mark" method. In this technique, edit points may be selected while tape is rolling by pressing a single, dedicated key. By selecting either the In or Out key the entire time-code number is transferred at once, instead of loading each digit via a key pad. This technique can be applied to the selection of all tracks or split tracks and it can occur quickly, while the VTR rolls, without requiring each point to be located with a still frame. Once an edit point has been selected by either method, trimming of an entry can be accomplished by either entering a new number or by shifting the existing point.

The majority of tape editing occurs in a sequential order. After the completion of the first edit, the next edit is butted adjacent to the first edit-out point. Instead of having to re-enter the out-



NOTE

Commands and Edit Decision Reports shown pertain to dissolve effects only. WIPE is substituted for DIS for wipe effects.

Fig. 9. Transition formats. (Courtesy Paltex)

time of previous edits, a dedicated key provides transfer of the previous out-time to the current edit-in time.

Once an edit-in time has been established, the edit-out time can be manually selected by using similar techniques. Often specific duration requirements will define the edit-out time. The calculation of the edit-out time can be done manually, using the electronic scratch pad, or provided automatically, in much the same way an electronics spread analysis sheet program calculates new data based on changing input variables. If the edit-out time is known and the edit-in time undefined, the duration can be entered and the edit-in time will be calculated.

Transition Selection

After the selection of the play/record segments to be used in the upcoming edit, the transition between segments must be specified. The variables to define are:

1. Type of transition (cut, wipe, dissolve, or key)
2. Duration of transition in frames.
3. Tracks affected: Video, Audio 1, Audio 2 (V,A1,A2)

The cut mode is the simplest and most direct transition between two sources. The second most common transition is the dissolve, see Fig. 9. Dissolves may be as *dissolve-in*, when the dissolve occurs at the edit-in point, or *dissolve-out*, where the dissolve occurs at the edit-out point. Delayed dissolves place the transition between the record edit-in and out points. Entry of a standard dissolve as an edit point requires selecting the dissolve start point and the dissolve duration. In the case of a delayed dissolve, the delay time must also be entered. This time must fit between the start of the edit-in point and the actual occurrence of the dissolve. The same considerations apply to wipe transitions.

The specification of a key transition involves defining how the key is to be brought in or taken out. The key transition commands, in their most general forms, are: Key-in, Key-out, Fade key-in and Fade key-out. The key-in command causes the foreground image to dissolve in over the background image at the specified rate. The fade key-in causes the foreground and background images to fade up together from black at a specified frame rate. The key-out and fade-out commands are used to terminate a key effect in progress.

Due to the tremendous growth in switcher and digital effects technology, many transitions necessary in modern post production are not addressed with specific edit decision list labels found in many EDL formats. In order to trigger these auxiliary device transitions, an event is often defined by a specific numeric code designating the type of device and function required. This special function code is stored with the time-code number designating the beginning of the transition.

Edit Preview and Recording

Once transitions have been selected, preview modes are used to rehearse an upcoming edit. An automatic preview cycle consists of cueing and rolling the designated VTRs through the pre-roll time while synchronizing in time to be locked and colorframed upon arrival at the edit-in point. After passing the edit-out time, all VTRs continue to roll for a pre-set length of time.

Edit previews may be viewed in a number of formats. A Video-Video-Video (VVV) mode presents the record machine playback video up to the edit-in point at which the new source material is switched-in by the preview switcher, and then switched-out at the edit-out time back to the record machine video. The Video-Black-Video (VBV) mode inserts black for the new source material, in effect creating a black hole. The Black-Video-Black (BVB) mode, conversely, presents only the newly inserted source material sandwiched between black segments.

Once a previewed event has been deemed acceptable, an edit record command is used to initiate sequence to the preview except that the source material is routed to the record VTR and recorded onto the tape. The event data are also stored in the edit decision list.

The edit source VTRs are recorded onto tape through the video switcher and audio mixer for the duration of the edit interval with effects transitions occurring as specified in the preview mode. At the conclusion of the edit record, the current event number will be updated to the next consecutive number. In the duration display, the show duration is updated to include the duration of the edit that has just been completed.

An alternative editing technique to A/B roll is the sync roll. Sync roll editing is the process of cutting between continuously rolling VTRs, each locked to the timetable of the original recorded event. Editing is done by switching between VTR sources much like switching between cameras during a live production. Just as in studio production, edit points can be selected on the fly, in "real event time". This technique assumes that the source material has been recorded on a separate reel for each source.

To achieve synchronization between event time related audio/video tracks with different time-code numbers requires that the operator manually synchronize the VTRs within a few frames of each other. Once the VTRs are within a few frames of each other the operator can enter the required offset to the out-of-phase VTR, and the system

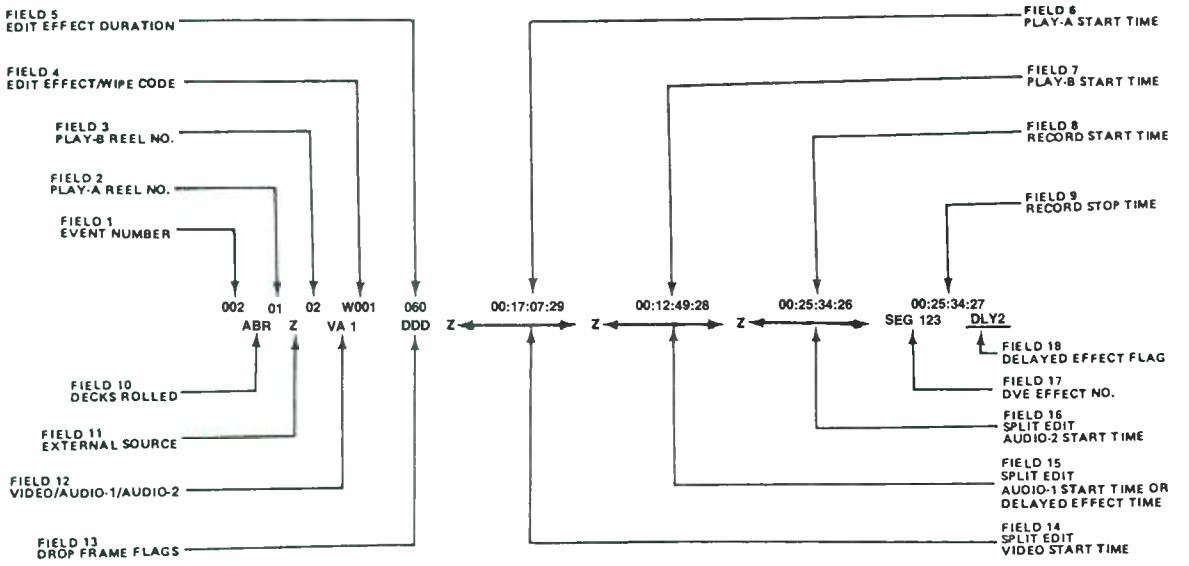


Fig. 10. Edit decision list format — Paltex ES-1. (Courtesy Paltex)

will automatically resynchronize. The offset required is then added to the edit-in time of the adjusted VTR.

The actual performance of a sync roll edit consists of a sync roll preview and then automatic assembly using the edit decision list produced in the preview mode. All VTRs re-cue and resynchronize as in the preview mode. However, source selection is now performed by the edit controller, according to the edit decision list, until the edit interval ends.

Edit Decision List

The edit decision list is a formatted data base defining a series of edit events. This data base is organized into fields by the editing equipment manufacturer. An example of an edit decision list format can be seen in Fig. 11.

These fields contain sufficient information to reconstruct a series of edit events from source material. This list may be generated by a main or on-line editing system or by a smaller scale off-line system.

An off-line system may consist of an ENG style cuts-only editor utilizing dubs of the original tapes with the "burned-in" time-code characters in the active picture area.

As approximate edit points are determined, time-code numbers can be manually logged for later entry into the on-line edit list. This approach reduces the amount of search time used in the on-line system.

Edit decision list information can also be manipulated using personal computers. A list can be loaded into a pc then edited via the keyboard and loaded back into the editing system using a floppy disc as the transfer medium. The pc can perform many of the sophisticated list management chores normally relegated to the on-line system. Systems that allow tc editors to transfer banks of edit information directly over a serial buss to a pc enable the pc to perform as an outboard data base manager and memory expansion.

Currently there are numerous EDL formats in existence, representing efforts to find a better way to preserve records of the edit events. Fortunately, with the drastic decrease in price of computing power, more editing manufacturers are providing for alternate formats in the hope of attracting a larger market through increased list interchange ability.

An effort to standardize on a common format is currently being attempted by the Video Recording and Reproduction Technology Committee of SMPTE. As of this writing the proposed format resembles the original CMX style format but provides additional inclusions of user data, virtual events and commands.

MEDIUM LEVEL TIME-CODE EDITING-CONTROLLER HARDWARE SYSTEMS

The hardware of many editing controllers can be divided into two major systems. The first contains the host microprocessor and I/O devices similar to those found in personal computer systems. The second major system category includes custom interfaces between the system buss and

the video/audio signal equipment. The combination of these major systems, operating under editing application software, comprises the overall editing controller system.

Most modern editing controllers use a technique known as distributed processing. This technique divides the computing task between a host computer and a number of slave computers. The host performs the task of systems supervisor, while the slave systems are dedicated to specific tasks. In the case of the VTR interfaces, each has a dedicated microcomputer slave system running a software routine specifically written for that type of VTR. This division of tasks has a number of advantages over a single centralized processor. Failure in one subsystem need not halt the overall process. In the case of cueing multiple VTRs, one failure to cue does not inhibit the cueing of others.

System Description

In Fig. 11 the host is shown communicating with the computer support and I/O devices. These computer devices consist of: the keyboard, the CRT controller, printer interface, and disc I/O. These devices combine with the host to provide a customized computer system optimally designed for the editing application.

The system host processor runs the main editing application program from internal programmable read-only memory (PROM). Once running and communicating with the CRT controller and keyboard, the host is ready to run an editing function where, operating as the central processor, it will arbitrate the data buss and provide service to each peripheral.

The keyboard, see Fig. 8, provides the major operator control point in the computer assisted editing system. Operationally there are two basic sections, the 86 key command section, and the rotary encoded VTR transport control. The keyboard area provides selection of system commands combined with numeric entry. Extensive use is made of dedicated keys in order to reduce the number of key strokes necessary to perform common functions. Certain keys are left as "user-definable". This allows the user to create custom commands consisting of a memorized sequence of other key strokes. This feature resolves the problem of trying to anticipate all desirable keystroke functions.

To provide hard copy of edit decision lists, the computer I/O system contains an EIA RS-232 serial port that is usable with most common printers. In order to use devices such as the Teletype Corporation's ASR-33, the serial port also provides a current loop driver for printer selec-

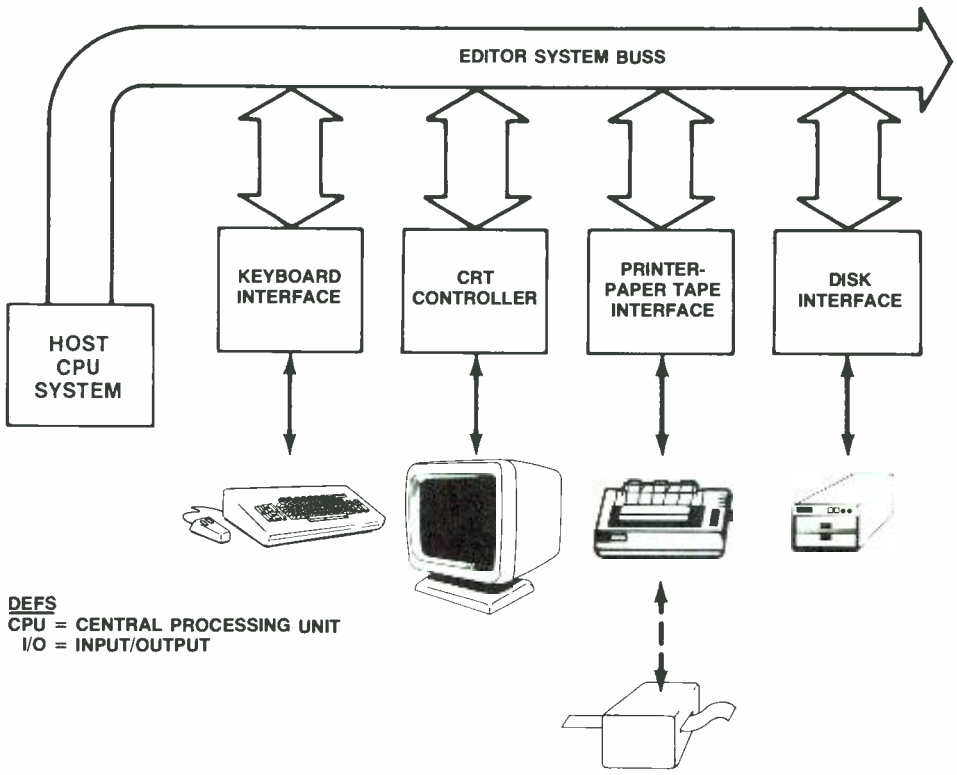
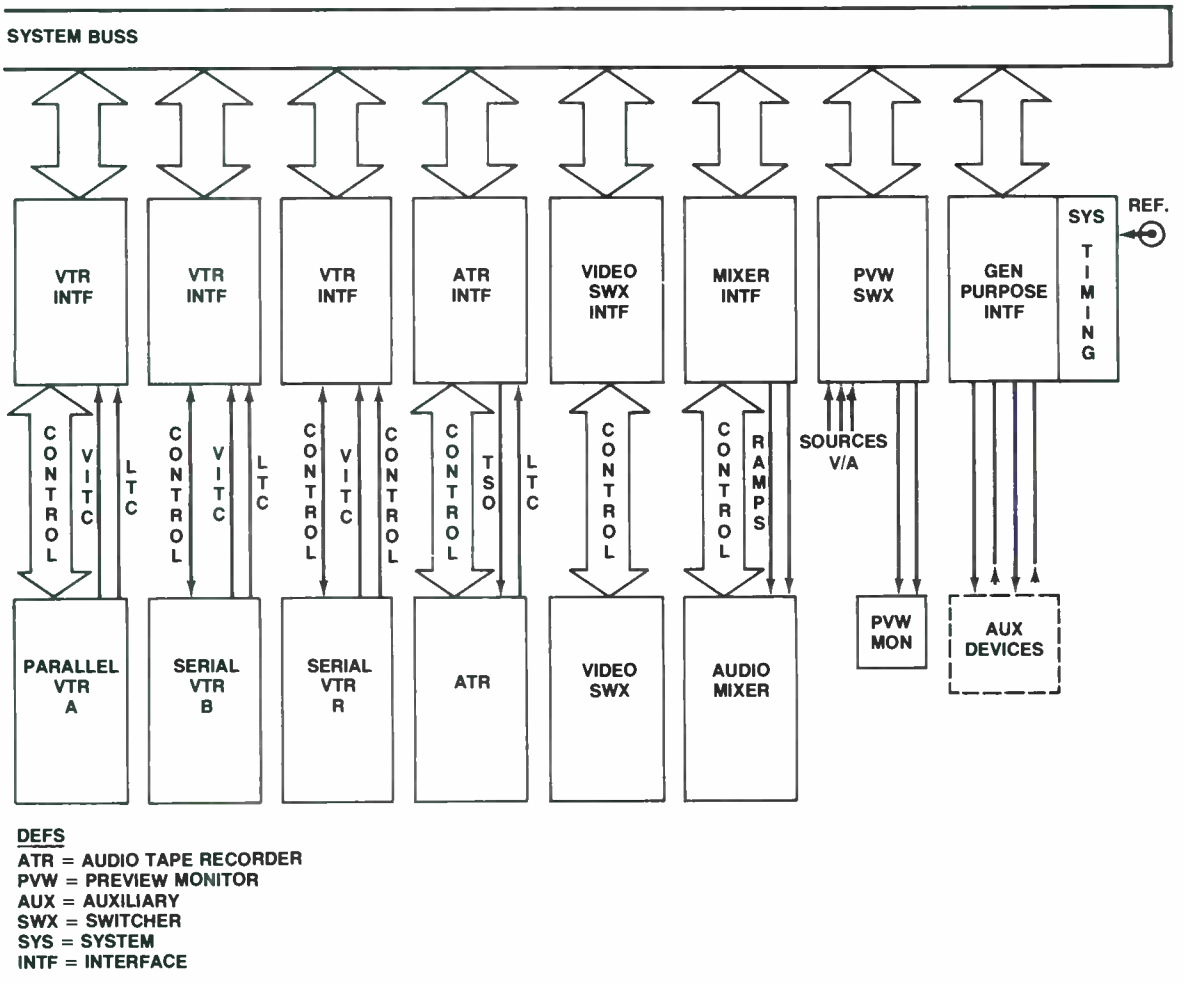


Fig. 11. Computer support and I/O devices.



DEFS
ATR = AUDIO TAPE RECORDER
PVW = PREVIEW MONITOR
AUX = AUXILIARY
SWX = SWITCHER
SYS = SYSTEM
INTF = INTERFACE

Fig. 12. Editor buss interfaced video and audio signal system devices.

tor magnets and internal paper tape reader/punch. Although paper tape is relatively slow and very noisy, there are some advantages. Paper tape is directly readable, printable, cannot be accidentally erased and is often the only medium available as removable storage on many of the smallest edit controller systems.

To provide random access storage for edit decision list information, the microcomputer I/O system also contains a serial interface to floppy disc drive unit. Floppy disc memory provides higher speed density and quieter operation than the paper tape storage technique. Edit decision lists can be loaded, changed, and rewritten easily; something that is a bit difficult to do with paper tape. An edit list can be stored by dumping the complete list to a file at the end of a session or by using the Protect mode, individual edit events are written to disc upon performing an Edit Record. In order to facilitate interchange, many manufacturers offer their own disk size and format and eight inch disk drive system conforming to SMPTE RP 132.

The second major system that the hardware can be divided into consists of the collection of interfaces used to control the video and audio signal system devices, see Fig. 12. This group of interfaces consists of: the VTR interfaces, the ATR interfaces, switcher interfaces, Audio Mixer interfaces, General Purpose interfaces, Preview switching and system timing.

VTR INTERFACES

Fig. 13 illustrates an example of a parallel VTR interface between a Type "C" VTR and an edit controller. Thirty-six command and tally lines interconnect the transport to the VTR interface on a one signal per wire basis. These signals may be divided into: transport commands, internal editor commands, tallies and control voltages. Transport commands such as Play, Stop, and Rewind are controlled by logic levels. Tallies from these commands are also returned by logic levels. Internal editor commands such as Insert or

Assemble are also selected by setting the respective control lines.

Exceptions to this simple "on/off" type of control are the tape speed override (TSO) and shuttle voltages. As their names imply, both are controlled by variable dc levels, each generated by a digital to analog convertor. Initial installation of a parallel interface requires calibration of buffer circuitry between the D to A converter output and the VTR analog inputs in order to match the required control range used by the VTR manufacturer.

The parallel interface technique is a very hardware intensive method from the viewpoint of the edit controller manufacturer. Since the editing controller is fundamentally a digital computer, all interfacing ideally occurs in the digital domain. As VTRs employ microprocessors for internal systems control, digital interfacing becomes the appropriate approach. By utilizing a serial data control link system, interconnection becomes simpler. Typically, a nine pin connector carries all the necessary lines to reproduce the functions provided by the parallel interface. Once encoded, the VTR control line can easily be switched between desired control points.

In order to apply the serial interface technique two links must be defined: the physical link and the data link. It is all too common to hear the terms "RS-232" or "RS-422" improperly used to define both the physical and data links. Either EIA standard defines a set of transmission signal levels and conditions for the physical link. The earlier RS-232 format utilizes "single-ended" or unbalanced techniques for driving the transmission line while the later RS-422 technique utilizes a differential or balanced line approach to improve noise immunity. Each standard defines a different voltage level representing data, and other line driver/receiver characteristics. Connector types and pin-outs are left undefined; baud rates and data formats are also omitted, therefore even though the two devices match the standard they may not be able to achieve communication.

An attempt to define these standards is contained in Proposed American National Standard PH 22.207 (reproduced at the end of this chapter). The signal conditions of RS-422 with the inclusion of a standard baud rate (38.4 kbd), interface connector (DB-25), pin assignment, plus definitions of data words, message paths and buss structure allow interconnection compatibility between different manufacturers.

Once the hardware is able to communicate using the same language, it is necessary to define who is going to speak to whom and when. This is defined by the SMPTE recommended practice RP113, reproduced for reference at the end of this chapter courtesy of SMPTE.

In Fig. 14 the same VTR and editing controller used in the parallel interface example have been reconfigured using the serial interface technique of PH22.207 and RP113.

Each VTR interface also contains a time-code reader as a subsystem. Its task is to convert off-tape time code into a compatible data format for use on the system buss and by the VTR interface. Two types of time code can be utilized by the reader: Longitudinal or Vertical Interval. Longitudinal Time Code (LTC) is recorded on a cue channel or, if unavailable, an audio channel. This code referred to as SMPTE Longitudinal Time Code is described in ANSI Standard V98-12 and can be found in the chapter on Video Tape

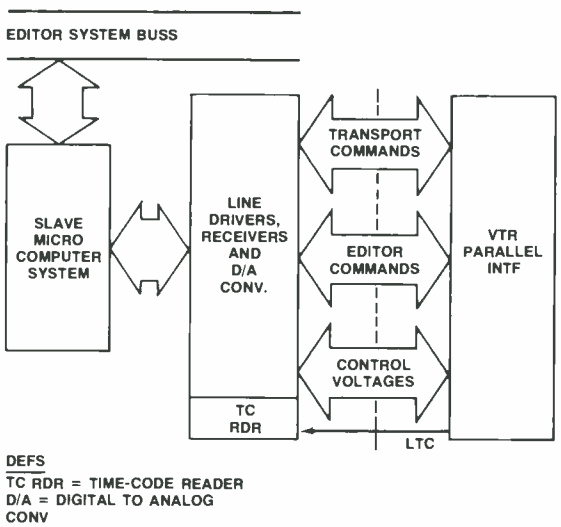


Fig. 13. Parallel port VTR and editor interface.

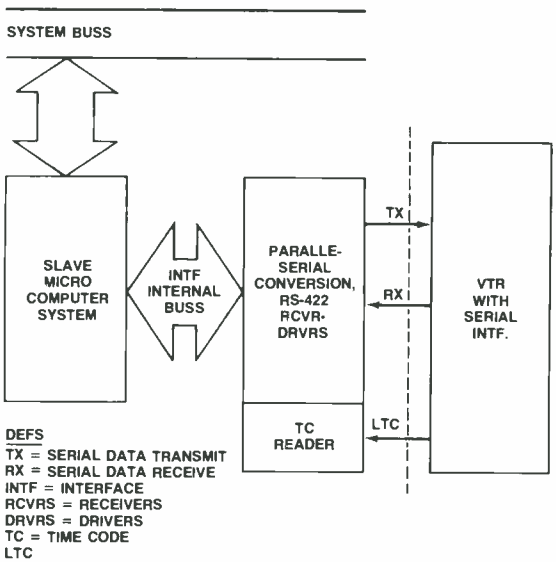


Fig. 14. Serial VTR and editor interface.

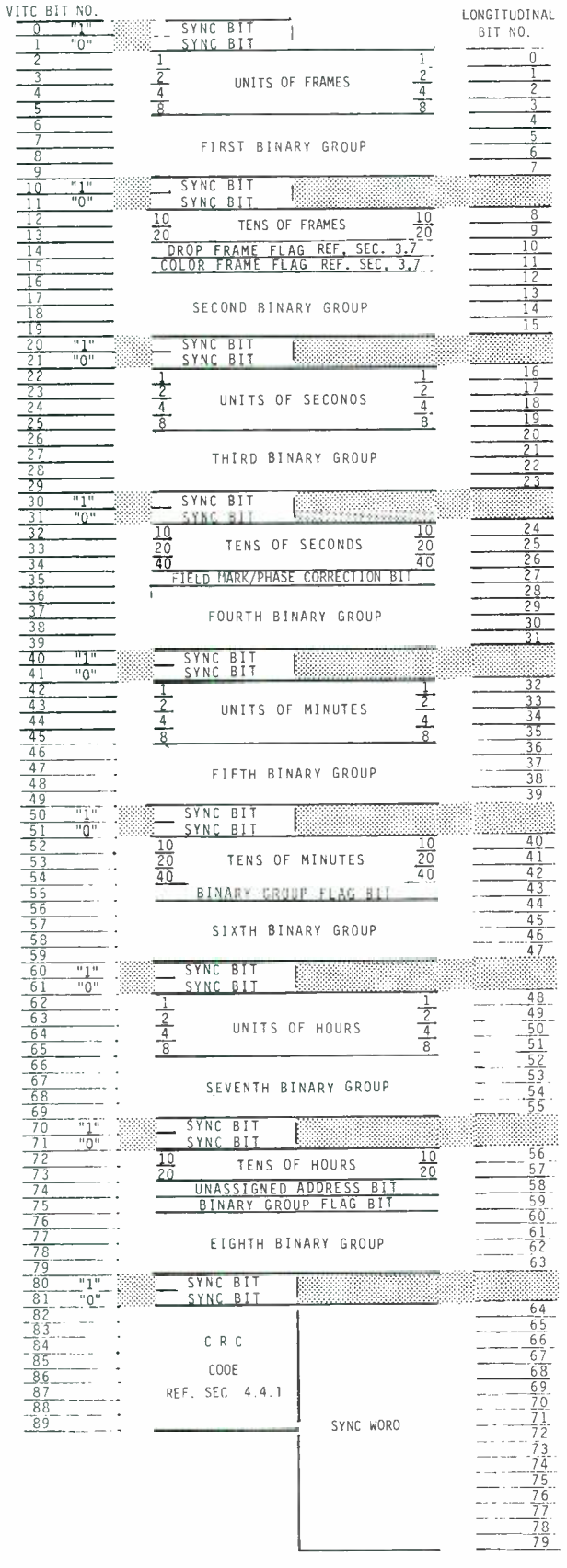


Fig. 15. Relationship of vertical interval time code to longitudinal code. (Reprinted with permission of SMPTE)

Recording, Section 5.5-105. LTC can be decoded at play or higher speeds, but as tape speed drops 1/20 of play signals reproduced by the stationary head become unreadable.

The time-code reader in this example can resolve this problem by utilizing a Vertical Internal Time-Code decoder. VITC contains the same information found LTC, but is inserted into the vertical interval of each field during a recording. During slow motion and still frame operation of helical VTRs, VITC data can be recovered from video. At high speeds where video is not recoverable the reader can revert to LTC.

VITC contains the same information found in LTC along with some additional improvements. An error check code called *cyclic redundancy check*, or CRC is included and VITC is recorded on two adjacent lines. These redundancy features help reduce code loss due to tape dropouts. Another improvement is the addition of field identification bit. In order to accommodate these additional features, VITC requires ten more bits than the 80 bits in LTC, see Fig. 15.

Audio Tape Recorder Interfaces

A multitrack audio tape recorder (ATR) designed for capstan servo and remote control may be interfaced to the edit controller buss much in the same way as a VTR, see Fig. 16.

Time code is recorded on a single track providing location reference. Off-tape time code is compared to the desired location in the interface microcomputer system which produces commands issued to the transport remote control until a near match is achieved. Frame lock is achieved by comparing the TC frame units to a reference frame pulse generated from house reference black burst. The resulting dc error voltage is applied to a voltage controller oscillator producing a tone proportional to the speed error.

The ATR accepts this speed tone as an input to the capstan servo comparator thus completing the overall servo loop.

An example of a suitable ATR for this application is shown in Fig. 17. Serial control is also available as the interfacing path utilizing similar techniques to those for serial control of VTRs.

Video Switcher Interfaces

The ability to control video switcher functions from the editing computer provides a number of advantages. Transitions such as dissolves, wipes or keys may be performed repeatedly without the inherent chance of error found in manual operation. This relieves tedium and provides continuity if edit lists are transported between similar editing suites. A number of interface configurations are

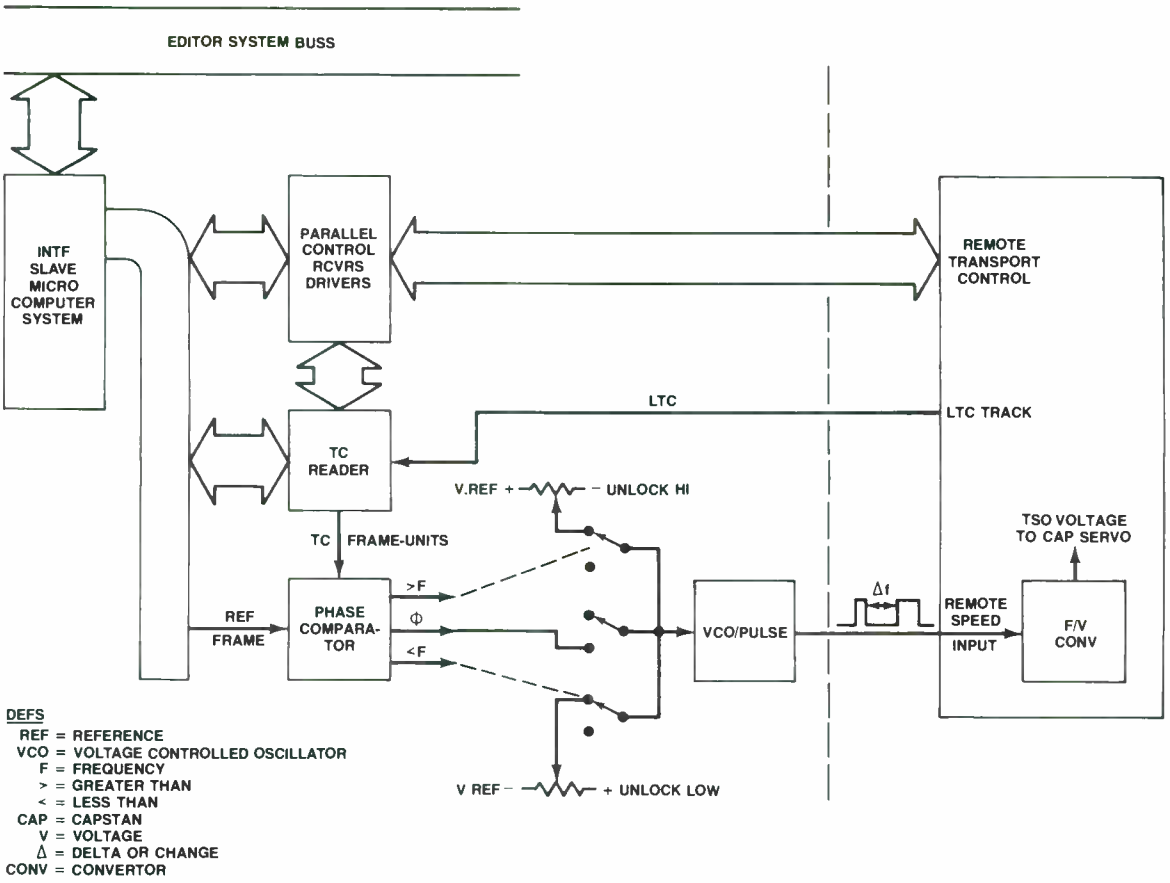


Fig. 16. Parallel port ATR and interface.

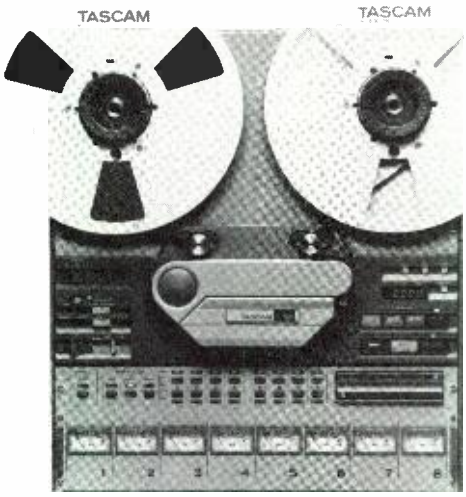


Fig. 17. Multi-track ATR suitable for editor control. (Courtesy TASCAM-TEAC)

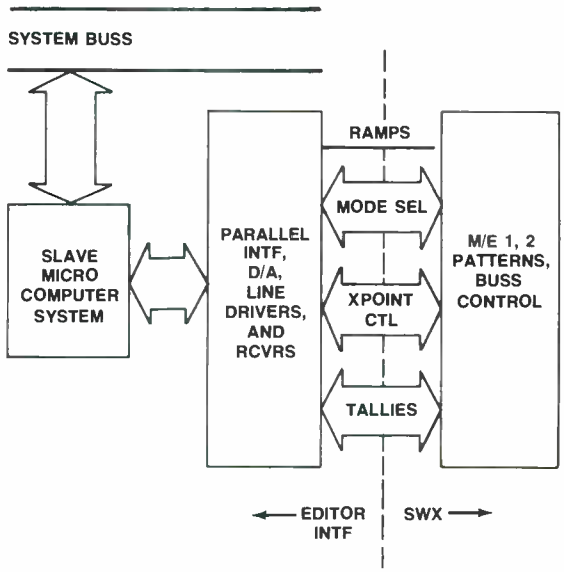


Fig. 18. Parallel port switcher and interface.

possible depending on the capability of the switcher. In Fig. 18 we see a parallel interface to a video switcher in which crosspoints, key functions, and wipe patterns are selected, and tallies received on a one wire per function basis. Fader arm and other control voltages are generated by a D/A converter and switched to the appropriate effects amplifiers to replace those produced by the manually operated transition lever arm. The wire per function method of the parallel interface technique becomes unwieldly as more functions are added to switchers. In Fig. 19 the task of automation has been divided between the switcher and the edit controller. Although crosspoints and effect types are selected by the parallel technique, the switcher contains an internal automatic transition system. Using this system, a transition may be manually rehearsed by the operator and automatically performed by the edit controller, recalling by the assertion of a single command. An example is shown in Fig. 20.

To alleviate the parallel wiring and to provide a memory system for switcher set-ups, an accessory is available for the parallel switcher, see Fig. 21.

This subsystem is inserted between the switcher control panel output and the switcher electronics frame control inputs, see Fig. 22. Manual operation of a panel control is converted from analog to digital form enabling it to be stored in memory. These data can be recalled and converted back to analog form for control of the switcher electronics frame. Instead of control panel information, data from the editor's serial interface can be converted to analog form for control of the switcher electronics.

As switcher architecture has evolved, the operator control panel can now be thought of as a specialized terminal. The various crosspoint selections, fader and knob positions are encoded into a bidirectional serial data stream. This data stream may be originated by the switcher control panel or an editor controller interface.

The edit controller's dedicated microcomputer system runs an interface program that converts data received from system buss into the com-

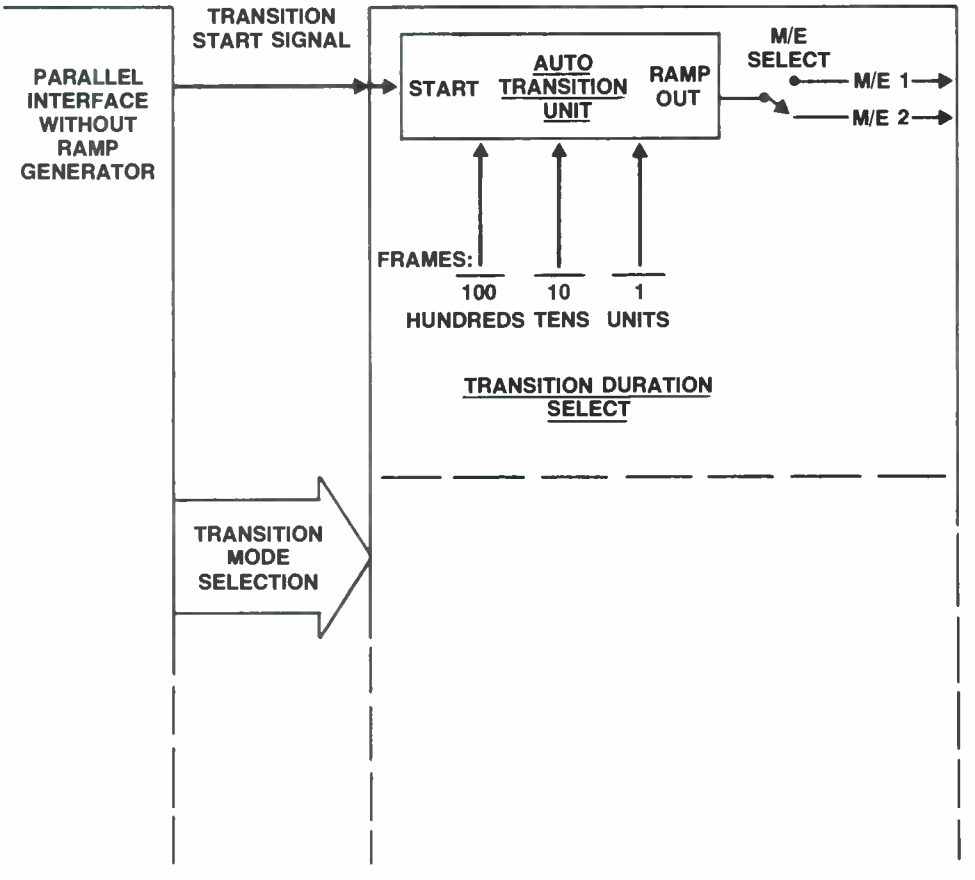


Fig. 19. Automatic transition unit added to parallel interfaced switcher.

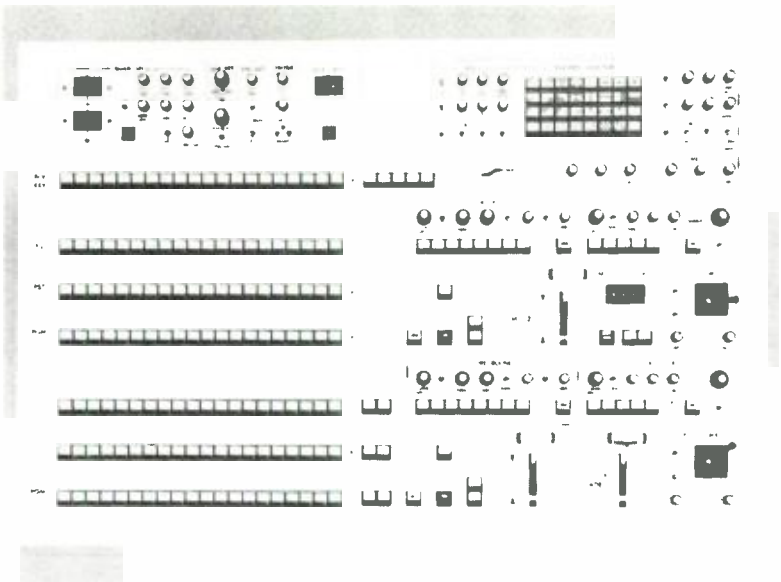


Fig. 20. Switcher containing automatic transition unit. (Courtesy Ross Video)

mand's specified by the switcher manufacturer. The switcher electronics frame decodes the data stream and implements these commands. Tally information sent in the reverse direction is decoded by the interface and placed on the system buss where it is available to the host.

The video switcher shown in Fig. 23 is an example of combining total serial control with automatic transition and set-up storage memory. A total of twelve switcher set-ups may be stored in the memory system and recalled via the serial interface. Multiple automatic transitions can be performed with complete control of the effects system.

Function selection and transition performance on the serially interfaced switcher occur by sending register select codes from the edit controller at the desired time-code trigger point (this information can be stored in the edit decision list and recalled later by using a special function cell of SFC). In this case, the SFC contains a number denoting a serial switcher and desired transition. Multiple SFC's can be activated during the edit intervals providing complete repeatable effects.

The ability to apply the SFC technique along with other powerful methods of switcher control via the edit decision list is currently hampered by the lack of interchangeable protocol and interface formats between manufacturers. In the case of the Ross 210 Switcher a decision to emulate the Grass Valley format allows one editor interface to be used with either manufacturer.

Digital Video Effects Interfaces

Interfacing to a digital video effects system (DVE) is also accomplished in this example by

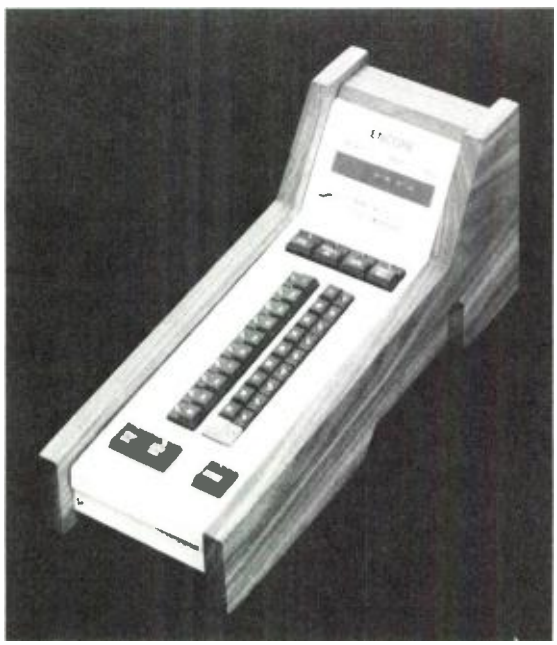


Fig. 21. Memory and serial interface for parallel port switcher. (Courtesy Ross Video)

use of the SFC system, relying on the ability of many digital effects systems to produce programmed effects on activation of a contact closure. The SFC device code for a relay closure is selected, which directs the software to the relay interface circuitry, and closes the appropriate contact pair. The edit decision list records the closure trigger time and the SFC code for a digital effect device. The manufacturer may offer a protocol

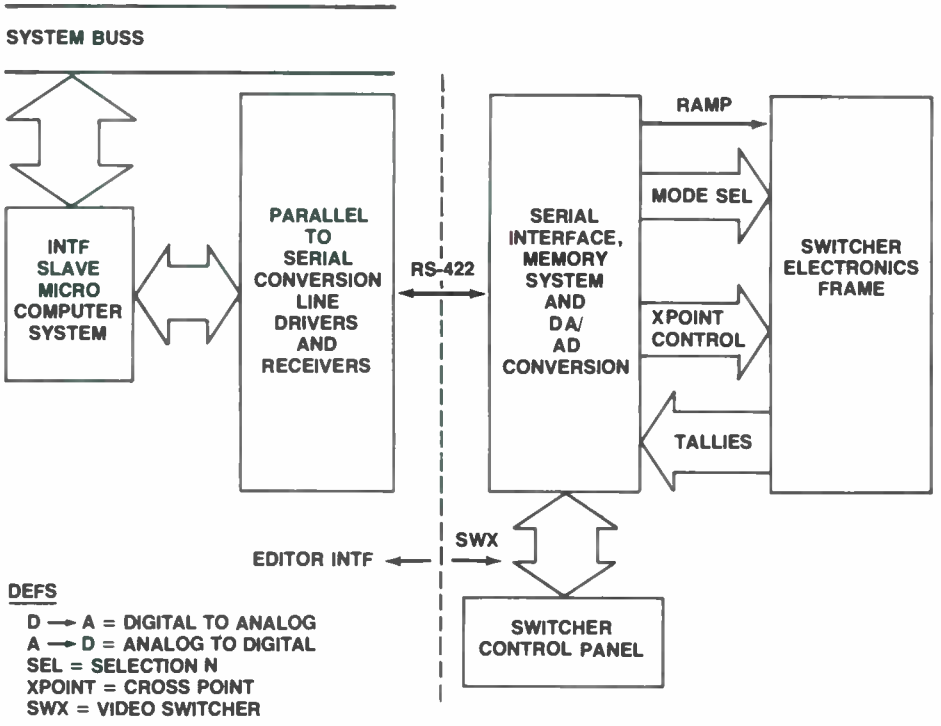


Fig. 22. Memory and serial interface system integrated into parallel port switcher.

Fig. 23. Ross RVS-210 (Courtesy Ross Video)

for an external interface designating each function. An SFC containing the required register selection can be used to select the desired effect under editor control.

Audio Mixer Interfaces

The ability to interface an audio mixer to the editing controller computer buss provides similar types of advantages to that of the edit system controlled video switcher.

In Fig. 24 we have an example of a parallel interface between the system buss and an audio console designed for editing application. Audio crosspoints are selected using a wire per function approach or by multiple data bytes transmitted sequentially across the parallel lines. These lines are optically isolated to insure minimal noise coupling between the interface and the audio console.

In order to provide remote control of mixing levels the interface provides an analog control voltage to the buffered input of a voltage controlled amplifier (VCA). This VCA can be located as a channel, submaster or master gain control cell. An example of an audio console embodying these features is shown in Fig. 25.

An alternative approach to the parallel interface method is exemplified by the audio mixer shown in Fig. 26. This approach utilizes the techniques of total serial control and automatic transitions. This device can perform as a stand alone audio mixer, under control of an editor serial interface, or slaved to a video switcher, see Fig. 27. By looping the video switcher interface serial control line through the AMS 210, commands issued to the video switcher can be followed by the audio mixer. The editing host controller running suitable software can select the desired crosspoint to follow video or provide split audio using one or two channels. Level trimming data are available to the edit controller to allow listings of trim values in the edit decision lists. Programmed transition modes available are "V"

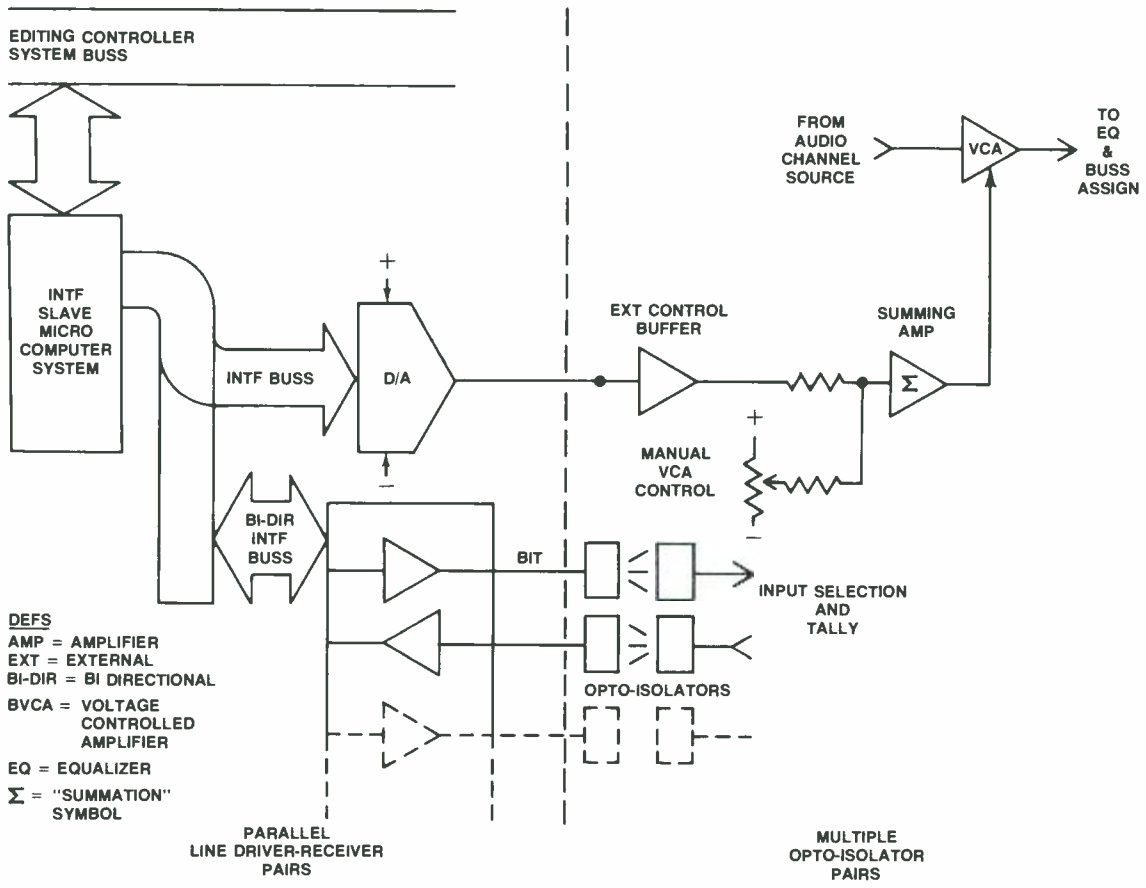


Fig. 24. Parallel port audio mixer with VCAs and interface.

Fig. 25. Post Pro 12 ADM Technology audio mixer. (Courtesy ADM Technology)

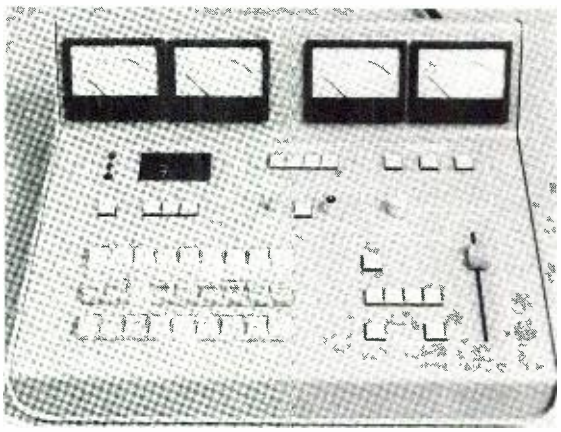


Fig. 26. McCurdy AM-210 post production audio mixer with serial control. (Courtesy McCurdy)

fades, cross fades, cut/fade and fade/cut. An "over" buss is selectable allowing common voice-over mixes to be summed into the master output.

Preview System

The Preview system provides an internal routing switcher for selecting the video and audio sources. Each VTR, Black, External Video, and Switcher output, with corresponding audio sources and audio mixer outputs is available on the switcher buss. Edit previews are automatically performed by the host CPU. Sources are switched at transition points to the preview audio and video

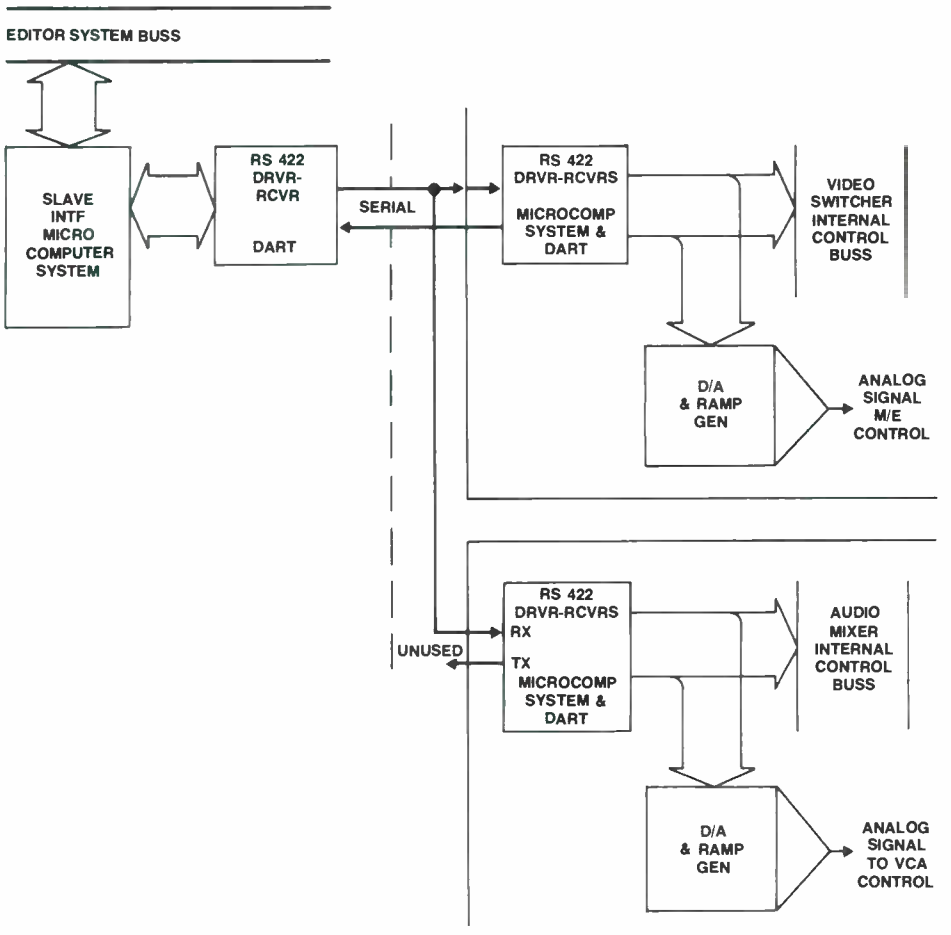


Fig. 27. Serial video switcher with audio mixer as slave.

monitors, thus simulate and edit. Inclusion of a preview switcher eliminates relying on a specific preview switching system being included in the record VTR.

General Purpose Interface

The general purpose interface system is the simplest and most versatile of the interfaces. Addressed by selecting a specific code for a special function cell, a contact closure or logic level can be asserted at a desired trigger time to activate external devices.

The triggered pulse is only a momentary command and may not be sufficient in duration for the controlled device, therefore a programmable timer allows the closure time to be lengthened in multiples of video frame duration.

Fig. 28 Editing suite utilizing external VTR machine room. (Courtesy Multivision)

EDITING SUITE DESIGN CONSIDERATIONS

Editing suite physical design comprises a sufficiently large subject so that it cannot be completely examined within the scope of this chapter. It is suggested that the broadcaster faced with designing an editing suite examine those found in commercial post production facilities. Conversations with the engineering and editorial staff will bring to light many points learned from

design and construction of numerous suites over several generations of changing technology.

Although the equipment level may exceed the broadcasters needs, the pressure of the commercial post production environment quickly exposes flaws in system lay-out or functional design. This information, combined with the experience already available on broadcast facilities design, can produce a well integrated and functionally efficient suite.

The following list is an abbreviated collection of topics to be examined during suite physical design.

Suite Design Physical Considerations

Traffic Patterns

- Client Access
- Operator Access
- Maintenance Access
- Observer

Technical Environment

- Temperature Control
- Humidity Control
- Power Quality
- Radio Frequency Interference Susceptibility
- Static Discharge
- Contamination Control

Ergonomics

- Operator Console
- Storage Facilities
- Seating Positions
- Client/Producer Work Space
- View Path
- Acoustic Path

Visual Environment

- Operating Lighting
- Service Lighting

Acoustical Environment

- Frequency Response
- Noise Containment
- Stereo Imaging

Traffic Patterns

Client Access—Ability to enter and exit suite with minimal disruption to operator

Operator Access—Operator can access secondary hardware located out of immediate reach without disturbing client

Maintenance Access—In case of failure, maintenance technician can patch in auxiliary equipment without disturbing client

Routine maintenance to unassigned equipment can be performed without disturbing operators or client

Observer Access—Provides enough observation access to tours to indicate the application of the facility while avoiding disruption of sessions

Ergonomics

Operator Console—Allows for the operator to reach primary controls without excessive motion, while monitoring their effect.

Placement of keyboard, switcher control panels, audio consoles, remote controls, etc. so that typical operation doesn't place two simultaneously needed controls out of reach.

Height, width and depth of cabinetry chosen to allow comfortable, prolonged operation.

Client/Producer Workspace—Provision for a dedicated location for comfortable workspace allowing the client or producer to work with the operator without being oppressively close. Position should provide writing space and include lighting that does not interfere with program monitors.

View Path—Placement of equipment and console heights to allow as parallax-free view of the program monitors as possible for both operators and clients by minimizing the angle away from in-line view that will occur as operator moves between positions. Accomplished by placing primary controls directly in front of or adjacent to an operator without using a horseshoe approach that requires excessive neck twisting.

Acoustic Path—Provision for a direct acoustic path for the desired sources such as the monitoring system while interrupting the path of noise sources such as equipment fans. Operator and client must be able to be located in this path at their normal locations.

Technical Environment

Temperature Control—Provision for sufficient cooling of equipment without freezing clients. Operating consoles often allow too little ventilation for the current generation of high density electronics.

Humidity Control—Inclusion of humidity controls such as a humidifier to suppress the generation of static electricity by personnel and hardware or, conversely, dehumidifiers to reduce excessive type adhesion produced by high humidities.

Power Quality—Editing suite power sources should receive the same general consideration as those in a computer facility. The likelihood of losing an edit session due to an edit computer program crash caused by a power line spike can

be reduced by utilizing any of the many line filters now commonly available for the larger personal computer systems.

Radio Frequency Interference Susceptibility—The equipment manufactured for an editing suite may not have been specifically designed for operation in a RF field. A typical commercial post production suite often does not have a broadcast transmitter, microwave transmitter, weather radar or numerous two-way radio systems operating nearby. Placing an editing suite in such a location may produce difficulties not normally experienced with similar broadcast equipment.

Static Discharge Control—Provision for a safe discharge path for the static charge that builds up on personnel utilizing the editing suite. Humidification, conductive floor treatments, and anti-static sprays are all good steps in reducing the likelihood of system crash due to static discharge. Combining these measures with operator static awareness training can significantly improve system reliability.

Contamination Control—In an editing suite with remotely located VTRs, the contamination precautions are the same as those in a studio control room with the added caution to avoid contaminating floppy disks used for edit list storage. Maintaining the contamination control level for a suite with on-site VTRs requires the same or stricter precautions as those used in a standard operating tape room. If dropouts are considered unacceptable so must be their human-generated causes. The multiple passes endured by the tape during computerized editing increase susceptibility to tape damage from any cause.

Visual Environment

Operations Lighting—Proper lighting conditions during an editing session will provide minimal glare on monitors and console surfaces, clear readability of controls, work light for scripts and walk away lighting for safety. Attention to color temperatures produced by lighting fixtures and monitors will minimize contamination. Room color treatment should be neutral and minimally non-reflective.

Service Lighting—Include an auxiliary set of lighting fixtures or a higher operating level for the existing operations' lights that provides sufficient illumination for equipment or general maintenance. The method of providing service lighting should not disturb the ability to quickly reproduce operational lighting conditions.

Acoustical Environment

Frequency Response—Care must be taken to minimize control room conditions that produce frequency response nonlinearities. Many edit points are selected relative to a specific aural cue. Loss or exaggeration of these cues may cause judgement errors in selecting appropriate edit points. These conditions may also interfere in performing objective quality control tests.

Stereo Imaging—Placement of monitor speakers, room obstructions and personnel must all be considered in order to provide an environment that allows the mixdown process to correctly place the stereo image. Frequency response and reverberation time have to be controlled in order to avoid distorting the monitored stereo image. It is advisable to draw upon the experience of persons who have successfully dealt with these issues in dedicated mixdown facilities.

As is often the case in broadcast facilities many commercial post production suites are built with a separate equipment room for VTR, digital effects and terminal equipment. This technique offers the advantage of keeping the noise and heat generated by such equipment away from the operating environment. In case of equipment failure, patching over to alternate equipment and service occurs with minimal alarm to the client.

Alternatives to the separate machine and control room approach become practical as VTR and terminal equipment size are reduced. In Fig. 30 the reduction in size and power provided by interformat editing allows all equipment to be placed in the suite. This centralization allows fast and efficient operation by single operator.

Systems Integration

Integration of the editing suite electronic components into the broadcast facility in order to utilize other plant facilities often involves consideration of the following systems.

External Devices Accessed By Edit Suite

Video
- Routing Switcher and Distribution System
- Digital Effects Equipment
- Character Generator
- Graphics Camera and Art System
- Still Store System
- Digital Noise Reducer
- Color Correction
- Test Signals

Audio
- Routing Switcher and Distribution
- Announce Booth
- Audio Sweetening Room
- Test Signals
- Intercom System

The integration of these systems may require provision of remote control panels, delegation

switching, delay compensation, distribution equalization and level compensation. Judging when it is practical to time share one piece of equipment or to purchase a smaller dedicated device must take into account the inevitable priority conflicts that will occur between the editing group and on-air operation

This problem is rarely permanently resolved due to the continual increase in the power of technology that can be purchased per dollar.

A typical situation is that the falling price of technology allows a character generator (CG) to be purchased for dedicated use by an edit suite. This solves the conflict over (CG) time but the same advance in technology that made the (CG) more economical also brought the price of an electronic graphics and paint system down to a level where the facility can afford to purchase one. This has been the case for digital effects, still store and noise reduction systems.

SMPTE RECOMMENDED PRACTICE

RP 113-1983

Supervisory Protocol for Digital Control Interface

1. *General*

1.1 Scope. This recommended practice defines the supervisory protocol used within a general purpose communication channel of an interface system which transports data and digital control signals between equipment utilized in the production, post-production, and/or transmission of visual and aural information. It is intended that the supervisory protocol described in this practice be part of an overall system, allowing interconnection of programmable and nonprogrammable equipment as required to configure an operational system with a defined function, and to allow rapid reconfiguration of a system to provide more than one defined function utilizing a given group of equipment.

1.1.1 The primary intent of this practice is to establish supervisory procedures of the communication channel for the purpose of transmitting control messages to equipment by external means. (The contents of the messages are not defined.) This practice, or sections thereof, may be applied to the interconnection of elements within an item of equipment.

1.2 Definitions. (See Fig. 1.) For the purposes of this practice, the following definitions apply:

Bus Controller: Each system contains one bus controller which supervises all tributaries in the system. Supervision is exercised through the use of this supervisory protocol.

Byte: A byte consists of eight bits of information. Bits used to effect transmission such as byte start, parity, or end are not part of the byte.

Tributary: A tributary transfers messages to and from an operational device via the interface system. The tributary is distinct from the function of the operational device and exists to transfer control messages between the communication channel and the device.

Word: A word consists of a byte and associated bits used to effect transmission such as start, parity, or end.

2. *Message Types*

Two types of messages shall be transmitted on the channel:

Supervisory Messages to supervise the channel and direct the flow of device messages.

Device Messages to control operation of equipment functions. This type of message shall be transmitted only within standard message blocks or during device defined communications modes. Details of device messages will be the subject of another document now in preparation.

3. *Tributary Addresses*

Tributary addresses shall consist of two bytes: the most significant byte, which is transmitted first, and the least significant byte. The most significant bit of both bytes shall be set to binary 1. This provides an address range starting at 8080_h. Each tributary shall be assigned two unique addresses, a SELECT address and a POLL address.

3.1 Select Address. An address in which the least significant bit of the least significant byte equals binary 0 is a SELECT address.

3.2 Poll Address. An address in which the least significant bit of the least significant byte equals binary 1 is a POLL address.

3.3 Group Addresses. Address pairs $8080\text{-}8081_h$ and $8082\text{-}8083_h$ through $81FE\text{-}81FF_h$ are reserved as GROUP SELECT addresses. The addresses in which the least significant bit of the least significant byte equals binary 1 (POLL address) shall not be used but are retained in the address numbering scheme for software considerations.

3.4 Discrete Addresses. Tributary addresses shall start at $8280\text{-}8281_h$. Precisely 8064 discrete tributary address pairs are available.

3.5 Address Allocation Table:

$8080\text{-}8081_h$	Group select—all call
$8082\text{-}80FF_h$	Group select—Groups 1-63
$8180\text{-}81FF_h$	Group select—Groups 64-127
$8280\text{-}82FF_h$	64 tributaries
$8380\text{-}83FF_h$	64 tributaries
⋮	
$FF80\text{-}FFFF_h$	64 tributaries

Copyright © 1983 by the
SOCIETY OF MOTION PICTURE AND TELEVISION ENGINEERS
862 Scarsdale Avenue, Scarsdale, NY 10583, (914) 472-6606

Approved 3 February 1983

Reprinted with permission of SMPTE.

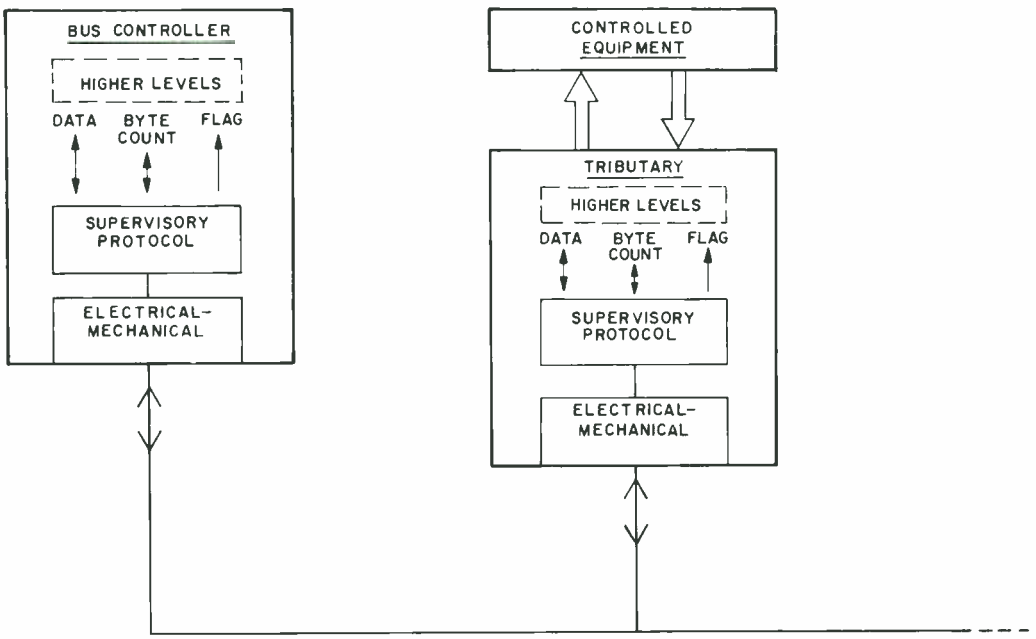


Fig. 1
System Elements

4. *Tributary Operational States*

A tributary shall be in one of five major operational states:

IDLE: The tributary shall not perform any communications. This state shall be exited only in response to BREAK.

ACTIVE: Prerequisite for transition to other operational states. The tributary shall enter this state whenever BREAK is received.

POLL: The tributary shall transmit a single status byte to the bus controller.

SELECT: A single tributary shall enter a communications mode with the bus controller.

GROUP SELECT: All tributaries or a selected group of tributaries shall enter a communications mode with the bus controller.

5. *Supervisory Messages*

Tributaries shall be directed to operational states through various communications sequences by supervisory messages as shown in Fig. 2. Supervisory messages consist of the following elements:

BREAK: Shall drive all tributaries to the ACTIVE state. (See American National Standard for Television—Digital Control Interface—Electrical and Mechanical Characteristics, ANSI/SMPTE 207M-1984, for code.)

(ADDR-POLL): A tributary poll address (ADDR-POLL) shall drive the addressed tributary to the POLL state.

(ADDR-SELECT): A tributary select address (ADDR-SEL) shall drive the addressed tributary to the SELECT state.

(GROUP ADDR-SEL): A group select address shall drive a group of tributaries to the GROUP SELECT state.

Supervisory Characters: Identify communications sequences and provide status information. Supervisory characters are single bytes within the range 00_h-$7F_h$. Supervisory characters shall consist of:

01_h	(GRP)	Group assign
02	(STX)	Start of message
03	(ESC)	Escape
04	(ACK)	Acknowledge
05	(NAK)	Not acknowledge
06	(BSY)	Busy
07	(RST)	Reset
08	(SVC)	Service request from controlled equipment
09	(TEN)	Transmit enable

All other supervisory characters are reserved. The use of other characters for tributary supervision is noncompliant with this specification.

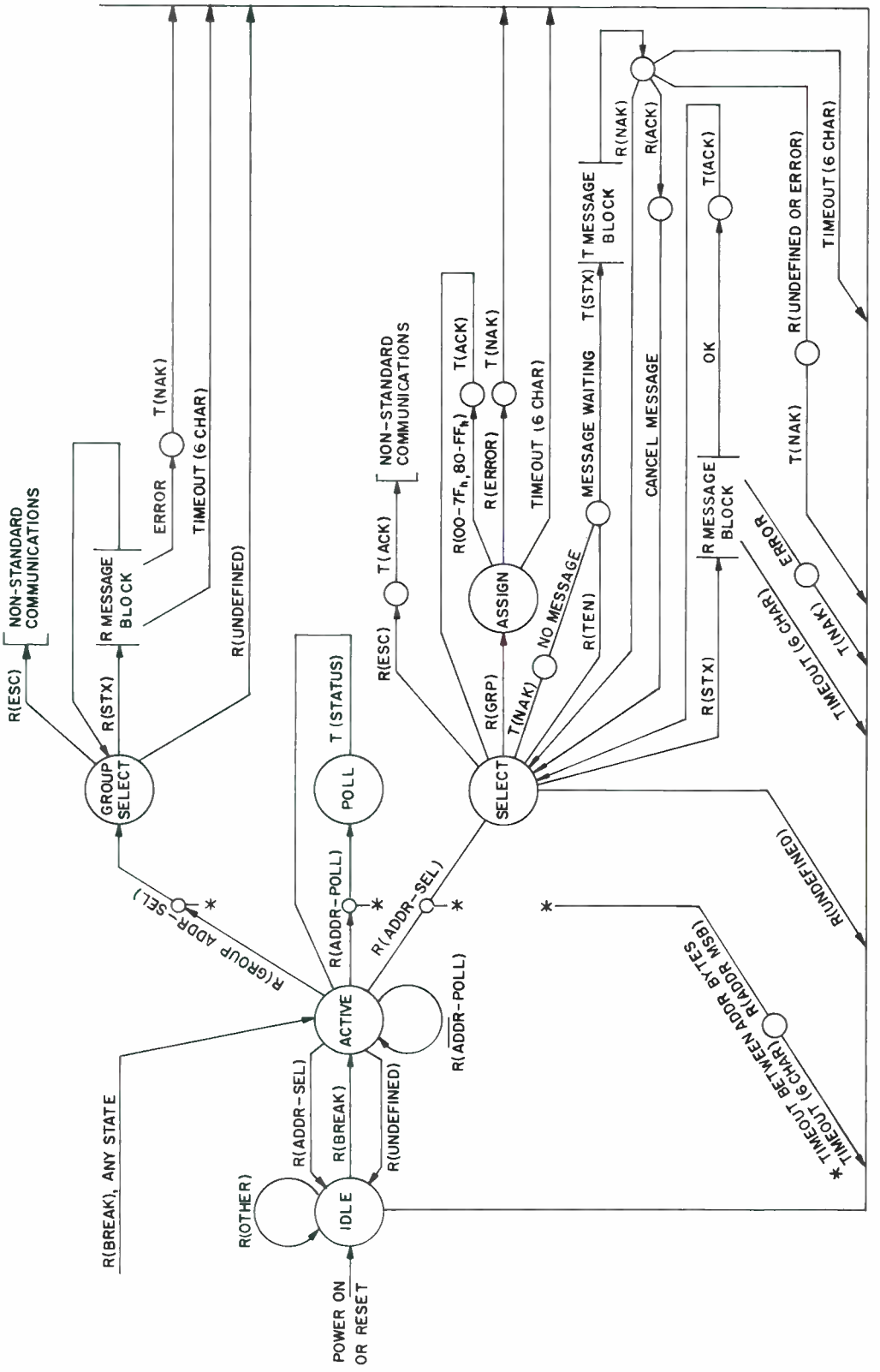


Fig. 2
Tributary Supervisory Protocol

6. *Operational Sequences* (See Fig. 2)

6.1 Idle. Tributaries in the idle state shall not perform any communications sequences.

6.1.1 Idle shall be entered under the following conditions:

Tributary power on or reset

Upon receipt of an (ADDR-SEL) not assigned to the tributary

Upon receipt of a GROUP (ADDR-SEL) not assigned to the tributary

When a specified time out of six words in duration occurs

On receipt of an undefined byte

On encountering a transmission error or ambiguous condition

6.1.2 A tributary shall exit the IDLE state only on receipt of BREAK.

6.2 Active. A tributary in the ACTIVE state shall perform communications sequences as directed by the bus controller.

6.2.1 All tributaries shall enter the ACTIVE state whenever BREAK is received and on completion of a poll sequence.

6.2.2 A tributary shall exit the ACTIVE state on receipt of an address which directs it to the POLL. SELECT, or GROUP SELECT states. A time out between the two address bytes shall cause the tributary to enter the IDLE state.

6.3 Poll. The POLL state shall be used to determine the presence and status of a tributary.

6.3.1 A tributary shall enter the POLL state on receipt of its poll address (ADDR-POLL). The tributary shall transmit one supervisory character to indicate its status, then return to the ACTIVE state. Tributaries not addressed shall remain in the ACTIVE state. Supervisory characters transmitted shall be of the following:

RESET (07_h): Tributary has powered up or been reset since last poll.

NAK (05_h): An exception (time out, undefined byte, etc.) condition has occurred since last poll or select.

BSY (06_h): Tributary not available to receive messages.

SVC (08_h): Service request from controlled equipment.

ACK (04_h): Tributary available to receive messages.

These characters rank in priority according to the order shown above.

6.4 Select

6.4.1 A single tributary shall enter the SELECT state on receipt of its select address (ADDR-SEL). All other tributaries shall transition to the IDLE state. A tributary in the SELECT state shall execute the communications sequences detailed in 6.4.1.1 through 6.4.1.4 as directed by the bus controller.

6.4.1.1 Receive Message. Supervisory character STX (02_h) shall be followed by a message block containing the following characters:

byte 1: byte count of bytes 2 thru n (0 = 256 bytes).

bytes 2 thru n: (256 bytes maximum)—device defined message.

byte n + 1: checksum = 2's complement of the least significant byte of the sum of bytes 1 through n.

The tributary shall indicate error-free reception by responding with ACK and shall return to the SELECT state.

On encountering an error during reception, the tributary shall respond with NAK, then transition to IDLE.

If transmission from the bus controller is interrupted for more than the time out period, the tributary shall transition to IDLE.

The tributary shall transfer a complete message, the byte count specified above, and a "block ready" indication to the entities using the system for control.

6.4.1.2 Transmit Message. A tributary shall notify the bus controller that a message is waiting by transmitting SVC (08_h) during POLL. Upon receipt of TEN (09_h) while in SELECT, the tributary shall transmit a standard message block as defined in 6.4.1.1.

6.4.1.3 Assign Tributary to Group. Supervisory character GRP (01_h) shall be followed by a single byte:

00_h deletes all previous group assignments of all tributaries

If the most significant bit of the byte following GRP (01_h) is a ZERO, the assignment of the tributary to the address represented by the following seven bits of that byte is deleted (1_h to 127_h).

80_h assigns the tributary to groups 1-127.

If the most significant bit of the byte following GRP (01_h) is a ONE, the tributary is assigned to the address represented by the following seven bits of that byte (1_h to 127_h).

A tributary may be removed from or assigned to more than one group by repeating the assignment sequence.

If transmission from the bus controller is interrupted for more than the time out period between receipt of GRP and the group assignment byte, the tributary shall transition to IDLE.

All group addresses except "all call" (8080_h) shall be deleted at tributary power-up or reset.

6.4.1.4 Nonstandard Communications. Supervisory character ESC (03_h) shall release a tributary to nonstandard communications sequences. The tributary shall respond with ACK; it shall exit ESC mode only in response to BREAK.

6.4.2 The tributary shall exit SELECT on receipt of BREAK or in response to the exceptional conditions noted in 6.4.1.1 through 6.4.1.3 above.

6.5 Group Select

6.5.1 Groups of tributaries shall enter the GROUP SELECT state on receipt of their group select address (GROUP ADDR-SEL). All tributaries not assigned to the group shall transition to IDLE. Tributaries in the GROUP SELECT state shall execute the communications sequences detailed in 6.5.1.1 and 6.5.1.2 as directed by the bus controller.

6.5.1.1 Receive Message. Supervisory character STX shall be followed by a message block as defined in 6.4.1.1.

Each tributary returns to GROUP SELECT state after error-free reception of the block; no response shall be transmitted.

On encountering an error during reception, a tributary shall respond with NAK, then transition to IDLE.

If transmission from the bus controller is interrupted for more than the time out period, tributaries shall transition to IDLE.

6.5.1.2 Nonstandard Communications. Supervisory character ESC shall release a group to nonstandard communications in accordance with 6.4.1.4. Tributaries shall exit this mode only in response to BREAK.

6.5.2 Tributaries shall exit GROUP SELECT on receipt of BREAK or in response to the exceptional conditions noted in 6.5.1.1.

7. *Bus Controller Operation*

7.1 System Synchronization. The bus controller shall transmit BREAK when power is turned on and after being reset.

7.2 Tributary Response Time Out. The bus controller shall transmit BREAK when a tributary fails to respond within the following time-out periods:

In response to ADDR-POLL, GRP (#), ESC, TEN, END OF MSG BLOCK 6 words

8. *Guidelines*

8.1 Function of This Practice. This practice specifies the supervisory protocol used within the communication channel. The protocol is the sequence of characters used to transfer messages between the bus controller and tributaries, provide recovery from error conditions, and generally supervise the usage of the communication channel. This practice is concerned only with channel supervision. Electrical/mechanical characteristics are specified in separate standards since many types of channels which can deliver eight-bit binary bytes and a unique BREAK condition can operate under supervision of the protocol Message content is specified by standards which are independent of both electrical/mechanical and supervisory characteristics of the communication channel.

8.2 System Configurations. This supervisory protocol permits supervision of point-to-point and multipoint systems.

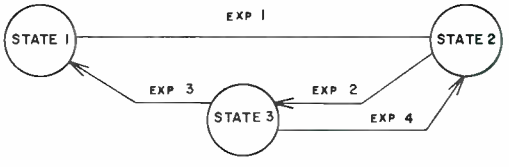
A point-to-point configuration is one in which a communication channel is connected to only one tributary. The bus controller may be connected to more than one channel, each having one tributary. This configuration has the advantage of speed since the dedicated channels provide access to all tributaries simultaneously.

The multipoint bus configuration is one in which more than one tributary is connected to a channel. This configuration has the advantage of reduced cabling costs and complexity. The main disadvantage of multipoint is that messages to different tributaries must queue up and be sent serially on the bus. This configuration is therefore slower in response time than point-to-point systems.

8.3 State Diagrams. The supervisory procedures are described by means of state diagrams that show how the interfacing hardware and software in a tributary follow sequences of bytes as they are received from the communication channel.

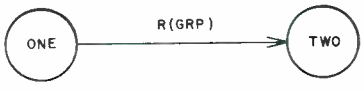
8.3.1 Each state (condition) that a tributary can assume is represented graphically as a circle; major states are identified by an upper case label or mnemonic within the circle:

8.3.2 All possible transitions between states are represented by arrows between the states; each transition is qualified by an expression which will produce the transition.



8.3.3 Expressions can be messages received from or transmitted to the communication channel, or local messages generated within the tributary.

8.3.3.1 Messages received from the channel are represented by R followed by the received message in parentheses:



indicates transition from state ONE to state TWO on receipt of the message GRP.

8.3.3.2 Messages transmitted to the bus are represented by T followed by the transmitted message in parentheses:

indicates transition from state THREE to state FOUR after transmitting the message ACK.

8.3.3.3 Local messages are represented by lower case labels:

indicates transition from state FIVE to state SIX when reset occurs.

8.4 Channel Synchronization. Data density is maximized by allowing the transmission of binary data in all device messages. This means that there must be no combination of transmitted bytes which can be interpreted as a channel synchronization command. The channel synchronization command is a unique transmission sequence called BREAK. This sequence cannot be accidentally generated by normal communications. Tributaries receiving BREAK are required to immediately transfer to the ACTIVE state regardless of what they are currently doing in relation to the communication channel. On power up, a tributary enters the IDLE state and ignores all bus transactions until it receives BREAK. Electrical specifications appropriate for use with this supervisory protocol assure that BREAK cannot be generated accidentally.

8.5 Supervisory Message Components. The protocol uses BREAK, tributary addresses, and a small number of predefined supervisory characters to manage the communication channel. Since the addresses and supervisory characters are eight-bit binary bytes, they must be recognized by being received immediately after BREAK. The only supervisory message that is unconditionally recognizable is the BREAK sequence.

8.5.1 Tributary Addresses. Tributary addresses consist of two bytes. Up to 8064 tributaries can be addressed uniquely. A one-byte addressing scheme would have served most small system applications with a saving in channel overhead, but complex reassignment strategies would have to be employed in order to accommodate larger users.

The address bytes are characterized by a 1 in the most significant bit. Each tributary is assigned two addresses, a SELECT address and a POLL address. The least significant bit of the least significant byte is set to 0 for SELECT and 1 for POLL.

A unique two-byte address serves as an all-call SELECT address. When this address is transmitted all tributaries in a multipoint system simultaneously receive and act on system messages.

Tributaries can be assigned to one or more of 127 group SELECT addresses. These addresses allow simultaneous operation with selected groups of tributaries in multipoint systems similar to all-call.

During all-call or group operation, transmission by the tributaries is allowed only when an error condition is encountered, since other transmission could cause channel errors as several tributaries attempted to transmit at the same time. When error conditions are encountered, tributaries transmit the supervisory character NAK; reception of the NAK, or an error indicating channel contention, alerts the bus controller to an error condition in one or more tributaries. The bus controller must assert BREAK and poll individual tributaries to determine which tributary (ies) has encountered an error and the nature of the error.

8.5.2 Supervisory Characters. The only supervisory characters used are those given in Sec. 5. Supervisory characters are single eight-bit bytes in which the most significant bit is 0. Implementations of this protocol must not use any other supervisory characters for nonspecified functions as such use would render a tributary incompatible with other systems and could occasion serious operational failures if other supervisory functions are added to this practice in the future.

8.6 Poll Sequence. The POLL sequence is used to verify tributary presence and status. In multipoint systems, the POLL sequence allows all tributaries to be scanned quickly to see if servicing or attention is required by any of them.

Status characters transmitted by a tributary inform the bus controller of the tributary's current condition. Characters associated with specific conditions are detailed in 6.3.1. The tributary is required to send the highest priority status character applicable to its condition if more than one applies. All status characters except service request (SVC) apply to conditions within the interface function. SVC is a pass-through condition which indicates a service need by the equipment controlled through the interface. Device messages are used to identify and provide the service required.

8.7 Message Receive or Transmit Sequences. Device messages are received or transmitted by a tributary by means of the message receive or transmit sequence from the SELECT state. This sequence offers message lengths of 1 to 256 bytes with checksum protection. Groups of tributaries can receive messages from the GROUP SELECT state.

On receipt of a message, the bus controller will transmit an ACK or NAK. It then waits for six characters for any exceptional condition. (See Fig. 2.)

All equipment control and status information is exchanged by means of device messages.

8.8 Escape Sequence. The escape sequence is provided for those users who wish to remain compatible with the electrical and supervisory protocol characteristics of the interface system but require nonstandard operational sequences or messages. Single tributaries or groups of tributaries may be placed outside the normal protocol limits using this sequence. The only protocol requirement which must be observed by devices while using this sequence is the requirement to enter the ACTIVE state whenever a BREAK is received from the communication channel.

8.9 System Design Considerations. This practice and associated standards specify characteristics for equipment compatible with the interface system. System function and configuration is left to the system designer. Certain cautions must be observed by the designer:

8.9.1 Device messages are specified by other standards. Only device messages which conform to those standards should be transmitted via the standard message receive/transmit facilities. Nonstandard messages should be transmitted via the escape sequence.

8.9.2 Switched Tributaries. This practice and associated standards consider operation of bus controllers and tributaries to be within one communication channel. If tributaries are transferred between channels, the system designer must provide means to place them in an appropriate state before connection to a new channel. It is recommended that the tributaries be forced to the IDLE state with all group address assignments cleared before connection. Procedures for notifying a bus controller of the attachment of a tributary will generally be required; these procedures are dependent on the nature of the system and are left to the designer's discretion.

ANSI/SMPTE 207M-1984

American National Standard for television— digital control interface— electrical and mechanical characteristics

Approved January 27, 1984 Secretariat: Society of Motion Picture and Television Engineers

1. General

1.1 Scope. This standard defines the electrical and mechanical characteristics of an interface system comprised of a general purpose communication channel and interface device(s) used for the transfer of data and digital control signals between equipment utilized in the production, post-production, and/or transmission of visual and aural information. It is intended that the communication channel and device(s) described in this standard be part of an overall equipment interface, allowing interconnection of programmable and nonprogrammable control and accessory equipment as required to configure an operational system with a defined function. The standard is also intended to allow rapid reconfiguration of a system providing more than one defined function utilizing a given group of equipment.

1.1.1 The electrical and mechanical specifications set forth in this standard are intended for use in both fixed plant and field operational environments. These specifications take into account the requirement to function reliably without causing undue interference with other signals normally found in these environments.

1.1.2 This standard defines the electrical and mechanical characteristics of the communication channel and the associated interface device(s), to the exclusion of design specifications, performance requirements, safety requirements, and the communications protocol used in or by such equipment.

1.1.3 The primary intent of this standard is to establish an electrical and mechanical interface and communication channel for the purpose of interconnecting equipment by external means. This standard, or sections thereof, may be applied to the interconnection of elements within an item of equipment.

1.2 Definitions. For the purposes of this standard, the following definitions shall apply:

Equipment means either a single device which connects to the interface system or a group of interconnected devices, providing a specified operational function, having one common connection to the interface system.

Interface Bus refers to the communication channel.

1.3 Object. The intent of this standard is to:

Define a general-purpose interface system for use in the environment specified in 1.1

Specify equipment-independent electrial, mechanical, and functional interface characteristics which permit equipment to connect and communicate unambiguously via the interface system

Specify terminology and definitions related to the electrical and mechanical portion of the interface system

Enable the interconnection of independently manufactured equipment into a single functional system

Permit equipment with a wide range of operational capabilities to be connected to the interface system simultaneously

CAUTION NOTICE: This American National Standard may be revised or withdrawn at any time. The procedures of the American National Standards Institute require that action be taken to reaffirm, revise, or withdraw this standard no later than five years from the date of publication. Purchasers of American National Standards may receive current information on all standards by calling or writing the American National Standards Institute Printed in USA

Copyright © 1984 by the Society of Motion Picture and Television Engineers. Reprinted by permission. ANSI1M384/6

American National Standards Institute, 1430 Broadway, New York, N.Y. 10018

Reprinted with permission of SMPTE.

ANSI/SMPTE 207M-1984

Define a system which is user configurable

Define a system based on readily obtainable standard components

1.4 Interface System Overview

1.4.1 This standard applies to systems, or portions of systems, which have the following characteristics:

A full-duplex four-wire communications channel is utilized

A nominal maximum bus length of 1220 m (4003 ft)

Data is transmitted asynchronously, bit serial, word serial

Standard transmission rate on the interface bus is 38.4 kilobits per second (kb/s)

Data exchange between devices is digital (as distinct from analog)

1.4.2 The function of the interface system is to provide an effective communications link over which messages are carried in an unambiguous way among a group of interconnected devices.

1.4.3 The interface system described in this standard assigns one of two operational characteristics to all devices:

Bus Controller. Each interface system contains one bus controller which supervises all tributaries in the system. This supervision is exercised through the use of interface protocol. The bus controller may also perform one or more functions in the operational plant in addition to its interface supervision. Although only one bus controller may be part of any particular interface system, it is recognized that an operational plant may make use of more than one interface system.

Tributary. A tributary transfers messages to and from an operational device via the interface system as specified in the interface system protocol. A tributary communicates messages through the interface bus only via the bus controller.

1.4.4 The basic message paths and the bus structure shall be as follows:

The basic message path utilizes asynchronous, bit serial/word serial transmission via a balanced wire pair

The interface bus may be utilized in either point-to-point or multi-point configuration including but not limited to

A point-to-point bus connecting one tributary to a bus controller

A multipoint bus connecting multiple tributaries to a single bus controller

The interface bus is a four-wire configuration which will effect two-way communication using a separate wire pair for each transmission direction; communication between tributaries is accomplished through the bus controller.

1.4.5 The data word and BREAK character utilized by the interface system shall be as follows:

The standard serial data word includes an eight-bit data byte; the complete serial data word consists of one start bit (SPACE), eight data bits (ONE BYTE), a parity bit (EVEN), and one stop bit (MARK). The least significant bit is transmitted first.

A BREAK character, comprised of 20 bits SPACE followed by a minimum of 2 bits MARK, is utilized to synchronize all devices connected to the interface bus.

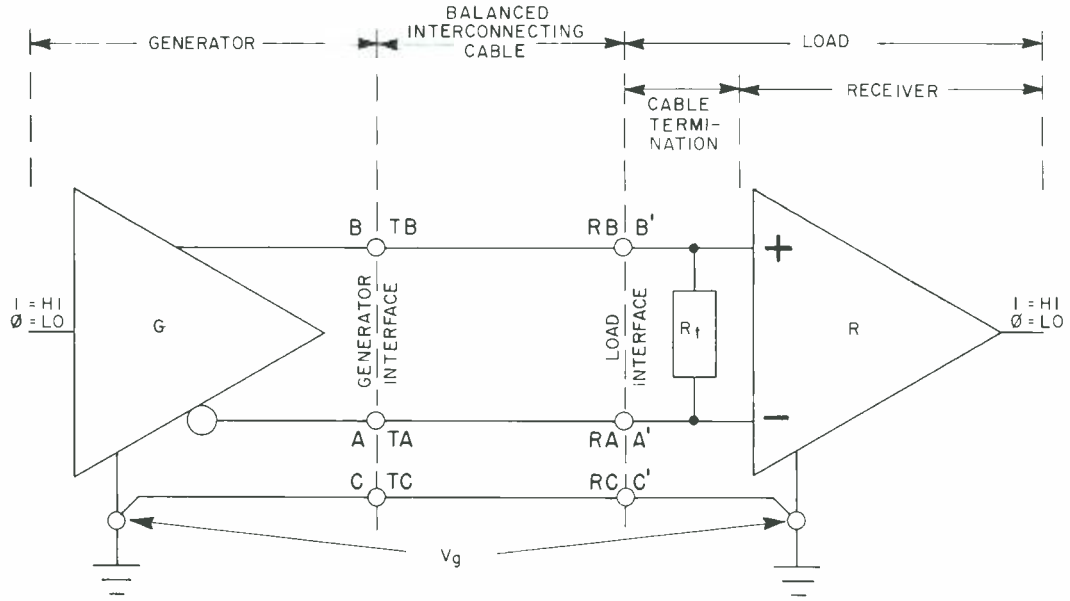
2. Electrical Characteristics

2.1 Interface Circuit. The balanced voltage digital interface circuit is shown in Fig. 1. The circuit consists of three parts: the generator, the balanced interconnecting cable, and the load. The load may consist of one or more receivers (R) and an optional cable termination resistance (R_t). The electrical characteristics of the generator and receiver are specified in terms of direct electrical measurements while the interconnecting cable is specified in terms of its electrical and physical characteristics.

2.2 Generator Characteristics. The electrical characteristics of the generator are specified in accordance with measurements described in 2.2.1 through 2.2.6 and illustrated in Figs. 2 and 3. A generator circuit meeting these requirements results in a low impedance (100 ohms or less) balanced voltage source producing a differential voltage applied to the interconnecting cable in the range of 2 to 6 volts. The signalling sense of the voltages appearing across the interconnecting cable are defined as follows:

The B terminal of the generator shall be positive with respect to the A terminal for a binary 1 (MARK) state.

The B terminal of the generator shall be negative with respect to the A terminal for a binary 0 (SPACE) state.



LEGEND

R_t	=	CABLE TERMINATION RESISTANCE
Vg	=	GROUND POTENTIAL DIFFERENCE
A, B	=	GENERATOR INTERFACE POINTS
A', B'	=	LOAD INTERFACE POINTS
C	=	GENERATOR CIRCUIT GROUND
C'	=	LOAD CIRCUIT GROUND

Fig. 1
Balanced Digital Interface Circuit

2.2.1 Open circuit measurement for either binary state shall be made in accordance with Fig. 2a. The results of this measurement shall be as follows:

The magnitude of the differential voltage (V_o) measured between the two generator output terminals shall not be more than 6.0 volts.

The magnitude of the voltage between either of the generator output terminals and generator ground (V_{oa} and V_{ob}) shall not be more than 6.0 volts.

2.2.2 The test termination measurement shall be made with a test load of two resistors, 50 ohm ± 1%, connected in series between the generator output terminals as shown in Fig. 2b. The results of this measurement shall be as follows:

The magnitude of the differential voltage (V_t) measured between the two output terminals shall not be less than either 2.0 volts or 50% of the magnitude of V_o, whichever is greater. For the opposite binary state the polarity of $\overline{V_t}$ shall be reversed (V_t).

The magnitude of the difference in magnitudes of V_t and $\bar{V}_t$ shall be less than 0.4 volts.

The magnitude of the generator offset voltage, V_{os}, measured between the center point of the test load and generator circuit shall not be greater than 3.0 volts.

The magnitude of the difference in the magnitudes of V_{os} for one binary state and V_{os} for the opposite binary state shall be less than 0.4 volts.

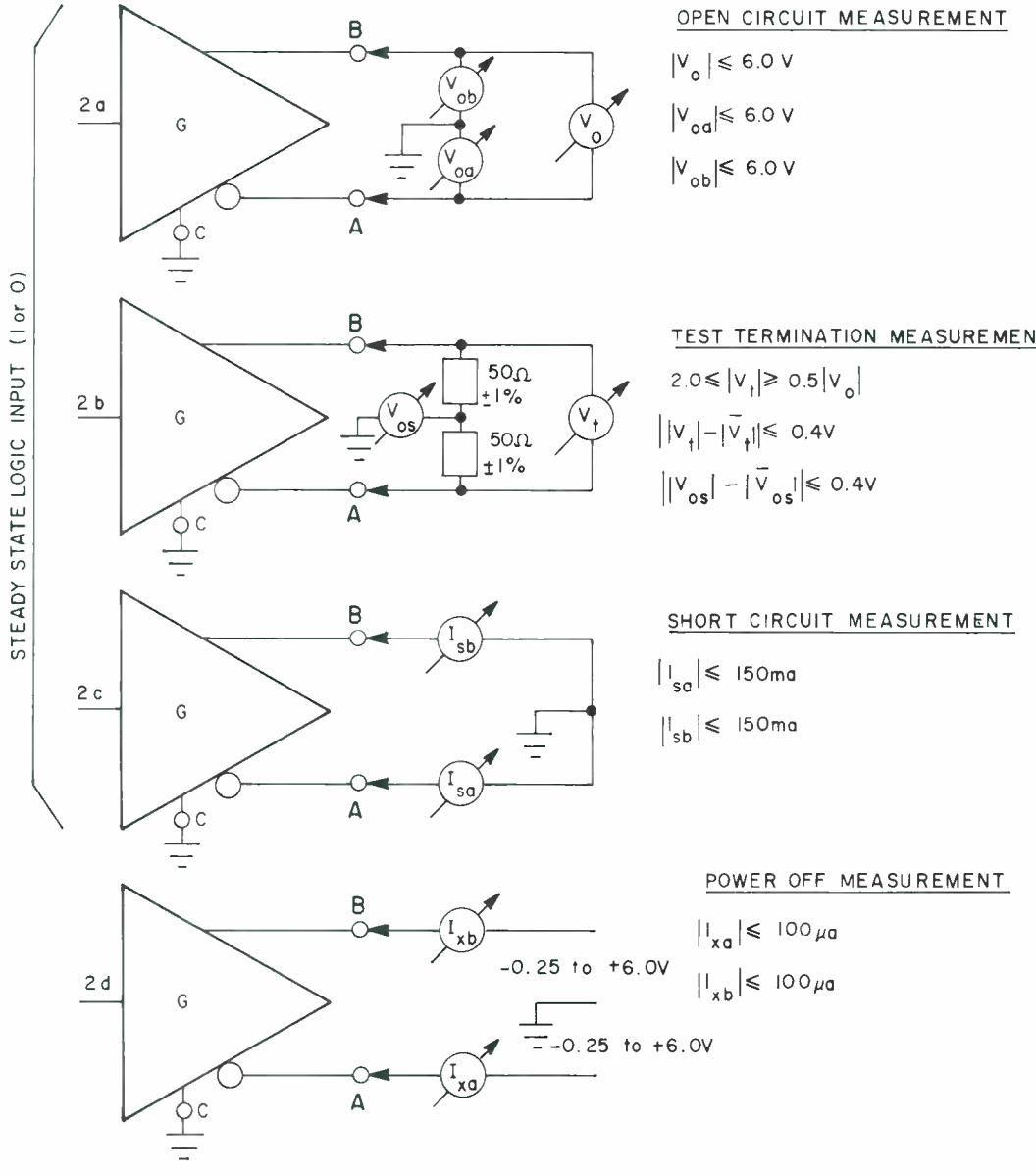
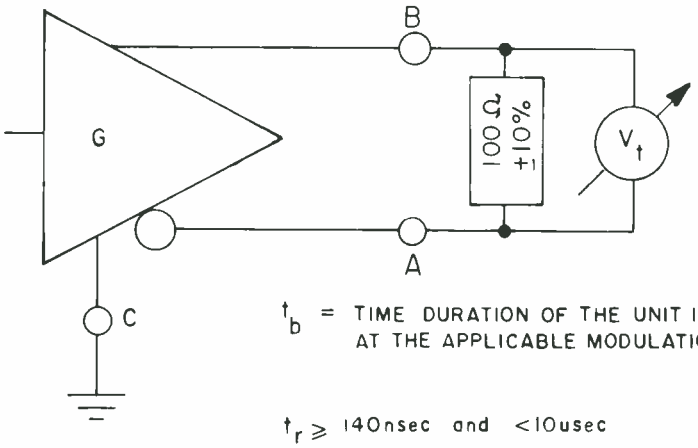


Fig. 2
Generator Parameter Measurement

2.2.3 The short circuit measurement shall be made with the generator output terminals short-circuited to generator circuit ground as illustrated in Fig. 2c. The magnitudes of the currents flowing through each generator output terminal during this test shall not exceed 150 milliamperes for either binary state.

2.2.4 The power-off measurement shall be made under power-off conditions and as illustrated in Fig. 2d. The magnitude of the generator output leakage currents (I_{xa} and I_{xb}), with voltages ranging between +6.0 and —0.25 volts applied between each output terminal and generator circuit ground, shall not exceed 100 microamperes.

2.2.5 The output signal waveform measurement shall be made using a test load consisting of a noninductive resistor with a value of 100 ohms ± 10% connected between the generator output terminals, as illustrated in Fig. 3. During transitions of the generator output between alternating



t_b = TIME DURATION OF THE UNIT INTERVAL AT THE APPLICABLE MODULATION RATE

$t_r \geq$ 140nsec and <10usec

V_{ss} = DIFFERENCE IN STEADY STATE VOLTAGES

$$V_{ss} = \left| V_t - \overline{V_t} \right|$$

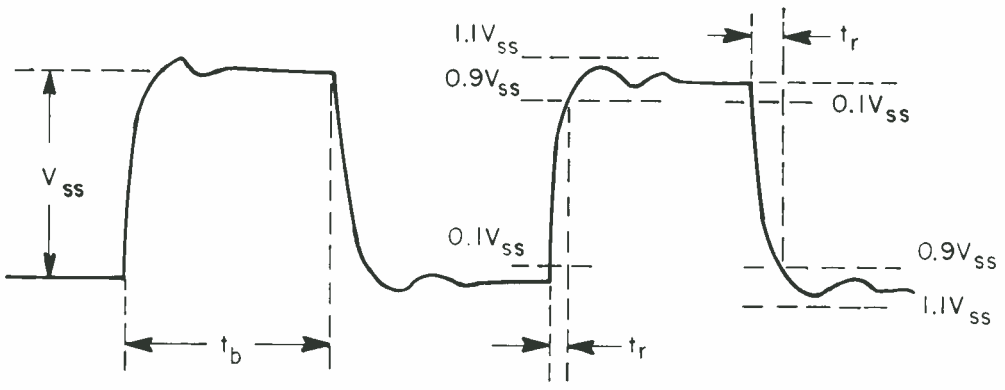


Fig. 3
Generator Output Signal Waveform

binary states (one-zero-one-zero, etc.), the differential signal measured across the test load shall be such that the voltage monotonically changes between 10% and 90% of V_{ss} at not less than 140 nanoseconds. Thereafter, the signal voltage shall not vary more than 10% of V_{ss} from the steady state value, until the next binary transition occurs. At no time shall the instantaneous magnitude of V_t or V_t exceed 6.0 volts nor be less than 2.0 volts. V_{ss} is defined as the voltage difference between the steady state values of the generator output.

2.2.6 The generator output shall be capable of being placed in a high-impedance state and when in such state shall withstand a common mode voltage swing of up to 7 volts.

2.3 Load Characteristics. The load consists of one or more receivers (R) and an optional cable termination resistance (R_t) as shown in Fig. 1. The electrical characteristics of a single receiver excluding both cable termination and fail-safe provision are specified in terms of the measurements described in 2.3.1 through 2.3.7 and illustrated in Figs. 4 through 6. A circuit meeting these requirements results in a differential receiver having a high-input impedance (> 4 kilohms), a small input threshold transition region between —0.5 and +0.5 volts and allowance for an internal bias voltage not to exceed 3 volts in magnitude.

2.3.1 The input current/voltage measurements shall be made with the voltage V_{ia} (or V_{ib}) ranging between —10.0 and +10.0 volts, while V_{ib} (or V_{ia}) is held at 0.0 volts (ground). This measurement shall be made with the power supply to the receiver in both the power-on and power-off condition. The resultant input current I_{ia} (or I_{ib}) shall remain within the shaded region shown in Fig. 4.

2.3.2 The input sensitivity measurement shall be made as illustrated in Fig. 5 over the entire common mode voltage (V_{cm}) range of —15 to +15 volts. The receiver shall not require a differential input voltage of more than 500 millivolts to correctly assume the intended binary state. Reversing the polarity of V_i shall cause the receiver to assume the opposite binary state. The receiver is required to maintain correct operation for differential input signal voltages ranging between 500 millivolts and 6 volts in magnitude. The maximum voltage (signal plus common mode) present between either receiver input terminal and receiver circuit ground shall not exceed 25 volts in magnitude. Application of voltages less than the maximum voltage (signal plus common mode) of 25 volts or a maximum differential signal of 15 volts at the receiver input terminals shall not result in operational failure of the receiver. The common mode voltage (V_{cm}) is defined as the algebraic mean of the two voltages appearing at the receiver input terminals (A′ and B′) with respect to the receiver circuit ground (C′). (Designers of terminating hardware should be aware that slow signal transitions with noise present may give rise to instability or oscillatory conditions in the receiving device and appropriate techniques should be implemented to prevent such behavior. For example, adequate hysteresis may be incorporated into the receiver to prevent this condition.)

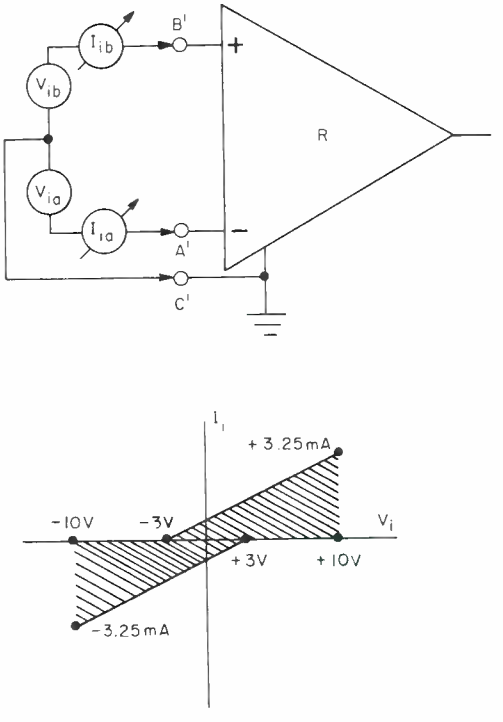
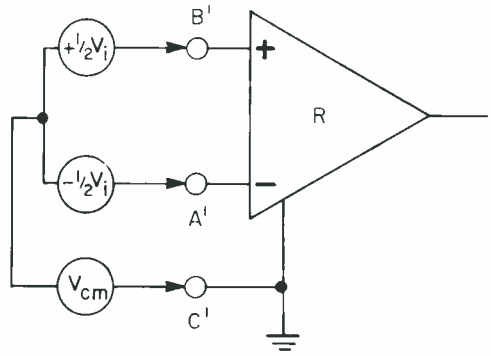


Fig. 4
Receiver Input Current-Voltage Measurement



V_{cm} = −15 to +15 volts

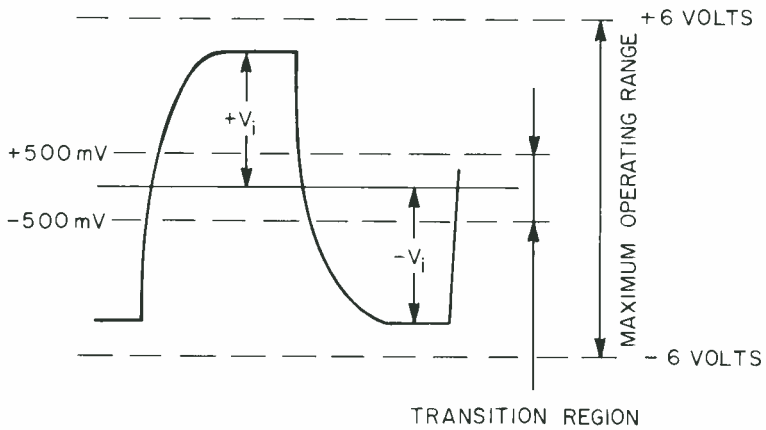


Fig. 5
Receiver Input Sensitivity Measurement

2.3.3 The Input balance measurement shall be made as illustrated in Fig. 6. The balance of the receiver input voltage/current characteristics and bias voltages shall be such that the receiver will remain in the intended binary state when a differential voltage (V_i) of 500 millivolts is applied through 500 ohms ± 1% to each input terminal and V_{cm} is varied between —15 and +15 volts. When the polarity of V_i is reversed, the opposite binary state shall be maintained under the same conditions.

2.3.4 The use of a noninductive cable termination resistance (R_t) is recommended. A distributed resistive load or a combined R/C load may be required in some cases (see 4.2.1) and the use of an active cable termination resistance is desirable for the purpose of reducing cross coupling when the bus controller is placed in a high-impedance state (see 4.2.2). Care must be taken not to exceed the limits on total load resistance or sensitivity. Refer to 2.3.7 for limits on the total load resistance.

2.3.5 The use of multiple receivers may be employed. Caution must be exercised to avoid performance degradation due to signal reflective effects from stub lines emanating from the load interface point to the receivers.

2.3.6 The interface system shall fail safe. This shall be accomplished by automatic disconnection of a tributary from the interface system in the event of a malfunction or power failure and incorporating in the receiver provisions to provide a steady binary MARK to protect against the following conditions:

Generator power-off

Generator in high-impedance state

Both signal wires open or shorted (Signal common return still connected)

Generator not implemented (Signal leads may or may not be present)

Open connector (Both signal leads and the common signal return are open simultaneously)

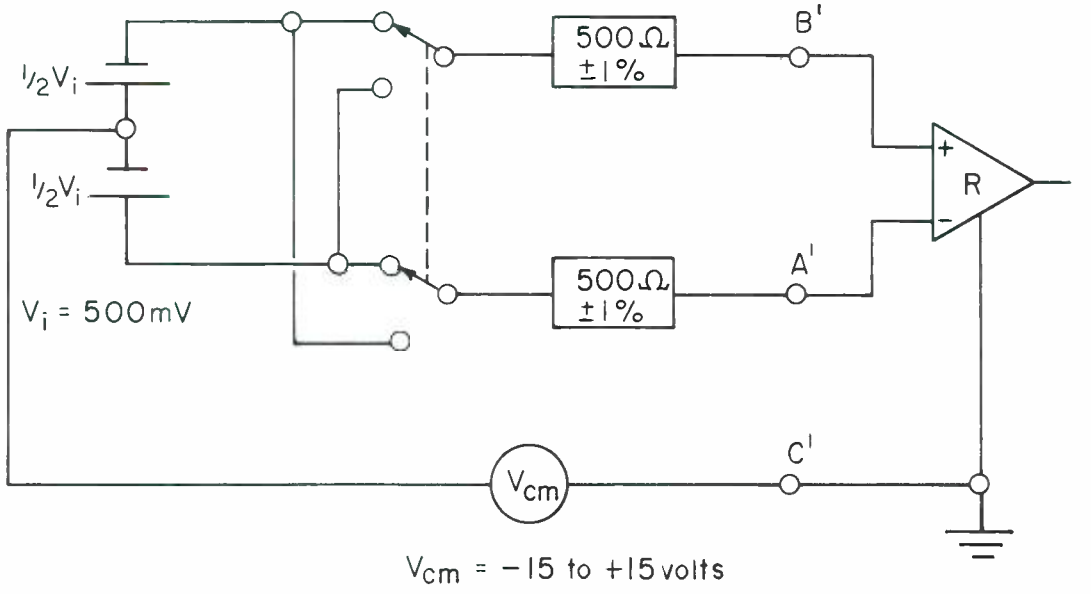


Fig. 6
Receiver Input Balance Measurement

2.3.7 The total load characteristics, including multiple receivers, fail-safe provision, and cable termination shall have a combined resistance greater than 90 ohms between its input points (A' and B' [Fig. 1]) and shall not require a differential input voltage of more than 500 millivolts for all receivers to assume the intended binary state.

2.4 Interconnecting Cable Characteristics. The physical and electrical characteristics of the interconnecting cable are given in 2.4.1 through 2.4.4 with additional guidance given in Sec. 4. An interconnecting cable conforming to this standard will result in a transmission line with a nominal characteristic impedance in the order of 100 ohms at frequencies greater than 100 kilohertz, and a DC series loop resistance not exceeding 240 ohms over an operational loop length of nominally 1220 m. The cable may be composed of twisted or nontwisted (flat cable) conductors possessing the characteristics described in 2.4.1 through 2.4.4. Most commonly available cable used for telephone applications (nonloaded) will meet these specifications.

2.4.1 Each conductor of the interconnecting cable shall be composed of either a stranded or solid copper wire conductor with uniform overall diameter of at least 0.5 mm (0.02 in). Use of noncopper conductors is allowed providing they are of sufficient size to yield a DC wire resistance not exceeding 10 ohms per 100 m (30 ohms per 1000 ft) per conductor.

2.4.2 Mutual pair capacitance, that is, the capacitance between one wire in the pair and the other wire in the pair, shall not exceed 65 picofarads per meter (20 picofarads per ft) and the value shall be reasonably uniform over the entire length of the cable.

2.4.3 Stray capacitance, the capacitance between one wire in the cable and all others in the cable sheath with all others connected to ground, shall not exceed 130 picofarads per meter (40 picofarads per ft) and shall be reasonably uniform over the entire length of the cable for any given conductor.

2.4.4 Pair-to-pair balanced crosstalk is defined as the crosstalk between one pair of wires and any other pair of wires in the same cable. This crosstalk shall be attenuated a minimum of 40 dB when measured at 150 kHz with each cable pair terminated in its characteristic impedance tested in the circuit in which it is to be used.

2.5 Environment. A balanced-voltage digital interface circuit conforming to this standard will perform satisfactorily at a data rate of 38.4 kb/s providing that the following operational constraints are simultaneously observed.

The interconnecting cable length is a nominal maximum 1220 m and the cable is appropriately terminated.

The common mode voltage at the receiver is less than 15 volts (peak). Common mode voltage is defined as any uncompensated combination of the generator/receiver ground potential difference, the generator offset voltage (V_{os}), and the longitudinally coupled peak random noise voltage, measured between the receiver circuit ground and cable, with the generator end of the cable short-circuited to ground.

2.6 Circuit Protection. The balanced-voltage digital interface generator and receiver device, in either the power-on or power-off condition and complying with this standard, shall not be damaged under the following conditions:

Generator open circuit

Short-circuit across the balanced interconnecting cable

Short-circuit to any other lead using electrical characteristics in compliance with this standard

Short-circuit to ground

(The faults above may cause the power dissipation in the interface device to approach the maximum power dissipation tolerable by a typical integrated circuit (IC) package. Caution should, therefore, be exercised when multiple generators or receivers are implemented in a single IC package since only one such fault per package may be tolerated at any one time without experiencing IC failure. It should also be noted that the generator and receiver device(s) complying with this standard may be damaged by spurious voltages applied between the input/output terminals and circuit ground. In applications where the interconnect cable may be subject to severe electromagnetic environment or the possibility exists that it may be inadvertently connected to circuits not in compliance with this standard, additional protection should be employed as may be appropriate.)

3. Mechanical Characteristics

3.1 Interface Connector. The interface connector shall be a 9-pin D-subminiature female (DE-9S) with metric (M3) female screwlock. A single interface connector shall be associated with any particular tributary device. Multiple interface connectors may be utilized on a bus controller in the case of a multipoint system or when the bus controller must communicate with more than one interface system.

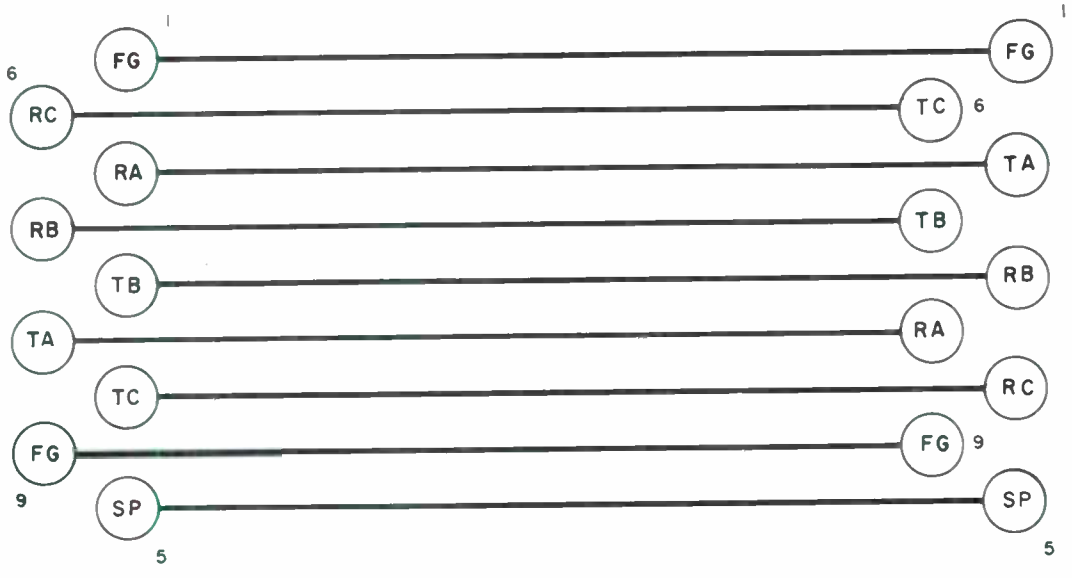
3.2 Pin Assignment. The pin assignments for the bus controller and tributary shall be as shown in Fig. 7. Use of the spare pin for unspecified communication or supervision is not in compliance with this standard. If used, it may not interfere with the normal operation of the standard interface system.

4. Guidelines

When interconnecting equipment using the interface system described in this standard, consideration should be given to some of the problems that may be encountered due to the characteristics of the interconnecting cable, cable termination, the number of devices in use, and grounding arrangements.

4.1 Cable. The interconnecting cable electrical characteristics are specified in 2.4. The following is intended to be used as additional guidance when considering the operational constraints placed on the system by the cable parameters.

4.1.1 The maximum length of cable separating the generator and receiver (load) is a function of modulation rate (influenced by the tolerable signal distortion), transmission losses, the amount of longitudinally coupled noise, and ground potential difference introduced between the generator and receiver circuit grounds as well as by cable balance. Increasing the physical separation and interconnecting cable length between the generator and receiver (load) interface points increases the system exposure to common mode noise, signal distortion, and the effects of cable imbalance. Users are advised to restrict cable length to the minimum consistent with the generator/receiver (load) separation requirements, and whenever possible to utilize cable specifically designed for balanced data circuits.



BUS CONTROLLER

TRIBUTARY

FG	FRAME GROUND
TA	TRANSMIT "A"
TB	TRANSMIT "B"
TC	TRANSMIT SIGNAL COMMON
RA	RECEIVE "A"
RB	RECEIVE "B"
RC	RECEIVE SIGNAL COMMON
SP	SPARE

A < B "MARK" STATE
A > B "SPACE" STATE

Fig. 7
Connector Pin Assignment

4.1.2 The nominal maximum cable length of 1220 m (4003 ft) is based upon:

Empirical data for nonloaded, twisted-pair telephone cable with copper conductors 0.5 mm (0.02 in) in diameter terminated in a 100-ohm resistive load

Signal rise and fall times equal to or less than 10 microseconds.

A maximum voltage loss between the generator and receiver (load) of 6 dB

(The user is cautioned that the nominal limit of 1220 m does not take into account cable imbalance or common mode noise beyond the limits set in this standard. Operation within the limit of 1220 m should result in a degradation of signal quality that will not exceed a zero-crossing ambiguity of 0.05 unit interval. It is recognized that many applications can tolerate a timing and amplitude distortion greater than this amount and in these cases correspondingly greater cable lengths may be employed. The use of cables specifically designed for the transmission of balanced data signals can also result in the ability to operate over substantially increased cable lengths.)

4.2 Cable Termination. The characteristics of the cable termination are specified in 2.3.4. The following is intended to be used as additional guidance when considering the operational constraints placed on the system by the termination resistance.

4.2.1 The determination of the type of cable termination utilized and its value must take into account the characteristic impedance of twisted-pair cable which is a function of operating frequency, wire size, wire type, and the kind of insulating materials used. The characteristic impedance of nonloaded, plastic-insulated, twisted-pair telephone cable with copper conductors 0.5 mm (0.02 in) in diameter is in the order of 100 ohms when measured with a 100 kHz sine wave.

The characteristic impedance of any cable typically contains an inductive component which could adversely affect the wave shape over extended cable lengths. Use of a composite R/C cable termination with a time constant of approximately 3 times the propagation delay of the cable may result in a significant improvement in the wave shape and a reduction in driving power requirements.

4.2.2 The presence of stray capacitance between the interconnect cable and any adjacent cable (Fig. 8) can result in interference being coupled to an adjacent cable when a transition occurs that is other than balanced. During normal operation, inter-cable coupling is at a minimum due to the use of a balanced transmission mode along with control of signal rise-times (2.2). When the driving device is placed in a high-impedence state, however, this control is no longer applied and the conductor in the pair that was at a positive value will transition to a less positive value. This transition, being uncontrolled and of an unbalanced type, may be coupled into adjacent cables.

Capacitive coupling of this type can be reduced or eliminated by utilizing shielded cables specifically designed for the transmission of digital data information. Although this approach is practical when installing the interface system in new plants, it may not be possible when working in existing facilities. When utilizing nonshielded cable, the use of an active termination is recommended. An active termination of the type shown in Figs. 9 and 10 will result in a balanced transition to a voltage that is equal on both conductors of the cable pair. The circuit shown in Fig. 9 also provides a fail-safe bias on the bus and allows for higher impedance terminations while the circuit shown in Fig. 10 is balanced with respect to the interface bus and does not introduce a differential bias on the line.

4.2.3 In general, reliable operation of the balanced interface circuit is not particularly sensitive to the presence or absence of the cable termination resistor when operating at 38.4 kb/s. The termination of the cable with a noninductive load in the order of 90 to 250 ohms tends to result in the preservation of the rise time in the generated signal and a reduction of line noise. Caution must be exercised in the value of termination selected as too low a value would result in a reduction in signal amplitude to the point where reliable operation of the system would be affected.

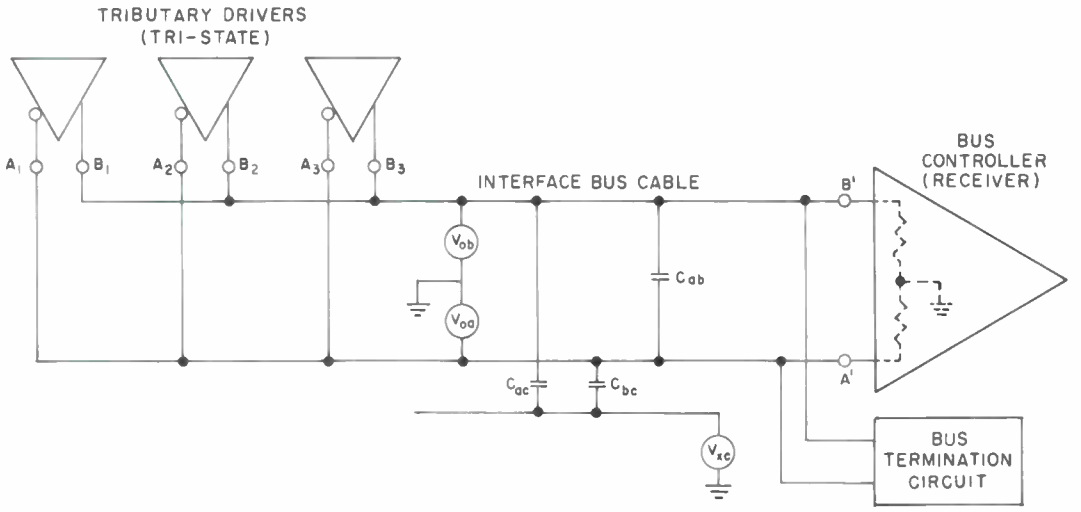


Fig. 8
Cable Model

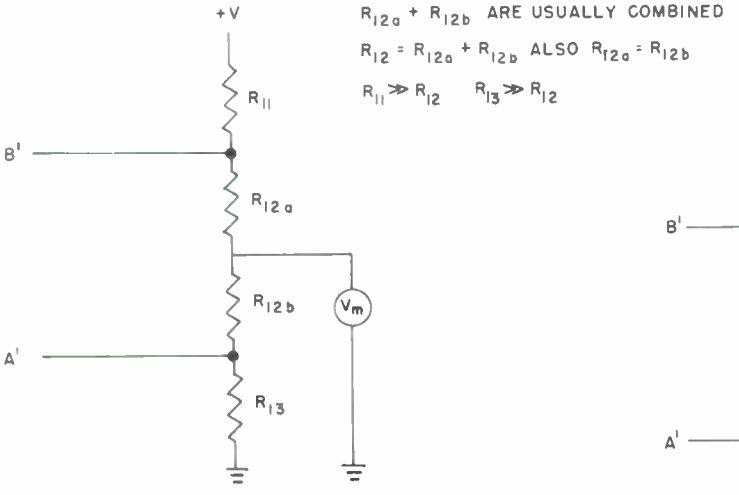


Fig. 9
Terminator Circuit 1

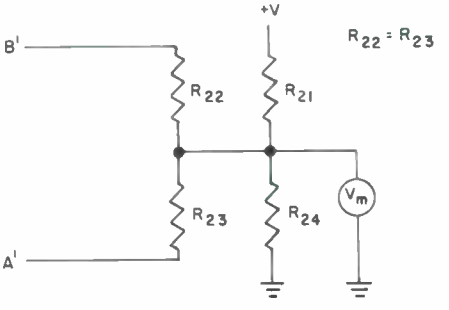


Fig. 10
Terminator Circuit 2

4.3 The data rate of 38.4 kb/s can result in a system response time within the equivalent of one television frame when the total number of tributaries is less than thirty-two. Higher data rates may be used when the operation of a specific system indicates this need. When higher data rates are used, the device(s) shall first establish communication at 38.4 kb/s. Operation at data rates lower than 38.4 kb/s is expressly prohibited due to the possible confusion of certain data patterns with the BREAK sequence.

5.11

Audio Magnetic Recording

Tim Bealor
Rick Carpenter
Tom Rosback
Broadcast Electronics, Inc.
Quincy, Illinois

INTRODUCTION

The goal of any audio recording system is to store and reproduce sound as faithfully as possible. Analog magnetic tape is the storage medium on which audio signals are represented as variations in the magnetization level along the tape. As with any analog storage system, performance is limited by the maximum undistorted output level on one hand and noise level on the other.

The purpose of this chapter is to trace the development of magnetic recording and provide you with some of the "why" behind the operation of magnetic audio recorders. If you wish more practical information on maintenance and machine operation, the balance of this chapter contains a wealth of useful information.

AN HISTORIC PERSPECTIVE

In 1897, Danish inventor Valdemar Poulsen invented a rudimentary magnetic wire recorder, which he called the Telegraphone. Unable to market the concept successfully, he sold his Telegraphone patents in 1905.

In subsequent years, organizations in several countries slowly improved magnetic recording, progressing from steel wire and steel tape to paper and celluloid tape. Even with significant improvements made in tape manufacture, primarily by BASF and AEG, the audio quality of magnetic recording was very poor. As late as 1948, 78 rpm lacquer and wax transcription discs, with their associated cutting lathes and reproducing apparatus, were still widely used for broadcast program storage and editing. The poor fidelity of dc bias magnetic recording stalled its commercial acceptance.

The German radio network, Reichs Rundfunk Gessellschaft [RRG], purchased several AEG Magnetophon recorders to see if audio performance could be elevated to broadcast levels. While investigating an improved record amplifier circuit he designed, RRG engineer Walter Weber found performance incredibly improved. Low noise, good frequency response, and low distortion; true high fidelity from magnetic tape. Investigation revealed that his amplifier circuit was oscillating at a high frequency, not an uncommon happening, even today! So, in 1939, Walter Weber stumbled on ac bias of magnetic tape quite by accident. In the same year, Marvin Camras independently discovered ac bias while working on improving wire recorders at the Armour Research Institute in Chicago. AC bias was employed on a Poulsen Telegraphone by U.S. Navy researchers Carpenter and Carlson sometime in 1921, but the project was dropped, and it took another 20 years for ac bias to be "rediscovered".

Late in 1947, the tiny Ampex corporation revolutionized the American recording industry by in-

troducing their model 200, the first truly successful high fidelity tape recorder. Since then, magnetic recording quality has steadily improved, with better head design, tape formulations, and advanced electronic design.

TAPE COMPOSITION AND TYPES

All magnetic tapes for audio recording are composed of microscopic needle-shaped magnetic particles that are attached to a plastic backing material with an adhesive binder. Variations in physical properties of the magnetic material, binder, and plastic backing result in the wide variety of tape types currently manufactured. The magnetic material itself largely determines tape electrical performance.

The oxide or metal particles used in magnetic tape are actually microscopic needle-shaped bar magnets about 0.5 microns long and 0.05 microns wide. (A micron is $1x10^{-6}$ meters). Each of these tiny particles produces a magnetic field of constant intensity. These particles can be thought of as binary switches which can exist in only two magnetic states. When an external magnetic field of opposite polarity is applied to an individual particle, that particle's magnetic polarity will switch at a certain field intensity. The magnetic field intensity which needs to be applied to a particle to make it switch states is called the coercivity of the particle. Coercivity is measured in Oerstads and abbreviated H.

Not all particles in a batch of magnetic material have the same coercivity. The familiar bell shaped curve describes the overall distribution of particle coercivity in a magnetic tape.

A tape is considered erased when the magnetic particles are randomly oriented so there is no net polarization. That is, there is no external magnetic field produced by the tape, because all its tiny internal magnets are opposing each other. When an increasing external field is applied to an erased tape, nothing happens at first because the field is not strong enough to switch any of the particles. (See Fig. 1) As the external field intensity increases, particles on the low end of the coercivity distribution curve start to switch. More and more particles switch as field intensity increases. When all of the particles are switched, increasing the external field intensity does not change magnetization. The tape is then said to be saturated. The magnetic field retained by the tape after saturation is called the retentivity. Retentivity is measured in Gauss and abbreviated B. The higher the retentivity of a tape, the higher its output. When a certain width of tape is specified, retentivity is expressed as remnance or fluxivity, and is measured in nanoWebers per meter.

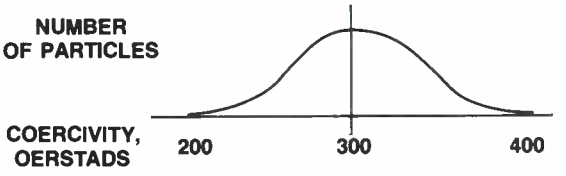


Fig. 1A. Coercivity distribution of magnetic particles in a ferric oxide tape (Gaussian distribution).

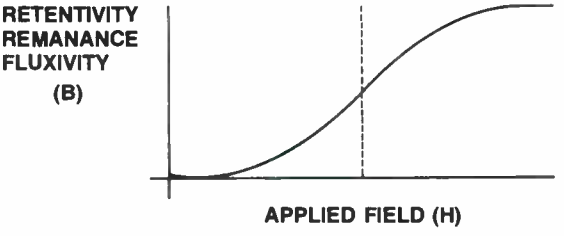


Fig. 1B. Magnetization curve of a sample ferric tape.

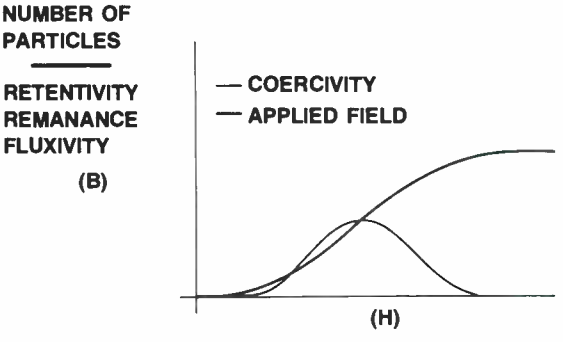


Fig. 1C. DC magnetization curve of the tape is derived by summing all the contributions of the individual particle coercivities and retentivities. More correctly, the DC magnetization curve of a tape is the integral (area sum) of the coercivity distribution of the individual particles.

This usage is the most common. So why is all this important? There are two reasons.

First, the magnetization curve in Fig. 1 is very nonlinear, which means that something needs to be done in the recording process to reduce distortion and produce a linear output. That something is ac bias, which will be covered later.

Second, different tapes have different values of coercivity and retentivity, which affects how they can be used. Tapes with high coercivity require higher magnetic fields for recording and erasing. These tapes are called high bias tapes. High bias tapes cause compatibility problems with

TAPE TYPE	RETENTIVITY	COERCIVITY	CURIE POINT
Ferric Oxide	1200 Gauss	300 Oerstads	470 C
Ferric Oxide Cobalt Doped	1500 Gauss	600 Oerstads	470 C
Chromium Dioxide	1500 Gauss	1500 Oerstads	130 C
Metal Particle	3000 Gauss	1100 Oerstads	770 C

Fig. 1D. Performance of common magnetic tape materials.

older equipment incapable of producing the large field strengths these tapes require. High coercivity tapes are less subject to a phenomenon called self-erasure, which degrades high frequency response.

The compact cassette, with its slow tape speed and inherently poor high frequency performance, led to the development of chromium dioxide and metal particle tapes, which have higher coercivity than conventional ferric oxide tapes. These new tape types have not been a problem in consumer applications, as models and features are changed with the seasons. Broadcast equipment lasts much longer, and most installations standardize on one type of tape so that recorders do not have to be constantly realigned. Improvements in audio mastering tape for broadcast have been directed toward increasing retentivity, and thus output level. High coercivity tapes are starting to become more popular as tape machines are updated to handle increased recording field intensities.

Tapes used in reel-to-reel and cartridge machines are usually ferric oxide types with little or no cobalt doping. The cassette format generally uses chromium dioxide or doped ferric oxide tapes, with some trend toward metal particle tapes for high quality recording.

A caution should be raised concerning the use of chromium dioxide tapes for archival storage of program material. The low Curie temperature of the magnetic material means that this type of tape may be more affected by heat. A controlled temperature environment is important for storage of all magnetic recording materials.

The overall performance of magnetic recording is limited by the tape itself. Maximum output level is limited by tape retentivity (fluxivity) after saturation, and noise is limited by the magnetic particle size. Particle size cannot be arbitrarily reduced to improve noise. Thermal energy would tend to randomize the orientation of very small particles, effectively erasing the tape. Also, electrical noise generated in the tape heads and reproduce circuitry is just a few dB below the noise level of modern tapes. Tape development has focused on increasing retentivity to increase output level, thus improving signal-to-noise ratio. High coercivity tapes improve high frequency response by reducing self-erasure.

THE RECORDING PROCESS

For any given type of tape, the physical track width recorded on the tape and the speed at which it is pulled across the heads will determine the best possible signal-to-noise ratio. Signal-to-noise performance improves approximately 3 dB for every doubling of the area recorded on. Increasing tape speed and increasing track width improve signal-to-noise ratio. Wide track tape running fast will outperform narrow track tape running slowly.

Fig. 2 is a chart depicting several tape types and their relative best-case performance. This chart will help you to evaluate different tape systems to determine which one suits your needs. Maximum level is considered to be the point where total harmonic distortion reaches 3 percent.

THE NEED FOR BIAS

The need for ac bias is best explained by looking back to Fig. 1B, which shows the magnetization characteristics of the tape. The curve shown is very nonlinear, indicating the severe distortion that would be produced if some type of bias were not used. DC bias would reduce distortion by operating in the linear portion of the transfer characteristic, but the limit to this technique seems to be about 5 percent THD. As described above it was accidentally discovered that imposing a high frequency bias signal on the audio waveform improved performance tremendously.

This ac bias frequency is usually about 5 to 10 times the highest frequency to be recorded, and the level is several times the peak amplitude to be recorded. With no audio signal applied, the

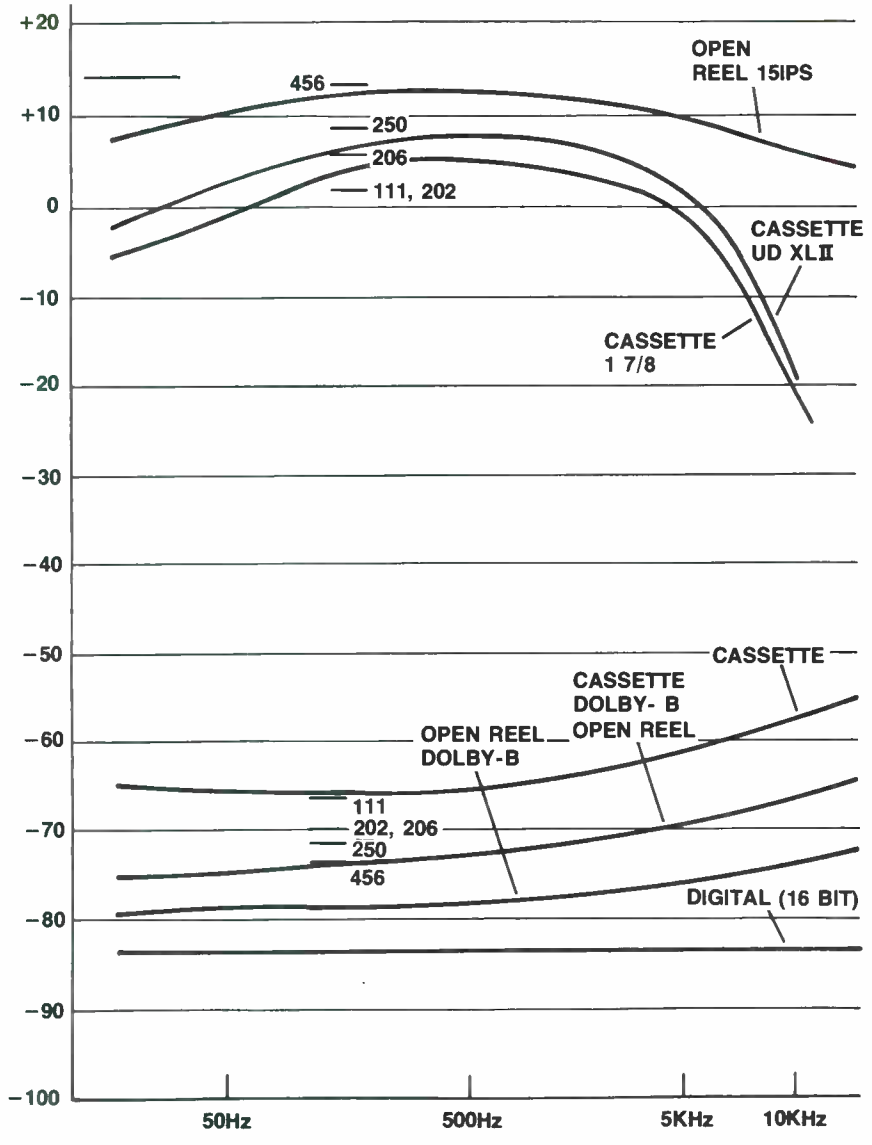


Fig. 2. Maximum output level and noise level vs. frequency for common tapes and formats.

bias waveform alternately flips the polarity of the tiny magnetic particles as they pass the record head. The field strength decays with distance from the trailing edge of the record head gap, resulting in a random distribution of magnetic particle orientation and no net magnetization on the tape. When audio is applied, the bias waveform is offset by the audio signal amplitude, producing a net magnetization of the tape at any given point. When the tape is played back, the audio will be recovered via those magnetization changes, which vary in frequency and intensity according to the original input signal.

Optimum Bias

Tape types have different bias requirements depending on their coercivity. If the bias field is too small, the tape is said to be underbiased. If the bias field is too large, the tape is said to be overbiased. When bias is reduced below its optimum level (underbias), distortion rises dramatically, noise increases and high frequency sensitivity improves slightly. The overall result is one of improved high frequency response with noticeable distortion. When bias is increased beyond its optimum value (overbias), overall sensitivity drops,

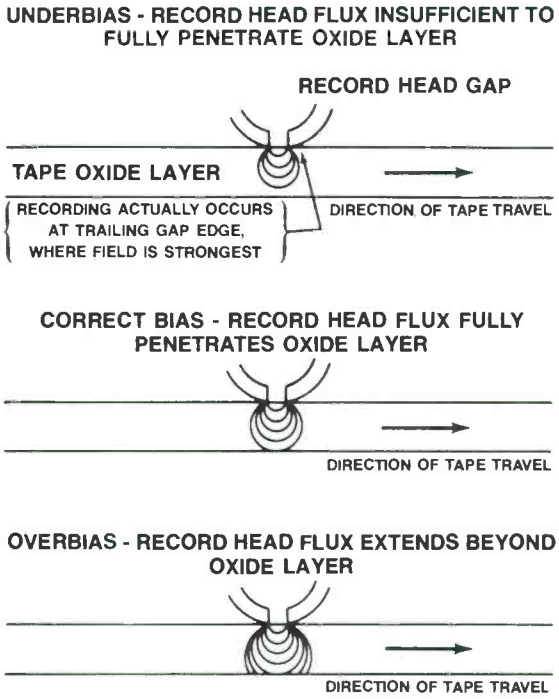


Fig. 3. Bias field penetration.

high frequency response is degraded, noise level drops, and distortion increases slightly. See Fig. 3. Optimum bias can be determined by using a distortion analyzer. Bias should be adjusted for minimum harmonic distortion in the range of 1 to 6 kHz. Since bias affects high frequency response, equalization must be adjusted after determining optimum bias. When setting up machines, it is safer to set bias slightly higher than the optimum for the tape used to make measurements. Then, normal variations in tape composition from run to run will not cause an underbias condition, resulting in excessive distortion.

SELF ERASURE

The magnetic field at the trailing edge of the record head gap diminishes rapidly with distance. However, at very short recorded wavelengths (high frequencies, slow tape speeds), the field is often strong enough to cause partial erasure of information already past the gap. This effect results in high frequency loss and increased distortion. High bias (high coercivity) tapes are less susceptible to self erasure. This means that less equalization is required during recording, improving signal-to-noise ratio and high frequency response. For example, the compact cassette format specifies 70 usec equalization for chromium dioxide tapes, and 120 usec for ferric oxide tapes. Chromium tapes require less high frequency equalization on playback, improving signal-to-noise ratio.

THE PLAYBACK PROCESS

Electrical and mechanical design of the playback head is much more critical than the record head. Since all recording is done on the trailing edge of the record head gap, the gap width is not as important as for a reproduce head. The only critical requirement is that the combination of bias and audio waveforms do not saturate the magnetic material in the record head.

In playback, gap width is critical because it determines the highest frequency that can be reproduced. Making the gap width extremely small reduces the sensitivity of the head. All tape heads have electrical resistance and magnetic reluctance, which produce thermal noise. As the gap width is reduced, output level will drop and signal-to-noise ratio will be degraded past the point where the tape itself is the limiting factor. When the recorded wavelength is equal to the width of the playback head gap, the *net* magnetic field inside the gap will be zero and there will be no output voltage.

Output voltage begins dropping long before the recorded wavelength is equal to the playback head gap width. This effect is called *gap loss*. A good rule of thumb is that the playback head gap should be from 1/4 to 1/10 the shortest recorded wavelength, resulting in a gap loss of 0.9 dB and 0.14 dB, respectively. The following formula may be used to calculate the gap loss knowing the gap width and recorded wavelength.

$$\text{Gap Loss (dB)} = 20 \text{ Log } \frac{\sin (180\ g/l)}{\pi\ g/l}$$

Where:
g = Gap Length in inches or microns
l = Recorded Wavelength in inches or microns

Recorded wavelength is determined by the tape speed and audio frequency in the following relationship:

$$\text{Recorded wavelength} = \frac{\text{Tape speed}}{\text{Audio Frequency}}$$

Wavelength drops as audio frequency increases or tape speed decreases. The wavelength recorded on tape for an audio frequency of 15,000 Hz and different tape speeds is shown below.

TAPE SPEED	RECORDED WAVELENGTH FOR 15 kHz
1.875 ips	0.000125 inches, or 3.175 microns
3.75 ips	0.000250 inches, or 6.35 microns
7.5 ips	0.000500 inches, or 12.7 microns
15.0 ips	0.001000 inches, or 25.4 microns
30.0 ips	0.002000 inches, or 50.8 microns

You can see that head gaps need to be vanishingly small as tape speed drops, leading to inevitable compromises in design that result in poor high frequency performance at low tape speeds.

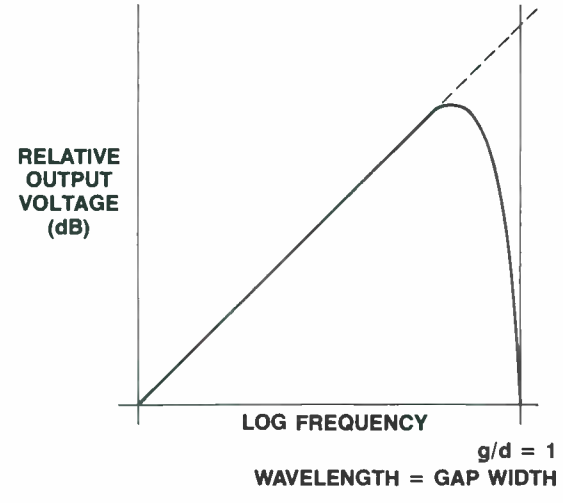
EQUALIZATION

The output voltage of a perfect playback head is directly proportional to the rate of flux change in its gap. The flux change is caused by the changing magnetization of the tape. For constant recorded flux intensity, the rate of change of flux increases with increasing frequency, producing an output voltage that increases linearly with increasing frequency. This rising response, along with the high frequency roll-off due to gap loss, is shown in Fig. 4.

In order to obtain flat playback response, a complementary equalization curve must be employed in the playback amplifier to boost the low frequencies. A playback equalization curve with a 50 Hz turnover frequency is widely used. This is also referred to as the 3180 usec curve. If the record and playback heads were perfect, and in perfect contact with an ideal tape, no other equalization would be necessary.

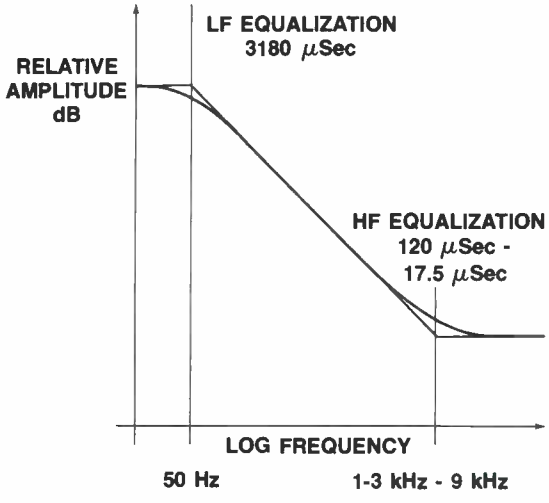
Tape self-erasure, head electrical resistance, inductance, and magnetic reluctance, along with imperfect head to tape contact result in the need to provide additional record and playback equalization.

Equalization is specified as a playback response curve for the total head, amplifier, and equalizer system. High frequencies are effectively boosted in playback by adding a high frequency RC time constant to the normal 3180 usec (50 Hz) RC time constant. What really happens is the roll-off provided by the 3180 usec time constant is stopped by this high frequency RC time constant. The equalization frequency varies from 9 kHz to 1.3



OUTPUT VOLTAGE FROM IDEAL PLAYBACK HEAD FOR CONSTANT RECORD FLUXIVITY, DOTTED LINE IS THEORETICAL RESPONSE, SOLID LINE TAKES INTO ACCOUNT GAP LOSS.

Fig. 4. Playback head response.



PLAYBACK EQUALIZATION CURVES SHOWING 3180 μSec LF TIME CONSTANT. HF TIME CONSTANT VARIES WITH TAPE SPEED, FORMAT, AND TAPE TYPE.

Fig. 5A. Ideal playback equalization curves.

SPEED	U.S.	EUROPE
1/4 in open reel	LF HF	LF HF
30.00 ips	3180, 17.5	3180, 35.0
15.00 ips	3180, 50.0	3180, 35.0
7.500 ips	3180, 50.0	3180, 70.0
3.750 ips	3180, 90.0	
1.875 ips	3180, 90.0	
Cassette format		
1.875 ips	3180, 120.0	ferric oxide tapes
1.875 ips	3180, 70.0	chromium dioxide and metal tapes

Fig. 5B. Magnetic tape playback equalization time constants in microseconds.

kHz according to tape speed. See Fig. 5A. Lower tape speeds require more equalization and so have longer time constants (equalization starts at a lower frequency).

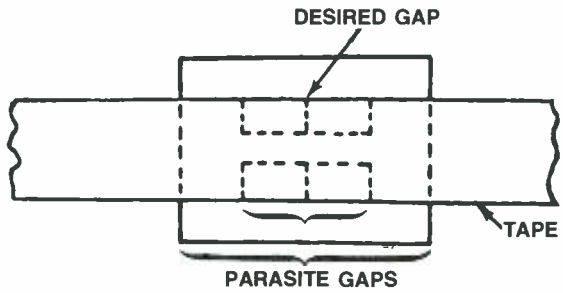
These system time constants and the equalization curves they represent are all referenced to constant fluxivity versus frequency in the playback head gap. These values are for gamma ferric oxide tapes. Many of these values are now considered obsolete, since newer high energy tapes do not require as much high frequency equalization as ferric tapes. The 3180 usec LF time constant is widely used although it is not a recognized standard. Consult the tape electrical data sheet, available from the tape manufacturer, for suggested equalization settings. Because of the variations in tape formulations, establishing a standard brand and type for use throughout the station will simplify setup and maintenance and give more uniform results.

Since equalization has been standardized somewhat, it can be generally ignored, except when setting up and checking the performance of a recorder-reproducer. In order to accomplish this task properly, the recorder-reproducer must be properly aligned mechanically, degaussed and adjusted for flat playback response using a standard test tape. The recorder equalizer is then adjusted to produce flat playback response.

When using cassette equipment, the tape type must be noted because of the different equalization curves employed. A chromium tape (70 usec) played back on a machine set up for ferric tape (120 usec) will sound overly bright due to the resulting 50 usec overall preemphasis (3 dB boost at 3 kHz rising to 10 dB boost at 10 kHz). Conversely a ferric tape played on a machine set up for chromium tapes will sound dull, being 3 dB down at 3 kHz and 10 dB down at 10 kHz. Some cassette players have automatic playback equalization switching keyed by a cutout in the tape housing.

PLAYBACK HEAD CONTOUR EFFECTS

There is a limitation on the lowest frequency that can be reproduced by a playback head. As frequency drops, the recorded wavelength increases and becomes large compared to the length of the entire playback head structure. The playback head structure, including the pole pieces and the case itself, becomes a parasitic gap. (See Fig. 6). Low frequency flux cuts this parasitic gap and produces an output that adds to or subtracts from the desired gap output, depending on frequency. The result is a series of low frequency response dips and peaks called head bumps. The pole piece length can be made very large, moving the effect out of the audio frequency range.



POLE PIECE AND CASE LENGTH PRODUCE PARASITIC MAGNETIC GAPS WHICH CAUSE LOW FREQUENCY CONTOUR EFFECTS, COMMONLY CALLED HEAD BUMPS.

Fig. 6. Playback head contour effects.

Contour effects are most pronounced on tape machines which have insufficient space for heads with long pole pieces. Professional reel-to-reel tape machines running at high speeds have pole pieces with faces in excess of one inch long. Special contour reproduce heads have been developed by several manufacturers for cartridge machines. These heads have been available since the late 1970's and largely overcome contour effects.

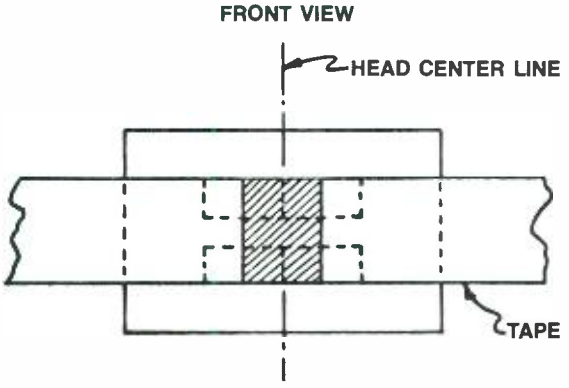
MECHANICAL ALIGNMENT

Correct mechanical alignment of magnetic recorders is absolutely necessary for proper electrical performance. Mechanical alignment is performed to insure that the tape contacts the head in the correct orientation. Head orientation is specified in terms of *height, zenith, azimuth,* and *meridian*. Fig. 7 shows each type of physical orientation.

Azimuth is the most critical of all the mechanical adjustments and the most difficult to hold correct in day-to-day operations. When record azimuth is correctly set, the tape will be magnetized in vertical bars exactly perpendicular to the direction of tape travel. At high frequencies and slow tape speeds, the width of these vertical bars is extremely narrow. Any departure from perfect azimuth in recording or playback will cause the tape head gap to cut across one or more these magnetized bars, reducing high frequency output. This azimuth loss effect increases with increasing track width and decreasing wavelength. It can be calculated using the following formula:

$$\text{AZIMUTH LOSS} = 20 \text{ Log } \frac{\sin 180\ w\tan\ (a/l)}{\pi\ w\tan\ (a/l)}$$

Where:
w = track width in inches
l = recorded wavelength in inches
a = azimuth error angle in degrees



CORRECT MERIDIAN ALIGNMENT TAPE CONTACT AREA SHOULD BE SYMMETRICAL ABOUT HEAD CENTER LINE

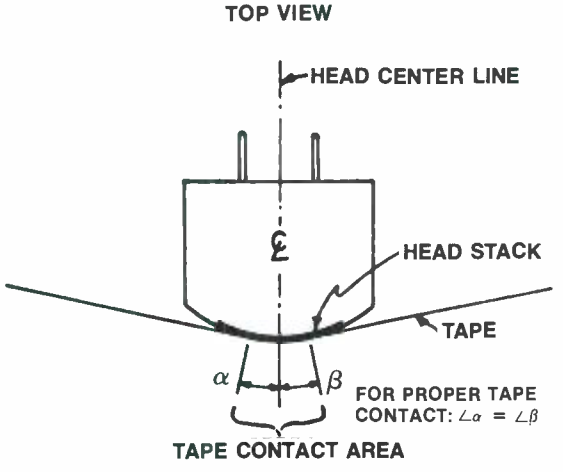


Fig. 7A. Mechanical alignment—meridian adjustment.

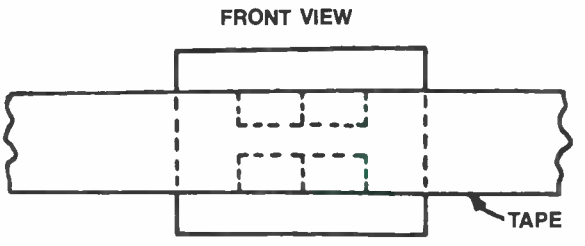
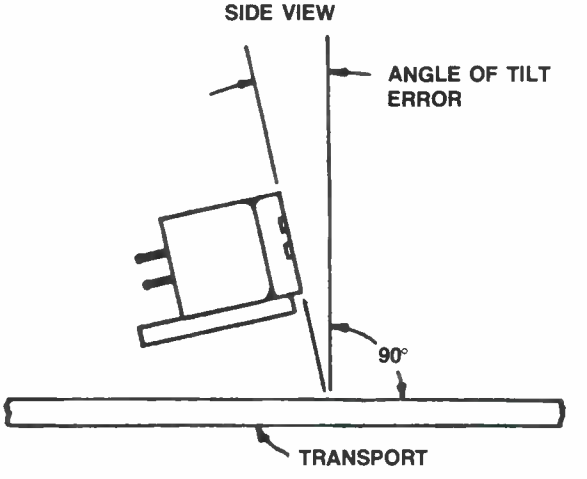


Fig. 7B. Mechanical alignment—height adjustment.



(ERRORS PRODUCE UNEVEN HEADWEAR AND UNSTABLE TAPE PATH PERFORMANCE)

Fig. 7C. Mechanical alignment—zenith adjustment.

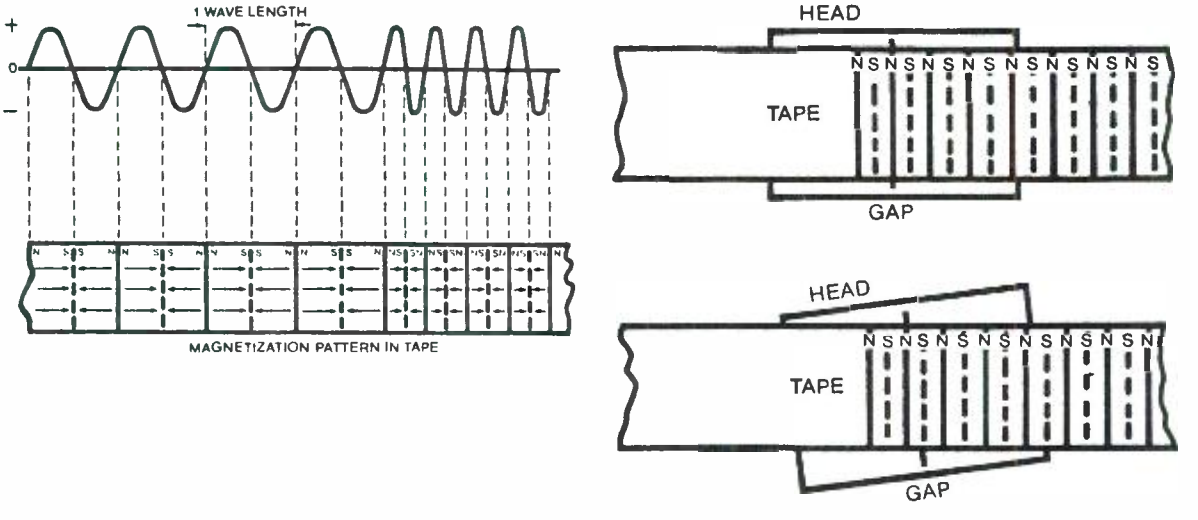


Fig. 7D. Mechanical alignment—incorrect azimuth can cause the head gap to overlap enough of a high frequency cycle, or cycles, to permit some degree of cancellation.

Azimuth errors of 0.5 degree and 0.1 degree will cause the following response roll-offs at 15 kHz:

TAPE FORMAT AND SPEED	0.5 Degree	0.1 Degree
1.875 ips stereo cassette-(track width 0.0235 in)	15.1 dB	-1.6 dB
3.75 ips ¼ in 2 track-(track width 0.075 in)	18.9 dB	-4.3 dB
3.75 ips ¼ in 4 track-(track width 0.043 in)	13.5 dB	-1.3 dB
7.5 ips ¼ in 2 track-(track width 0.075 in)	13.9 dB	-1.0 dB
7.5 ips ¼ in 4 track-(track width 0.043 in)	10.5 dB	-0.32 dB
15 ips ¼ in 2 track-(track width 0.075 in)	7.3 dB	-0.25 dB
15 ips ¼ in 4 track)-(track width 0.043 in)	2.1 dB	-0.08 dB

As you can see, there is no substitute for high tape speed when good high frequency performance is desired. The relatively good performance of the cassette format is due to its narrow track width. Most quality recorders can hold azimuth error angle down to better than 0.1 degree.

In stereo tape machines, azimuth error produces an additional high frequency effect called *mono sum loss*. Azimuth error in a stereo machine produces a slight time delay between the two channels. This time delay causes a corresponding phase shift between audio in the left and right channels. If the phase shift reaches 180 degrees at some frequency, and the two channels are electrically summed to mono, total cancellation will occur, creating a response notch.

SYSTEM PERFORMANCE SUMMARY

Tape performance is determined by the tape type itself, the track width, and the speed. High bias (high coercivity) tapes are less susceptible to self erasure than ferric oxide tapes and so provide better high frequency performance. In addition, they have higher output due to higher retentivity (remenance, fluxivity), which results in better signal-to-noise ratio. All other things being equal, doubling the track width will improve signal-to-noise ratio 3 dB. Increasing track width, however, results in greater azimuth loss given a fixed azimuth error angle. Increasing speed improves high frequency performance by reducing azimuth loss and gap loss. Increasing speed degrades low frequency performance due to head contour effects.

Improving System Performance

Analog tape performance has steadily improved over the years, but signal-to-noise ratio is still a concern. Several noise reduction systems have been developed to improve tape system noise performance. Noise reduction systems fall into two categories. The most effective are encode-decode systems that process the audio signal during recording and playback. Dolby™ and dBx™ are both encode-decode systems. Single ended noise reduction systems operate on playback only, eliminating the need for encoding.

Encode-Decode Systems

Dolby™ noise reduction was the first electronic system designed to reduce tape noise. The basic principle is to boost the high frequency content of low level passages during recording. On playback, a complementary high frequency cut is employed to restore correct frequency response. The end result is about 10 dB better signal to noise ratio (B system). Dolby Labs™ has three main systems for tape noise reduction. Dolby A™ is a four-band system designed for maximum performance and is primarily used in recording studios. Dolby B™ is a two-band system that has found universal acceptance due to its simple setup and good performance. Dolby C™ is similar to Dolby B™, but provides more correction.

The dBx™ noise reduction system uses complementary compression and expansion to improve tape signal-to-noise ratio. Signals are compressed 2:1 before recording. This means that a 20 dB input level change is transformed into a 10 dB level change on the tape. During playback, the recorded signal is passed through a 2:1 expander. This means that the 10 dB level change on the tape is transformed back to the original 20 dB level change. In addition to complementary compression and expansion, the dBx™ system uses preemphasis and deemphasis to further improve signal to noise ratio. Theoretically, a recorder with 60 dB dynamic range could be made to have 120 dB dynamic range.

Single-ended Systems

All single-ended tape noise reduction systems rely on the principle of auditory masking to

reduce noise. High frequency noise and noise when no signal is present are the most audible forms of tape noise. Since tape noise is directly proportional to bandwidth, single-ended noise reduction systems reduce playback bandwidth during quiet passages when no high frequency program information is present. DNR and Dynafex are the two most popular single-ended noise reduction systems currently in use. The Dynafex system also uses additional amplitude expansion, an audio processing technique, to reduce playback noise.

All tape noise reduction is limited by a phenomenon called *modulation noise*. The surface of magnetic tape is not perfectly smooth. Irregularities in the tape surface produce a noise which is related to the signal. If you were to record a single tone and then filter out that tone on playback, you would notice that playback noise increases with increasing recorded level. This modulation noise is usually masked by the signal, and is not noticed. Tape noise reduction systems make modulation noise more noticeable. In general, the deleterious effects increase with increasing noise reduction. Additionally, scrape flutter components produced by idler wheels, tape stiction, tape guides, reel flanges, and even pressure pads all contribute to modulation noise components.

THE FUTURE OF ANALOG RECORDING

This chapter was written in 1985, a truly exciting year in the history of audio program storage. The digital audio compact disc and digital audio recorders are sweeping the consumer audio market. Many radio stations are programming extensively from CD's. One must ask the question: How much longer before analog magnetic tape will be obsolete?

Sales of prerecorded compact cassettes exceeded sales of LP records in 1982, about 15 years after the cassette became a popular storage medium. Presently, the high cost of digital audio tape recorders suitable for broadcast use is preventing their universal acceptance. A look back to Fig. 2 will reveal that present tape formulations, properly used, can come within a few dB of the 16 bit digital audio recording process. Since the best broadcast channel signal-to-noise ratios are presently about 80 dB, analog tape will provide excellent cost effective service well into the next decade.

TAPE MACHINE ELECTRONICS

Although the tape machine is a complicated electromechanical system, the main electrical functions of any tape machine can be broken down into four main areas:

1. Bias
2. Equalization
3. Control
4. Interfacing

Bias

A large ac bias current is mixed with the signal to be recorded on the tape to permit low distortion recording (see: THE NEED FOR BIAS). The bias signal is an ultrasonic (60 kHz—200 kHz), low distortion sinewave usually generated by a digital divider and low pass filter in modern equipment (Fig. 8) or a crosscoupled transistor oscillator in older equipment (Fig 9). The bias signal is then mixed with the audio signal either actively or passively and applied to the record head. In passive mixing (Fig. 9), a parallel resonant circuit (L3,C61) is needed to isolate the bias signal from the remainder of the audio circuitry. With active bias mixing (Fig. 10), the isolating property of an op- amp summing junction is used to add the bias signal, reducing or eliminating the need for a bias trap.

The adjustment of bias current is usually performed with a potentiometer in series with the bias line. There are several systems in production which vary the bias current in order to squeeze the last possible amount of head room from the tape in use. Since high frequency audio material acts as a bias signal, the ultrasonic bias can be reduced in proportion to the amount of high frequency audio material present. This allows the high frequencies to be recorded at a higher level than would be possible with a fixed bias system and reduces the possibility of tape saturation.

Equalization

Equalization is the electrical alteration of the amplitude versus frequency characteristic of a particular frequency or band of frequencies. In the absence of equalization circuitry, the response of a tape machine would be the inverted "U" caused by the combination of severe bass and treble loss inherent in the response of magnetic tape heads (See Fig. 4). The factors responsible include the increasing output of magnetic playback head with increasing frequency (6 dB/ octave) low frequency "contour" effects and tape self-demagnetization. The equalization circuits of a tape machine create the necessary compensating bass boost and treble boost to achieve flat audio response at the machines's output (Fig. 5). Since the output voltage of a typical head is only 1 millivolt at 1 kHz, the equalization stage also pro-

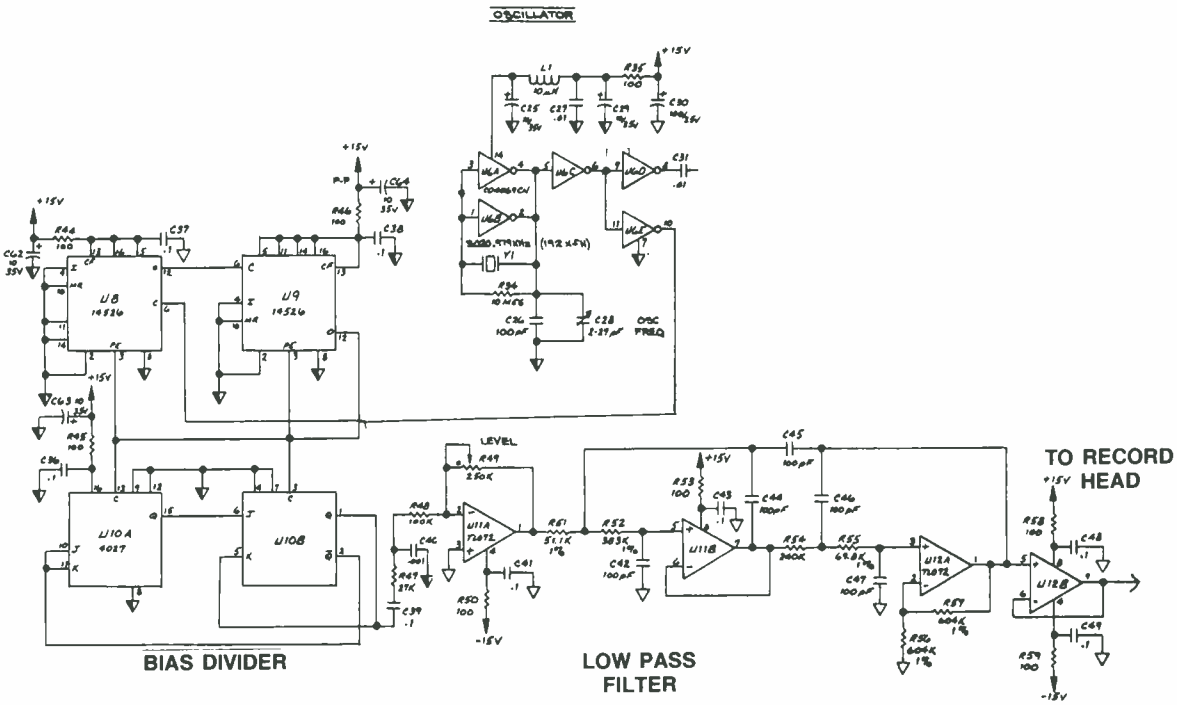


Fig. 8. Digital bias oscillator.

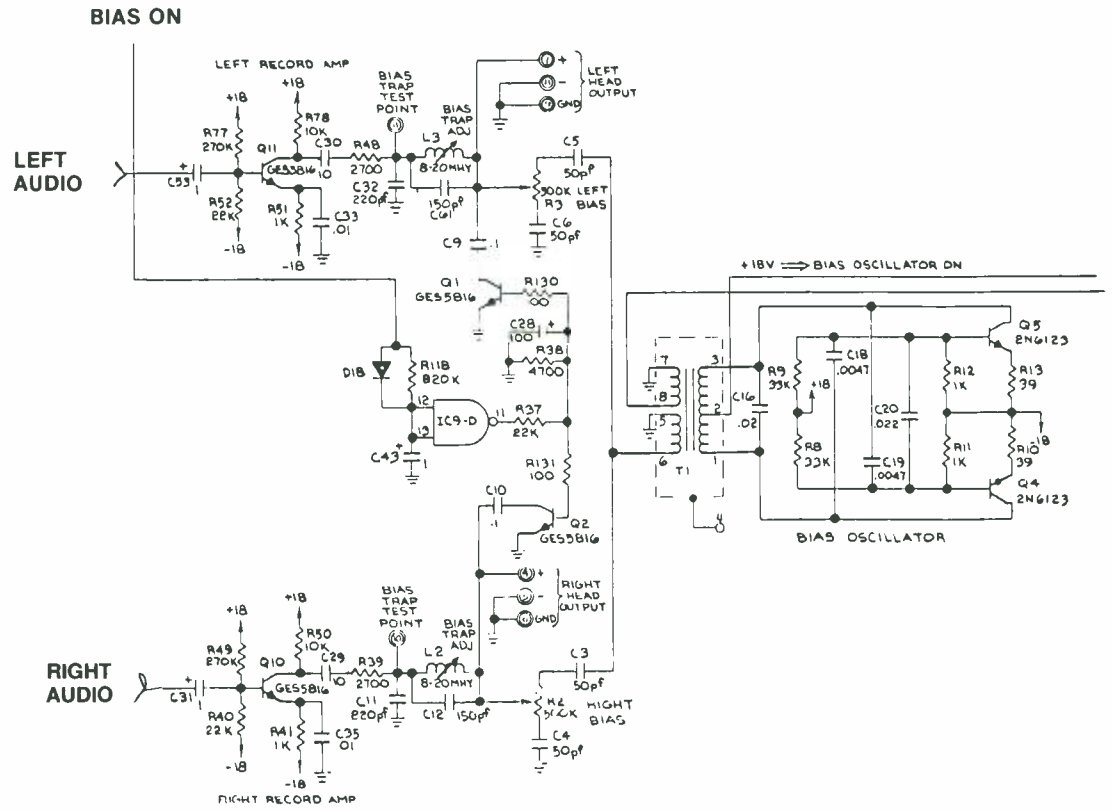


Fig. 9. Analog bias oscillator.

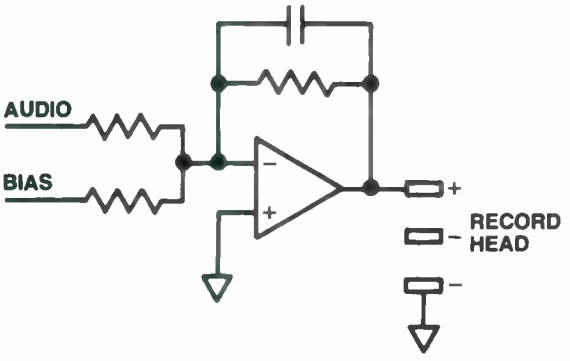


Fig. 10. Active bias summing.

vides some or all of the 60 dB of gain necessary to drive the output circuitry. The low head output voltage also requires that a low noise, high speed circuit be used as the equalization amplifier.

A typical circuit used to generate this playback response curve for a NAB cartridge machine is shown in Fig. 11. The resulting curves are usually referred to in terms of the time constants (or turnover frequencies) of filters which would result in the given amplitude response. The relationship between time constants and turnover frequencies is :

$$F = \frac{1}{2 \pi T}$$

Where:
F = Frequency in Hz
T = Time in seconds

For example, 50 microseconds (5×10^{-5} sec) is equivalent to 3180 Hz. In Fig. 11, the R3/C1 values set the low frequency turnover and R2/C1 sets the high frequency turnover. Both the high and low frequency turnovers allow a small adjustment range to compensate for variations in head performance. The gain of this circuit is about 40 dB at 1 kHz.

Control

The internal control of tape machines is now accomplished with digital logic in either discrete or microprocessor form instead of the mechanical or relay logic found in earlier tape machines. The amount of control included is dependent on the sophistication of the machine and its perceived applications.

All tape machines require the following control logic functions just to interface with the operator:

1. POWER ON
2. PLAY
3. STOP
4. RECORD

The following functions are included in reel-to-reel and cassette machines and some cartridge machines also:

5. FAST FORWARD
6. REWIND
7. TAPE SPEED SELECTION

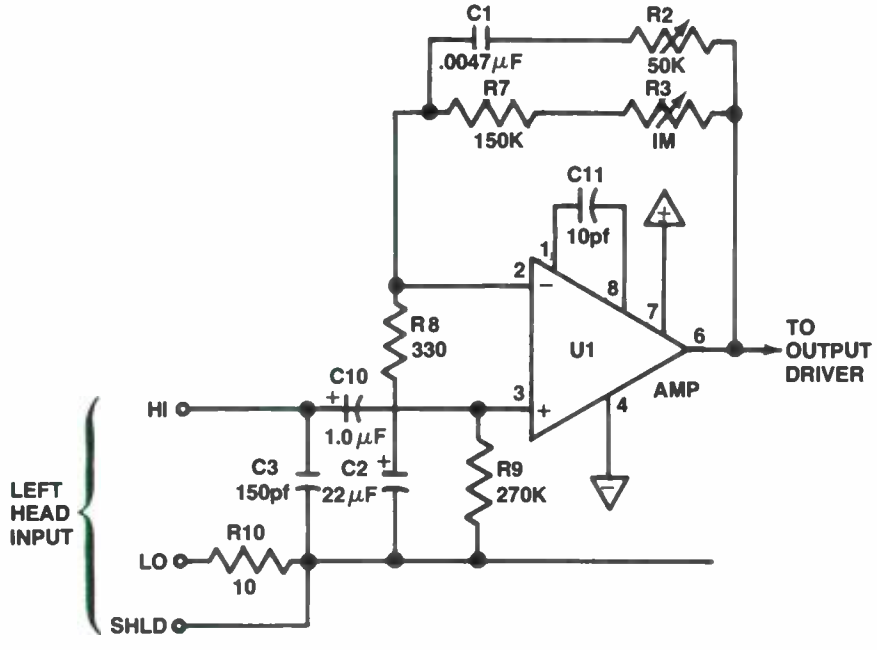


Fig. 11. NAB playback equalizer circuit.

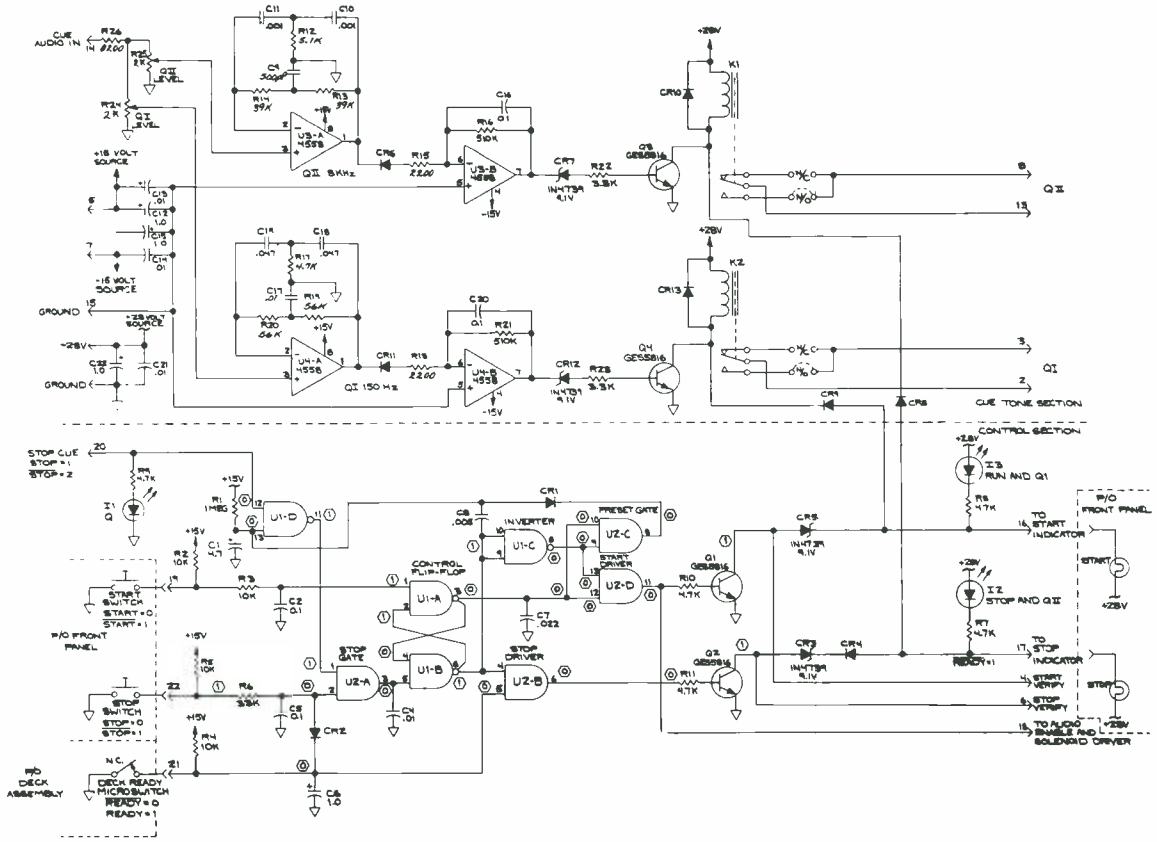


Fig. 12. NAB cartridge control circuitry.

8. EQUALIZATION/BIAS SELECTION

9. NOISE REDUCTION SELECTION

These functions are usually controlled by front panel pushbuttons or internal, user-selectable programmable jumpers.

Beyond these user interface functions, there are also the internal machine control functions to be performed. The control circuitry of a cartridge machine will be used as a example.

The *Control PC Board,* on upper deck, is shown in Fig. 12. Standard circuitry on this board provides:

(1) *START* and *STOP* action for the associated tape transport deck
(2) logic signals that activate front panel status lights
(3) *START* and *STOP* verify signals
(4) sensing and control logic for the Secondary and Tertiary cue tones (optional)

The control board responds to the start and stop pushbuttons, the ready micro-switch, and the 1 kHz tone sensor input.

Fig. 12 shows the logic status of the control board under initial conditions, ie., not loaded with a cartridge. The "0" and "1" figures at the

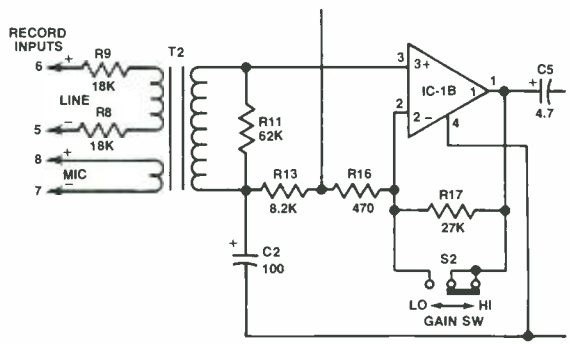


Fig. 13. Transformer coupled input circuit.

IC terminals (not to be confused with the terminal numbers themselves) indicate the logic status during the unloaded condition. Loading a cartridge, pushing the start and stop pushbuttons, and sensing the 1 kHz tone will change the logic states.

When a cartridge is loaded, the inserted cartridge opens the ready micro switch. The Control PC Board then lights the LED on the rear of the board and the ready light in the stop pushbutton on the front panel. CR8 permits the same two indicator lights to display the presence of a Cue II tone by lighting both to full brightness when the tone is present. CR4 provides isolation, while

zener CR3 limits the dc voltage to the indicators to 20 volts. Q2 provides a stop/verify current sink to the rear panel connectors for use in applications requiring external status sensing (eg. automation). Other logic elements remain unchanged when a cartridge is loaded.

When the start pushbutton of a loaded deck is pushed, the logic status of U1A and U1B changes, causing the deactivation of all stop/ready indicators and the stop/verify output current sink. Integrated circuits U1C, U2C, and U2D also undergo logic changes; activating the solenoid, the start/verify, the start LED, the the start front panel indicator light.

U2C and U1D combine in a circuit that presets the Cue-stop. When a cartridge is started, U1D is set up to stop the tape motion when a decoded 1 kHz signal is detected by U1D (at terminal 12). R1 and C1 delay U1D for about 3 seconds after the deck starts to insure that a previous stop cue-tone will not stop a newly started cartridge. At the end of the recorded message, the 1 kHz tone will trigger a cue/stop signal in the Control Board, stopping the tape.

Alternately, pushing the front-panel stop pushbutton will also stop the running tape, but will trigger a stop/verify signal. While a tape is running, pushing the stop button changes the logic state of U2A, which stops the tape and turns on all stop indicator lights. This also provides a stop/verify signal to the output connector for external status sensing.

Interfacing

The interfacing requirements of tape machines can be divided into two basic areas; audio and remote control.

Audio

The nominal input level is in the range of 1 volt, but tape recorders must accept a large range of audio input amplitudes, usually between ±20 dB, without overload and with excellent common mode rejection. The two types of recorder input circuits used are the transformer isolated (Fig. 13) and the balanced differential instrumentation amplifier circuit (Fig. 14). With the declining cost of integrated circuits, an excellent transformer coupled circuit is more expensive to produce than an excellent balanced differential circuit. At high input levels low frequency distortion can be a problem in transformer coupled circuits.

There are three types of instrumentation amplifiers usually used as audio input circuits. As in most other applications, the most expensive three op-amp circuit has the best performance. In the circuit of Fig. 14A, the input impedance is low and unequal, the common mode rejection (CMRR) is low and is dependent on the balance of the source's output impedance and the matching of all four resistors. Also, two resistors need to be changed to vary the gain. The circuit of Fig. 14B overcomes most of the drawbacks of the first circuit. Input resistance is high, CMRR is dependent only upon the resistor match, and gain can be set using only one resistor. The major disadvantage is that the common mode voltage input range is gain dependent and can be very poor at high gains. The best choice is Fig. 14C, where the input impedance is high, the CMRR is dependent only on the ratio of R2, R2', R3, R3' not on R1, R1', making the CMRR independent of gain.

The professional tape machine must be able to drive long, balanced 600 or 150 ohm audio lines at levels between ±10 dBV, with low distortion, reasonable headroom and good dc isolation. These performance criteria require the use of some sort of balanced output driver circuits. The output circuit choices are similar to those for the input circuits, either transformer coupled (Fig. 15) or electronic balanced and floating (Fig. 16). The transformer coupled output offers very good CMRR and very good dc isolation with disadvantages in size, cost and higher low frequency distortion.

There are three choices in electronically balanced output configurations shown in Fig. 16. The circuit shown in Fig. 16A has the virtues of simplicity and one resistor gain adjustment, but is not truly balanced. If you ground the positive output terminal the output drops 6 dB, but if you ground the negative output terminal all output is lost! The circuit of Fig. 16B loses 6 dB of output if you ground either output terminal. The circuit in Fig. 16C is a balanced and floating design, which is an electronic approximation of a transformer. This design includes crosscoupled feedback which keeps the output level constant even if one output terminal is shorted.

Remote Control

The remote control interface to most professional tape machines is a simple open-collector active pull-down transistor circuit, with the appropriate pull-up supply voltage available at the remote connector of the machine (Fig. 17). Some microprocessor-controlled machines do have serial interfaces, usually RS-232, available also. Although barrier strips and "Jones" connectors were once the connectors of choice, most new machine remote interfaces are the 25-pin "D" connectors made inexpensive and widely available by the personal computer industry. Some machines have dry relay contacts available for other interface controls.

For some machines with digital control logic, special optically isolated remote control interfaces

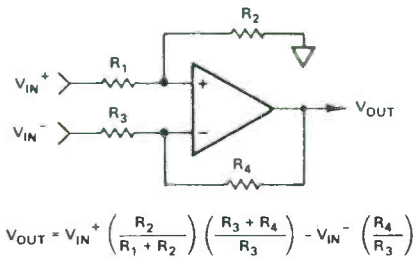


Fig. 14A. Simple differential input circuit.

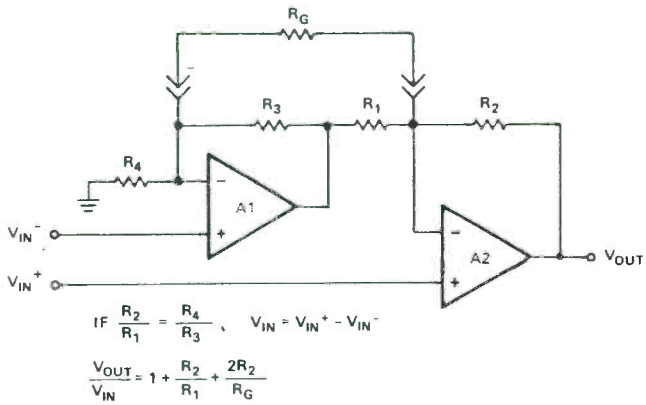


Fig. 14B. Two op amp differential input circuit.

may be necessary to prevent crosstalk between control circuit and avoid digital ground loops.

One of the problems in using cassette machines in professional applications is the lack of machines with easily implemented remote controls. The consumer units usually use a hand held infrared remote, which requires circuit surgery to use the simple contact closure remote controls available from consoles and other professional equipment.

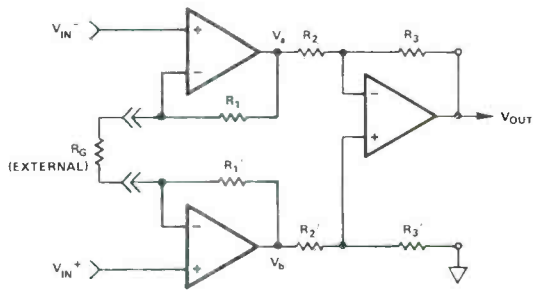


Fig. 14C. "Classic" three op amp differential input circuit.

TAPE MACHINE PERFORMANCE COMPARISON

The following material is presented in order to give an idea of the relative performance level of each format presented. It is representative of the median performance level of professional machines gleaned from industry test reports of machines in each category.

I. SIGNAL-TO-NOISE (3% THD Reference Level, No Noise Reduction)

Cassette	@55 dB
Reel-to-reel	@65 dB
Cartridge	@60 dB

II. DISTORTION (THD referenced To Normal Operating Level)

Cassette	1.0%
Reel-to-reel	0.5%
Cartridge	1.5%

III. FREQUENCY RESPONSE (±3 dB)

Cassette	(1 7/8 IPS) 20-20 kHz (-20 dB below reference)*
Reel-to-reel	(7.5 IPS) 20-22 kHz (-10 dB below reference)
Cartridge	(7.5 IPS) 30-18 kHz (-10 dB below reference)

*The small tape area and slow speed of cassette machines mean that they are more susceptible to tape saturation, so cassette machine frequency response drops drastically at higher levels such as -10 dB or 0 dB below reference.

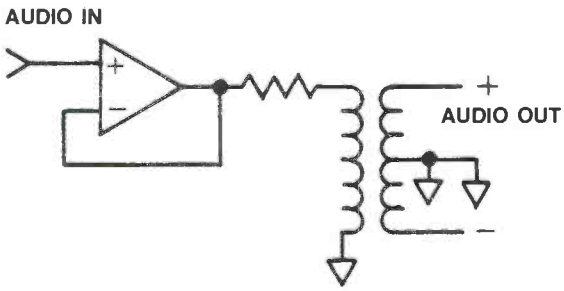


Fig. 15. Transformer coupled output circuit.

IV. HEADROOM

Cassette	3 dB (above 200 nWb/m)
Reel-to-reel	10 dB (above 320 nWb/m)
Cartridge	10 dB (above 250 nWb/m)

V. WOW & FLUTTER (DIN WTD PEAK)

Cassette	.05%
Reel-to-reel	.04%
Cartridge	.1%

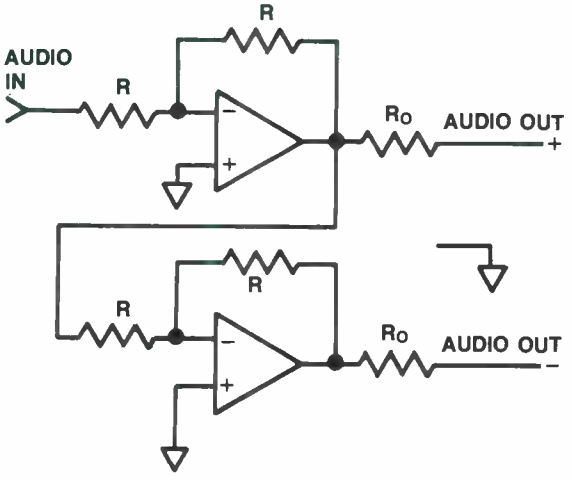


Fig. 16A. Simple op-amp line output circuit.

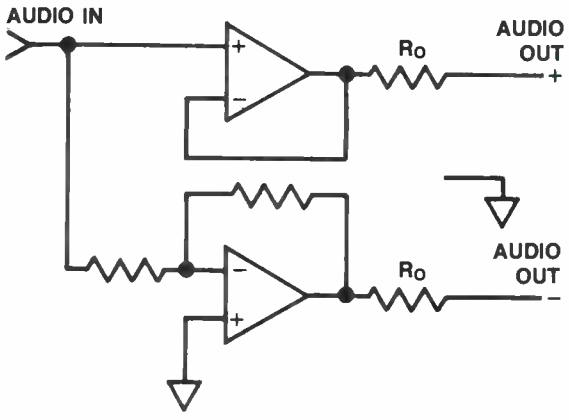


Fig. 16B. Balanced (not floating) line output circuit.

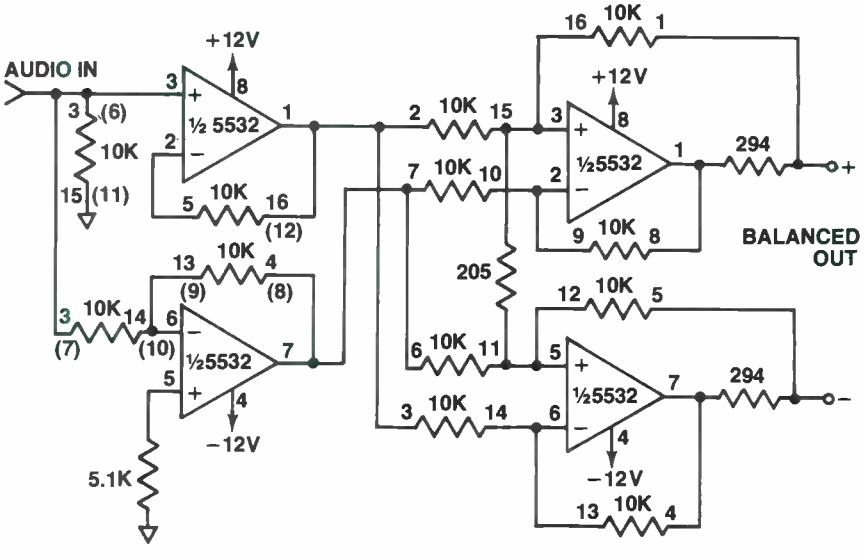


Fig. 16C. Balanced and floating line output circuit.

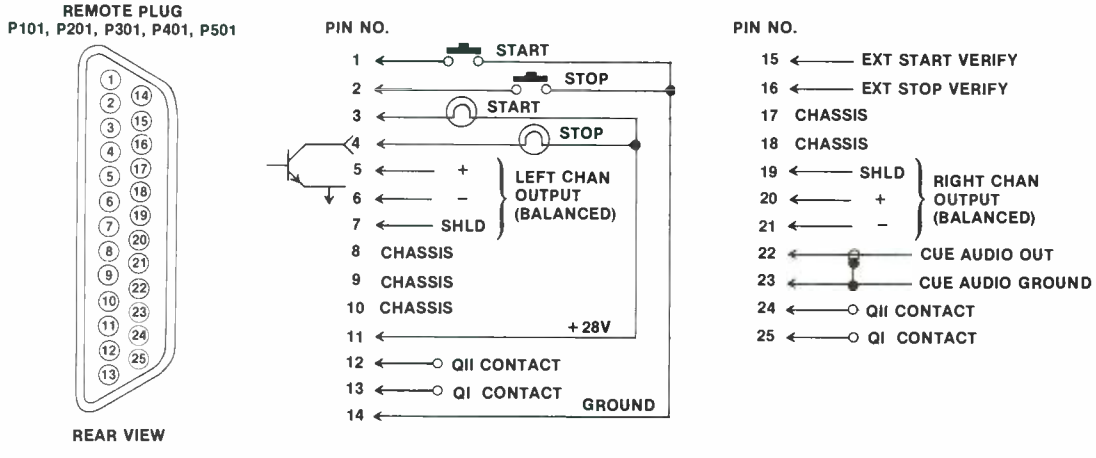


Fig. 17. Typical remote control interface circuit.

A Note About Reference Levels

Each format has its own particular "official" tape reference flux level. Manipulating the reference level in published material to enhance machine specifications (especially signal-to-noise) is a old and hallowed sales technique. The table below gives relative reference levels for several of the more popular levels and the formula for calculating the difference. Simply adding or subtracting the dB difference in reference levels between two different sets of specifications will allow a more accurate specification comparison.

FLUX LEVEL (nWb/m)	dB DIFFERENCE
160	(NAB 1975 Test Tape Reference)
185	1.3 (Ampex Reference Tape)
200	2 (MRL Reference Tape)
250	3.9 (Elevated Level #1)
320	6.1 (Elevated Level #2)

FLUX LEVEL (dB relative) = 20(log new level-log reference level)

Example: The cart machine being considered for purchase has a signal-to-noise of 65 dB referenced to 400 nWb/m instead of 160 nWb/m reference level for another cartridge machine which has a signal-to-noise of 57 dB.

Difference = 20(log 400-log 160) = 7.96 dB
57 dB + 8 db = 65 dB

This calculation shows they basically have the same specification.

FUTURE TAPE MACHINE DEVELOPMENTS

The performance of the conventional analog tape recorder has reached the point of diminishing returns. Recent advances in oxide particle size and packing, the introduction of alloy tape formulations and new head materials have given analog tape better dynamic range and high frequency performance. The addition of various noise reduction systems has slowly increased the sound quality of conventional tape systems. However, at the present stage of development, it is increasingly difficult to carry out any further major improvements in the performance of conventional tape recorders due to physical limitations.

One of the ways in which to overcome this problem is to use digital techniques of signal representation. The most prevalent form of digitizing for audio signals is pulse code modulation (PCM). There are three fundamental differences between digital and analog tape recorders.

1. A PCM tape recorder requires 30 times the bandwidth required for an analog recorder, requiring increasing recording density.
2. Because bits are recorded on PCM equipment, it is possible to disperse the data bits comprising one channel onto a number of recorded tracks.
3. Linearity is not important because only two states are recorded on the tape.

In May of 1967, NHK gave the first public demonstration of a 12-bit companded PCM digital audio tape recorder designed around a 1-inch, 2-head helical scan VTR.

In May of 1978, the EIAJ standard for PCM adapters was adopted and in 1985 a digital audio stationary head (DASH) tape recorder standard was proposed. With the advent of the Compact Disc, digital audio is becoming accepted in both the consumer and professional worlds.

There are basically two PCM recording systems in use, the rotary head (VTR based) and the stationary head (DASH) format recorder. The simpler, cheaper rotary head system will be used for consumer home recording. A DASH format recorder is necessary for recorders requiring sophisticated editing capability for 4 channels or more. The professional two-channel recorder is the area where the two systems are competing with each other. It will require more technological innovations to make two-channel stationary head systems cost competitive with two-channel rotary head systems.

AUDIO TAPE MACHINE MAINTENANCE

Introduction

This section will cover general maintenance procedures along with specific maintenance areas such as heads, pressure rollers, motors and electronics. There will also be a short discussion on troubleshooting and some general considerations. All tape machines have one thing in common; they cannot perform to their designed specifications if they are not properly maintained. Often the maximum performance of a machine is determined by the level and frequency of care rather than design or construction limitations.

General Maintenance Procedures

One of the best tools for keeping tape machines in good working order, especially in a broadcasting environment where many such machines are involved, is a scheduled maintenance system. The design and implementation of a good maintenance system can prevent most common types of problems from affecting the on-air signal.

The best type of system identifies each individual machine by serial number, location in the system and date of original installation. Since maintenance level varies with the area of use, it is essential to know the location of each machine at all times. This tracking of individual units allows rotating machines with spares, and it gives an accurate record for insurance and warranty information. The location record for each unit should also include its problem history record. This problem history can provide information on machines that would otherwise be lost. This information can help point out all types of trends such as the need for increased maintenance in a certain area, shortcomings in equipment design, and environment problems.

One of the most important pieces of information that can be provided by the equipment history card is the cost of repairs. This helps in deciding when it is no longer economical to continue to repair a tape machine.

There are many possible formats for logistically handling both the maintenance schedule and the problem history; however, with the advent of business and personal computers, the job has become much more simplified. It is now possible to set up your system so that at the beginning of each day, or each week, you can obtain a printout of the work scheduled for that given week or day. This allows efficient scheduling in either a large or small installation.

Putting a Machine in Service

The first step in setting up any system is establishing initial conditions: design specifications and the results of initial tests by the manufacturer and purchaser. When a new machine is received, it should have a test data sheet with it, usually included with or bound into the service manual. This will show results of final tests conducted by the manufacturer prior to shipment, typically:

- Signal-to-noise ratio for a given flux level,
- Frequency response at one or more flux or record levels,
- Operating levels,
- Wow and flutter and measurement standard,
- Distortion in percent for a given flux or record level and frequency,
- Crosstalk between channels at a given frequency and record level,
- Verification of functions such as tone sensing and start and stop times.

These data should be checked to the extent that time and available test equipment permit. Then the new machine should be re-equalized for the station's preferred tape and any new measurements recorded.

This overview of maintenance systems is intentionally broad. While a program for maintenance is essential, the specific system must be tailored to fit the individual installation. It must be set up so that it is easy to work with and convenient to use, otherwise it will not be followed. Use something that works for you.

Daily Maintenance

Daily maintenance tasks are those that must be performed routinely to insure continued good performance and prevent failures not related to mechanical wear or electronic failure. These are some of those tasks.

Head Cleaning

This is probably the most often performed maintenance task and one that is given possibly the least consideration. It is very easy to provide a cotton swab and a bottle of alcohol to the machine operators and tell them to clean the heads at the beginning of each shift. However, consideration should be given to several of the items involved in the head cleaning process.

First, head cleaning fluid; there are nearly as many head cleaning fluids available as there are heads to clean. Everyone has a favorite, and there are just a few basic things to consider when using head cleaners.

- Safety for the user. Some liquids, such as carbon tetrachloride, which might be used as head cleaners are dangerous to breathe. The more common alcohol cleaners are effective and safer.
- Safety for the tape, heads, and other hardware. Strong solvents might dissolve materials used in the construction of heads, rollers and other hardware. Tape, itself, may be vulnerable to solvent remaining after the cleaning process. Furthermore, a liquid may be spilled or oversprayed and cause damage to other parts of the equipment.

Lacking specific recommendations from the equipment manufacturer, the safest cleaners are those made with ethyl alcohol (ethanol) or isopropyl alcohol or freon. These substances evaporate quickly and leave no residue. Do not use rubbing alcohol as it may contain some substances which will not evaporate.

Remember that the more effectively a solvent dissolves the oxide buildup on heads, the more effectively it may dissolve tape and other materials.

Second, the cleaning utensil. Cotton swabs, available at drugstores and drug departments, are the most commonly used means of cleaning heads. These provide the user with some extra reach so that hard-to-get-to heads can be cleaned more easily and thoroughly; however, they have

two main drawbacks. The first is that they tend to shed the cotton that is twisted onto the ends of the stick. Second, the surface that can be put in contact with the head at any one time is quite small. If swabs are used, the heads should be carefully inspected for cleanliness and debris before putting the machine back in service.

Another common head cleaning utensil is a clean, soft lint-free cloth. This method allows pressure to be applied as needed to remove dirt build-up. There are, however, two drawbacks to using a cloth. Sometimes it is not possible to get your fingers into some of the heads in some machines. Extending your reach by wrapping the end of a screw driver or pencil eraser is not advisable because of the possible damage that could be done to the head assembly. The other problem is possible excessive pressure on the heads. This may cause mis-alignment of the head assembly. Finally, tools such as screw drivers tend to become magnetized and should not be placed close to heads and other tape contact surfaces.

Tape Path Cleaning

Another daily maintenance chore that goes with head cleaning is the cleaning of the rest of the tape path. Pressure rollers, capstan shafts, idler wheels, guides, etc., should also be cleaned with the same diligence as the head. While they are not in the audio path itself, they contribute to the overall performance of your tape machine by affecting such parameters as wow and flutter and pulling torque.

Head and Tape Path Demagnetization

Another task that should be performed daily, demagnetization, or degaussing, is a two edged sword. Not only can heads become magnetized through normal use, but improper demagnetization can also leave residual magnetism in the head, the result of which is not only poor audio performance from machines, but partial erasure of high frequencies on the tape.

A variety of head demagnetizers is available from various sources; however, the following should be taken into account when purchasing a demagnetizer. Heads for tape machines have a wide range of hardness which affects the retentivity of the material. Some of the harder heads consequently require a much more powerful demagnetizer. An under-powered demagnetizer, no matter how many passes are made at the head, will not demagnetize an extended-life head. The other prime factor in buying head degaussers is the accessability of the heads. Some degaussers are available in cartridge form, and while they do an excellent job on cart machines heads, they are, of course, not suitable for any other application. Be sure your demagnetizer is powerful enough and will fit the units you need it to service.

After selecting the appropriate tool, it is no less important to use it properly. If operators are to perform the degaussing of heads, they should be properly trained. In general, the procedure should include the following steps:

- Turn off power to the tape machine. The degausser induces strong magnetic fields which could severely overload sensitive circuitry.
- Turn on or plug in the degausser at least 3 feet from the tape machine.
- Slowly wipe the tip across the heads, guides, rollers and other components in the tape path. Avoid touching tape contact surfaces unless the tip is protected with a clean, soft cover material.
- Slowly remove the degausser while rotating. The degausser should be at least 3 feet from the heads before it is turned off.

In order to verify that the heads have been completely degaused, take a blank tape and check the machine's signal-to-noise figure. If it shows an increase in the signal-to-noise over the normal level, repeat the demagnetizing process. Once the people performing this task have gotten used to the tool, it becomes an unneeded check. Just as in the head cleaning process, all other metallic components in the tape path should be demagnetized regularly.

These daily maintenance tasks should be performed without fail. Postponing these tasks can only result in poor on-air performance. Be diligent!

Weekly Maintenance

Weekly maintenance should consist mainly of a brief physical inspection of the unit for obvious problems such as noisy motor bearings, excessive debris on the deck or in the guidance from oxide shedding. In other words, just make it a point to look at the machine and verify that it is still in the building. Also talk to the operators. They can help you head off failures by letting you know if a machine is acting differently. Operators are not the enemy.

Monthly or Quarterly Maintenance

This section is given a dual heading because of the variation in usage at every installation. The frequency of the checks outlined here may vary. It will depend on how the machine is used, the environment it operates in, and the reliability of the individual unit. Some units may require that these checks be made more frequently than others, but this is something you will not know until you have developed some service history records. Start by using a relatively short interval; and if no corrections are required, you can lengthen the interval. However, remember that

the primary purpose of a regular maintenance program is to *prevent* failures, not fix them. Do not allow the service interval to become too long. Also, most of these checks require that the machine be taken out of service, so it would be advisable to stagger the schedule.

General Cleaning

Each unit should be carefully dusted by using either a soft-bristled brush or low pressure air. Covers should be removed during this process, where it is convenient, so that debris is free to fall clear of the machine. This is also a good opportunity to clean the tape path thoroughly and demagnetize all the areas that are difficult for the operators to get to.

Visual inspection of the mechanical parts should be made to check for head wear, deck wear in cart machines, guidance wear, and any other mechanical parts that are subject to fatigue or constant abuse.

Motors should be checked for bearing noise. While small amounts of bearing noise may not be a sign of eminent failure, they should be considered a warning signal. Listening to the mechanical sounds of a machine can often tell as much as more sophisticated tests for wow, flutter and torque.

General Performance Check

Aside from any obvious faults that you or your operators may have noticed in a unit's on-air performance, there are a few quick checks which will determine if the unit is performing up to standard. First of all, typical performance numbers for each machine should be kept on file with the history card. Most manufacturers will provide test data sheets that provide all this information. Data taken at each performance check should be compared back to the original. Second, the test tapes used should be those recommended by the manufacturer and adjustments made should be done in accordance with the specific equipment manual.

Azimuth and Phase Response

The significance of these adjustments is discussed in another section of this *Handbook* so the only comment here is they are important to good performance. If you find that azimuth is unstable or hard to align, look for some mechanical problem in the head mounting assembly or the tape guidance system. The important thing is to get a good "feel" for how the machine reacts to adjustments. This is the best way to obtain an accurate setting.

Playback Frequency Response

A quick check of playback response will provide warning of the beginning of head wear and drift in response and output levels. A worn playback head will begin to lose the high end response. A certain amount of this can be compensated for by re-equalizing the playback electronics.

Record Frequency Response

Proper record frequency response is essential to the sound of your station. A quick check of this spec can tell if the unit needs complete record alignment and will provide information concerning wear of the record head.

Record/Playback Distortion and Noise

These two parameters will give more clues as to the overall performance of the tape machine electronics than any other measurements. Poor signal-to-noise figures or high distortion can be the forerunners of many more severe problems that can be prevented if action is taken early. Take the time to investigate these symptoms when they begin to appear.

Wow and Flutter and Tape Torque

These measurements can indicate impending failure of motors or bearings. The equipment to measure wow and flutter is expensive and usually not found in stations, but it can be rented for periodic checks. Listening to the sounds of motors and bearings can tell a lot and listening to a tape with a continuous tone will give a good qualitative check of wow and flutter.

For cart machines, a quick test of wow, flutter and torque can be made using a tone recorded on the longest cartridge available, thus placing the greatest load on the mechanical system.

Although the five performance checks described above represent a complete testing of the unit, they can be performed in less than 30 minutes per machine in most cases. The time spent on these tests is well worth it.

Semi-Annual Maintenance

Maintenance performed at this interval should be an in-depth version of the monthly or quarterly tasks. Complete specification verification should be done along with a thorough mechanical analysis. It should be determined that all motors have sufficient torque, both starting and pulling, that solenoids, brakes, and other electromechanical devices all operate smoothly, and that all mechanical operation is quiet.

Again, at this point, the timing of these procedures becomes dependent on the use of the machine. In machines that receive relatively light duty, this thorough examination would not be required nearly as often. However, in an "On-Air" tape machine, any maintenance that is done less frequently than on a semi-annual basis provides no protection at all against failures between checks.

Summary

These general maintenance procedures are those that can and should be performed on a regular basis. When a good program and system of records is set up and maintained, it will help make the engineer's job much easier and provide time for dealing with the few emergencies that are inevitable outside your tape equipment.

There are, however, a few general considerations that should be mentioned that are not directly involved with the tape machine proper, but will have a direct affect on the performance of the unit. The following is a brief look at some of these considerations.

Tape and Tape Cartridges

One of the major keys to good performance is consistency in all areas, tape and tape cartridges is no exception. Once a certain type of tape and one certain brand of tape cartridge has been chosen, stay with them. Optimize the machines to the type of tape and use it throughout the system.

Test Tapes and Alignment Tools

Test tapes are an essential part of the equipment needed for proper care of tape machines. The manufacturer usually recommends a certain test tape for their machine; however, if you have more than one brand of cart machine or reel-to-reel, by all means use only one test tape, and not a separate one for each brand of machine.

The care of test tapes is important, and a few basic rules should be followed. Aside from the normal care considerations given when the tape is not being used, *always* demagnetize all heads and tape path components before playing the tape. Also insure that no stray bias or dc voltage is present on the heads before using. The normal useful life of a test tape with proper care should be several hundred passes.

Aside from normal hand tools, some manufacturers recommend certain head, motor, and guidance alignment tools. These tools can be useful when used properly; however, remember that again consistency is the key.

Conclusion

In wrapping up this section on tape machine maintenance, there are two key factors to remember. First, be diligent in the maintenance program and most problems will never get onto the air or into a final production. Second, be consistent with procedures and all machines will perform the same in the news room, the control room, the remote van, or the production room.

Following these tips should give you the maximum life and performance out of every tape machine.

5.12

Microphones

Greg Silsby
Marketing Manager Studio Products
Audio-Technica
Stow, Ohio

TRANSDUCER TYPES

Any discussion of microphones should begin with some understanding of what a microphone is and what it does. A microphone is a transducer, a device which, when activated by energy from one system, converts that energy to another form and supplies it to another system. In the microphone, acoustical energy (sound waves impinging on the diaphragm) is converted to an ac voltage. The method by which the microphone converts acoustical energy to electrical energy is one of the ways by which microphones are differentiated.

Carbon

The earliest transducer principle used to construct a microphone was variable resistance. This is the principle by which the carbon element operates. The carbon microphone contains carbon granules which are compressed and decompressed by the movement of the microphone's diaphragm as it responds to air pressure changes. As direct current is passed through the granules, the changes in density result in a variable resistance to the current flow. The resistance change bears the characteristics of both the amplitude and frequency of the sound waves that act upon the diaphragm.

While carbon microphones offer excellent durability, they do require a power supply. More serious deficiencies include their high distortion and limited frequency response range. Their common application in recent years has been in telephones and other communications areas, such as military and aviation communications. Even in these fields, carbon microphones are regularly being replaced by dynamic and condenser systems.

Dynamic Ribbon

The ribbon, or velocity microphone, utilizes a very thin, corrugated metallic foil ribbon suspended within the flux field of a permanent magnet (Fig. 1). The ribbon is referred to as a velocity microphone because it responds to air particle velocity at the ribbon. The term "pressure gradient" is also used to denote that the pressure exerted on the ribbon is in proportion to the difference between the pressures present on each side. While the ribbon's ends are held in place, the rest of it is allowed to move freely back and forth in a sympathy-induced mechanical recreation of the amplitude and frequency of the sound presented it. The ribbon's movement causes it to cut the lines of flux between the magnet's poles, inducing a small ac voltage onto the ribbon. The leads from the ribbon's ends connect it to a step-up transformer which converts the extremely low impedance of the ribbon (approximately 1 ohm) to a usable figure which might lie between 50 and 500 ohms.

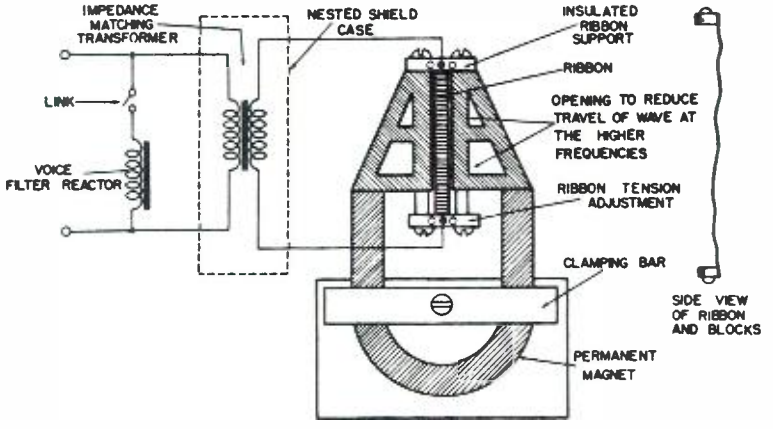


Fig. 1. Construction of a ribbon, or velocity, microphone. (Courtesy of Audio Cyclopedia)

While the inherent directional characteristic of the ribbon microphone is bi-directional ("figure-eight" polar pattern), other patterns have been derived to allow much more flexibility in their application.

Ribbon microphones have historically been noted not only for their potential for delivering a very "warm" sound, but for their susceptibility to damage from air blasts. Blowing across the ribbon, coughing into it, or subjecting the ribbon microphone to the wind in location recording could easily stretch or break the ribbon. Even rapid panning on a studio boom has caused ribbon failure. Newer designs, however, have provided considerable improvements in durability and a lower failure rate.

Dynamic Moving Coil

Although the ribbon microphone is a type of dynamic microphone, transducers of this type are usually referred to by the terms "ribbon" or "velocity microphones". In common usage, the "dynamic microphone" has come to mean a moving coil dynamic microphone.

The dynamic microphone has a diaphragm to the back of which is attached a voice coil (Fig. 2). This extremely light-weight coil of wire is suspended in a magnetic field supplied by a permanent magnet structure. The ends of this voice coil are brought out to stronger leads which connect to either a transformer or the microphone's output connector.

Sound waves acting upon the diaphragm cause it to move back and forth in sympathy. The attached voice coil is then forced to cut the lines of flux in the magnetic field causing a small ac voltage to appear at the ends of the leads. This signal should closely emulate the sound waves in terms of frequency and amplitude. The dynamic element is sometimes referred to as a generator or motor mechanism. It is, by design, very similar to a speaker. Loudspeakers are often used as both the speaker and the mike in an intercom.

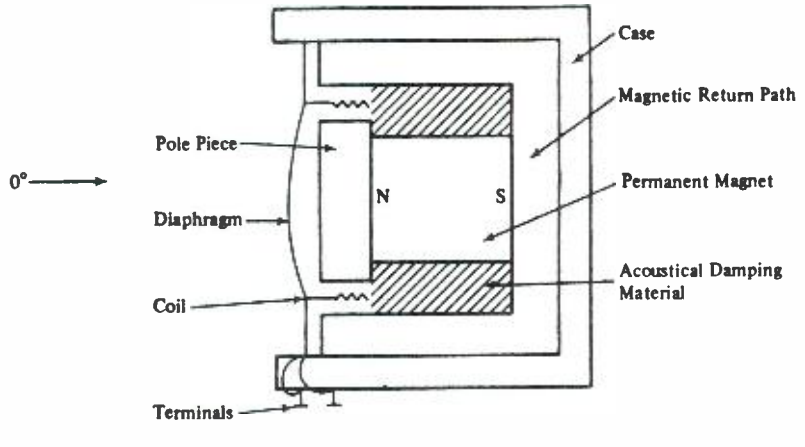


Fig. 2. Dynamic moving coil element. (Courtesy of Audio Cyclopedia)

The diaphragm design is crucial to good dynamic microphone performance. It must be highly compliant to allow effortless excursion at all frequencies of interest. In addition, this movement must be accomplished with maximum linearity and a minimum of break-up modes. Nonlinearities of diaphragm movement would include, for example, any tendency for a rocking motion to be set up which, at some frequencies, would allow one side of the voice coil to be travelling downward while the other side is moving upward. Such rocking results in phase cancellation and a dip in the frequency response.

Break-up modes occur when a portion of the diaphragm resonates independently of the rest of the surface. Again, phase cancellation results; and, with it, response anomalies occur.

The design and construction of a high quality dynamic microphone suitable for broadcast use is a blending of science and art. As with other transducers, much of its design may be modeled by the use of equivalent electrical circuits. The process is similar to the computer assisted design of loudspeakers using Thiel parameters. In the microphone, however, the seemingly infinite variety of complexities in certain parts of its design is so great that the artistry of the microphone engineer is constantly called upon.

In the design process, the goals set before the microphone design engineer are sometimes all but impossible to achieve within the same product. As is true in other areas of engineering, design trade-offs are numerous and the laws of physics tend to win in the end.

Dynamic Microphones: Effects of Small Size

Size plays an important role in the performance capabilities of the dynamic microphone. Small dynamic motor mechanisms tend to be very inefficient. Their acoustic sensitivity is low while their mechanical sensitivity is high by comparison. The result may be a poor system S/N ratio and a lot of handling or stand-born noise. Internal shock-mount systems may be used to reduce the mechanical excitation but the design goal of small size may then be defeated.

Small size usually means sacrificed low-frequency response in dynamic microphones. This is not to say that large dynamic microphones will always have an extended low frequency response. Very small dynamics will almost certainly, though, be lacking in low frequency output.

Still another physical characteristic of the dynamic microphone that affects its performance is the mass of the diaphragm/voice coil assembly. The greater the mass, the more limited will be the high frequency response. Common design practice includes the use of Helmholtz resonators immediately in front of the diaphragm. These create peaks and effectively extend high frequency response beyond the normal limits of the system (Fig. 3).

Most broadcast quality dynamic low-Z microphones accomplish their impedance as a function of the turns and gauge of their voice coil wire. Some more public address-oriented older microphones employ a transformer within their housing to correct for design trade-offs in their voice coil. The transformer not only adds to the microphone's cost, however, but may restrict performance, limiting the frequency response limits and increasing distortion. Properly designed dynamic microphones can be the most rugged of the high-quality transducer types; some have truly become legendary for their ability to provide high quality broadcast audio with virtual bullet-proof construction.

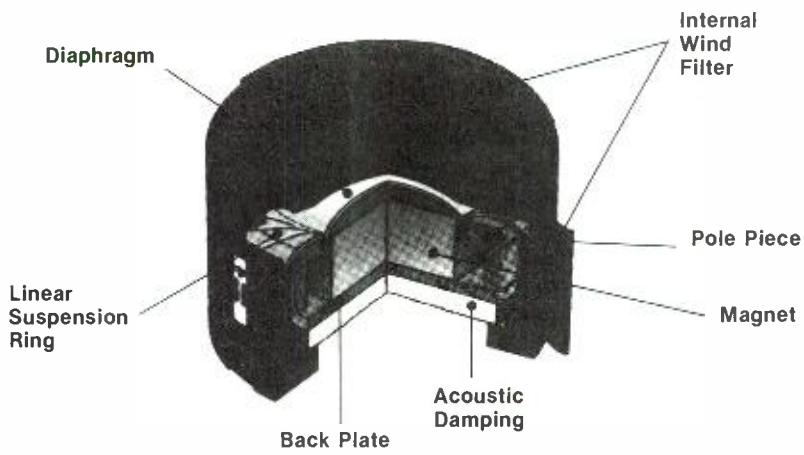


Fig. 3. Cutaway drawing of a dynamic element showing Helmholtz resonators.

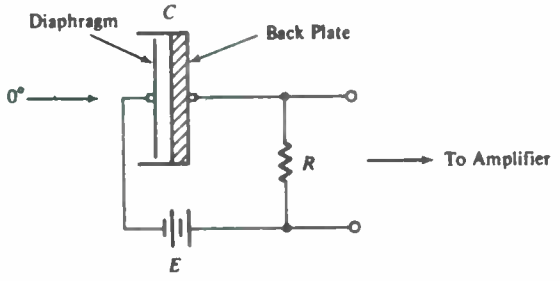


Fig. 4. Conventional capacitor microphone system.

Condenser

In the condenser microphone, a capacitor forms the generating element (Fig. 4). One side of the capacitor is the diaphragm; the other is the fixed backplate. Air between these two plates acts as a dielectric. The capacitor, of course, must possess a positive electrical charge on one and a negative charge on the other of the two plates. The conventional or "discrete" condenser gets this polarizing or bias voltage from an external dc power supply. In older condenser microphones, separate leads were required to deliver dc from the power supply to the microphone. Today, "phantom power" is used in most conventional condenser systems to deliver the required dc voltage to the microphone over the same conductors and their shield that are used to carry the audio signal. Upon activation of the power supply, a positive voltage is quickly built up on the rear surface of the diaphragm. This causes an electrical current to flow through the resistor until the surface of the backplate finally receives a negative charge of equal value.

As sound waves (air pressure changes) strike the diaphragm, causing it to move back and forth, the distance between the two plates rapidly increases and decreases. This causes proportional changes in the capacity of the condenser to hold a charge. The result is an ac current flow in the resistor and a voltage across the resistor that corresponds to the excursion of the diaphragm. While this voltage effectively represents the output voltage of the microphone, the source impedance is far too high to be carried for any distance over microphone cable. This output signal, then, is presented to an impedance converter (often an FET) inside the microphone. Power for the impedance converter is derived from the same source as that which provides the polarizing voltage for the element. The impedance converter delivers a low impedance output that can be fed down long microphone cables with minimal loss.

Electret Condenser

The electret condenser microphone utilizes a material which has the ability to hold a charge applied during the manufacturing process. Most high-quality electrets apply this material to the fixed back plate of the capacitor (Fig. 5). Some designs employ a charged diaphragm instead, but pay several performance penalties in doing so. Lowering the mass of the diaphragm by moving the electret material to the backplate results in lower handling noise, extended frequency response and improved transient response.

The electret functions much like the discrete condenser, but produces its output voltage without the need for an external high-voltage dc supply. An impedance converter is still required. The low voltage needed to power it, however, may be derived from internal or external batteries or an external ac-powered supply.

PHANTOM POWER

Phantom power, or "simplex" power, provides one means for remote powering condenser microphones. Phantom power requirements of various microphones may fall anywhere between 9 and 48 V. External supplies are most often designed to deliver 9, 12, 18, 24, 30 or 48 V. While many electrets will operate on any of these supplies, some modern discrete condenser designs require 48 volts. The phantom supply voltage in non-electret condenser microphones is often stepped-up by an internal circuit to provide a sufficient capacitor polarizing charge for good signal-to-noise figures.

In a phantom power circuit, the plus side of the dc supply is applied equally to both of the signal conducting leads of a balanced microphone line. This may be done by means of either a build-out of matched precision resistors, or via a center-tapped transformer. In each case, the return path

Fig. 5. Cutaway drawing of an electret condenser microphone element.

is the shield. In the microphone, the dc may be similarly tapped via the resistor or center-tapped transformer method to provide the power it needs. The dc is prevented from being seen at the impedance converter output by dc-blocking capacitors or the internal center-tapped transformer.

If a balanced output dynamic microphone is connected to a line with phantom power present, performance should not be altered; nor should damage occur to the dynamic element. The voice coil or output transformer winding connects across the two signal leads and should see no potential difference between them. Because there is no connection between either lead and the shield (the dc return path), there is no circuit. If an unbalanced dynamic microphone is connected to a phantom supply, the dc will pass through the voice coil, causing the microphone's whole life to pass by before it.

A less common powering system called "A-B" or "T" powering is not compatible with dynamic or phantom powered microphones. A-B power puts the positive side of the dc on one signal lead and the negative on the other. This is not a nice thing to do to a dynamic microphone.

FREQUENCY RESPONSE

One of the first specifications looked at, on a microphone data sheet, is the frequency response range or limits. The required low and high-frequency limits may depend upon the nature of the sound source that is being miked, the medium by which the signal is to be stored and transmitted and the environment in which the miking is to be done.

Often, unfortunately, more attention is given to the response limits than to how the microphone actually sounds in its intended application. Nonlinearities of the response often contribute more to the listener's subjective impression of the microphone than do the response limits. A specification that reads "Frequency Response 40-18,000 Hz", by itself, says virtually nothing. Add to that some limits, like ± 3 dB, and our knowledge of the microphone, while improved,

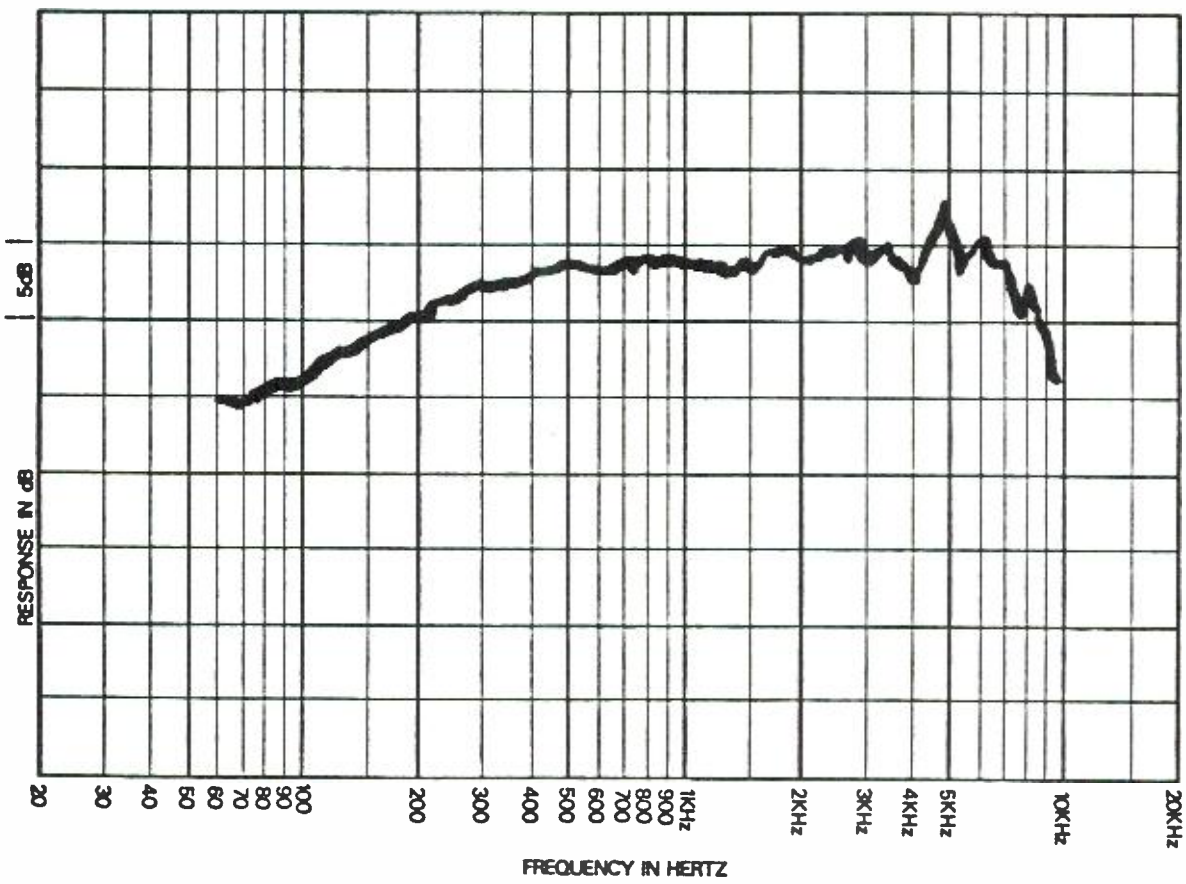


Fig. 6. Frequency response curve of a shotgun microphone tailored for distant miking.

is still extremely scant. The shape of the response will tend to contribute to the character or "personality" of the microphone's sound.

Non-linearities can create acoustic feedback in sound reinforcement, nasality, poor intelligibility, excessive sibilance, muffled sound or any of a variety of other acoustic problems. On the other hand, a microphone's response may be deliberately, carefully tailored by the design engineer to solve problems rather than create them. A rolled-off low frequency response and a rising high frequency response may be employed in a microphone that is intended for use at a considerable distance (Fig. 6). This tailoring can reduce the effects of unwanted low frequency information, such as traffic noise or the rumble of air handling systems, while boosting the high frequencies that are normally attenuated with distance.

Microphones that are intended to be worn on the body usually exhibit a response that compensates for their positioning where the lip and chin "shade" the microphone from the sibilance in speech.

A rolled-off low end response may help considerably in attenuating handling or stand-born noise as well as wind noise or the breath blasts of explosives in speech.

Unfortunately, published specifications can serve as only one guide in our efforts to understand a microphone. The extent to which they serve any function at all is, of course, dependent upon the credibility of the source. This may help to explain why a very poor sounding $10 microphone might show limited specifications that appear superior to an excellent-sounding $100 microphone.

Certainly, a response curve drawn with the microphone directly facing the sound source (on-axis response) will give us a clearer picture of the instrument than will a statement of its response limits. Even curves from well respected manufacturers, however, may be difficult to compare due to the variety of test procedures and standards. For example, the frequency response chart is an X-Y graphic that compares decibel output to frequency. If that chart is compressed vertically or stretched horizontally, the response curve will automatically appear more linear.

Frequency response plots for the same microphone may also vary greatly when run on the same equipment, with the same graph paper. Such variables as the pen speed, damping or even the direction of the tone sweep (low to high or high to low) may result in vastly different curves.

Directional microphones present still another possible anomaly in the testing process. These microphones exhibit a phenomenon known as "proximity effect" which results in a bass boosted output when close-miking a sound source. Proximity effect is neither good nor bad; its value is dependent upon the intended application. Various designs will differ in the amount of proximity effect that is possible to attain. A singular response curve of a directional microphone, tested at some particular (or worse, unknown) distance may be of little value to someone who wishes to use it at another. Ideally, directional microphone data should include close and distant curves (Fig. 7).

POLAR PATTERNS

As difficult as it might seem, at times, to pick up the audio signal that is desired, the real problem more often lies in eliminating those sounds we don't want to pick up. Microphones with various directional patterns are often enlisted to improve the ratio of desired signal to ambient noise.

For most miking applications, a suitable on-axis curve alone may not be satisfactory. Ambient noise, "leakage" from other instruments in a band or orchestra, room reverberation and feedback potential from PA floor monitors are some of the reasons why it is important to know what the off-axis response of the microphone is, as well. The best view of the microphone's off-axis response is obtained by examining several different polar plots. These should be drawn at low, mid-band, and high frequencies. Overlaid, these plots should reveal how well the microphone maintains its directionality at each frequency.

There are several broad classes of microphones, based on fundamental polar patterns, to which most microphones' directional characteristics conform, to some extent or another. These include:

1. Omnidirectional
2. Cardioid
3. Supercardioid
4. Hypercardioid
5. Bi-directional

The accompanying chart shows the relative data for each of the various patterns (Fig. 9). The data, however, is taken from mathematical models representing the perfect polar in each example. Actual microphone polars may vary from near perfection to close resemblance. In the real world, the microphone design engineer must go beyond the math equations to somehow accomplish a desired axial response and sensitivity with the proper polar pattern while maintaining polar uniformity. It is truly a blending of art and science.

Polar Scaling and Dynamic Range

Care should be taken when reading polar patterns to observe several variables in the way that they may be represented. These variables can

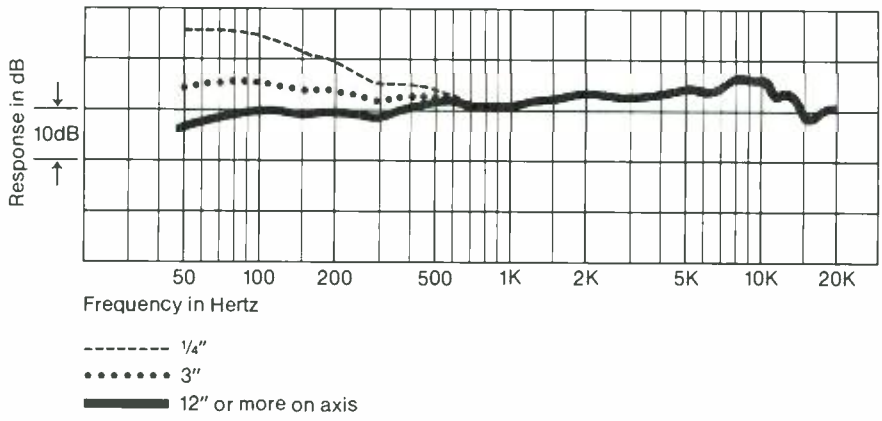
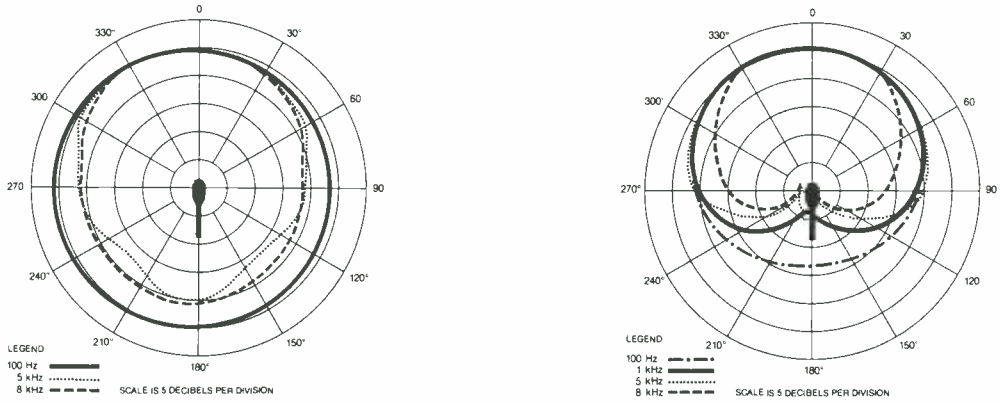


Fig. 7. Influence of proximity effect on a cardioid microphone



Typical Omnidirectional Pattern

Typical Unidirectional (cardioid) Pattern

Fig. 8. Polar patterns drawn at several frequencies.

drastically alter the perception of the mike's directionality if not examined closely.

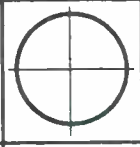
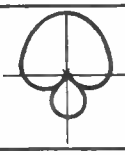
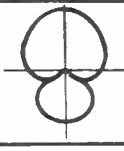
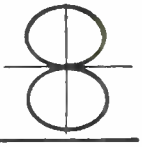
First, check to see whether the scaling is logarithmic or linear. A log scale (the most commonly used) will show a fairly modest inward curve of the cardioid pattern at 90 degrees, indicating a 6 dB drop in level. The linear scale polar for the same microphone will show a polar pattern that appears much more directional. The outside circle of the linear polar represents 100% while the center of the circle equals 0 output. Since a 6 dB loss is equal to a 50% drop in voltage, the polar curve at 90 degrees sweeps in to half the distance between the outside of the circle and its center.

Second, determine the graduations between concentric circles. Are the darker lines 5 dB or 10 dB apart? Finally, take note of the "dynamic range" of the polar pattern. This may be determined by counting graduation lines inward from the point where the polar crosses 0 degrees, in 5 or 10 dB steps (as marked) to the smallest inner circle. Polars may be found in most any range, with 25, 30, 40 db all being common. These differences will also alter the shape of a polar pattern.

Keep in mind that the polar pattern represents a cross-sectional, two dimensional diagram of a three dimensional function. The 131 degree arc, for example, that is described by the 3 dB down points on either side of the axis of the cardioid mike can really best be thought of as a conical area within which the mike is virtually uniformly sensitive. This area is often referred to as the mike's "angle of acceptance" or "included angle".

Omni Observations

The omnidirectional microphone is the easiest type to make. It consists of a diaphragm and gen-

CHARACTERISTIC	OMNI-DIRECTIONAL	CARDIOID	SUPER-CARDIDID	HYPER-CARDIOID	BIDIRECTIONAL
Polar response pattern					
Polar equation	1	$.5 + .5 \cos \theta$	$.375 + .625 \cos \theta$	$.25 + .75 \cos \theta$	$\cos \theta$
Pickup ARC 3 dB down (1)	—	131°	115°	105°	90°
Pickup ARC 6dB down	—	180°	156°	141°	120°
Relative output at 90° dB	0	−6	−8.6	−12	$-\infty$
Relative output at 180° dB	0	$-\infty$	−11.7	−6	0
Angle at which output = 0	—	180°	126°	110°	90°
Random energy efficiency (REE)	1 0dB	.333 −4.8dB	.268 −5.7d8 (2)	.250 −6.0dB (3)	.333 −4.8dB
Distance factor (DF)	1	1.7	1.9	2	1.7

NOTE:
1 = Drawn shaded on polar pattern
2 = Maximum front-to-total random energy efficiency for a first order cardioid
3 = Minimum random energy efficiency for a first order cardioid

Fig. 9. Microphone polar patterns and their characteristics.

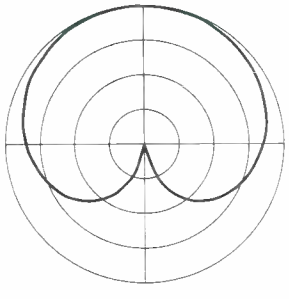


Fig. 10A. Cardioid log scale polar. Scale is 10 dB per division.

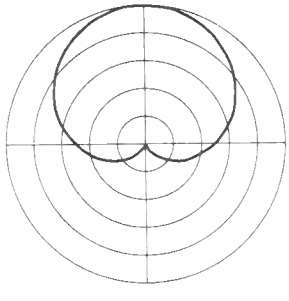


Fig. 10B. Cardioid linear scale polar. Scale is 10 dB per division.

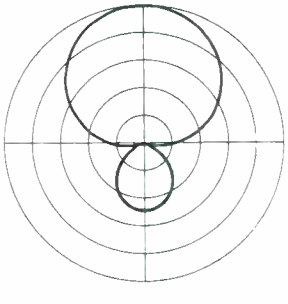


Fig. 11A. Hypercardioid linear scale polar. Scale is 10 dB per division. Dynamic range is 50 dB.

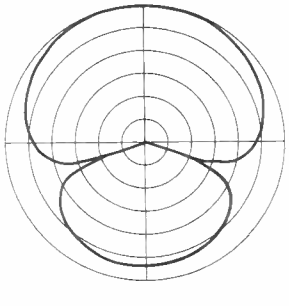


Fig. 11B. Hypercardioid log scale polar. Scale is 10 dB per division. Dynamic range is 40 dB.

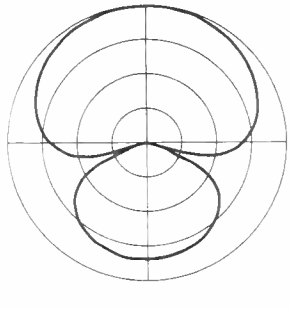


Fig. 11C. Hypercardioid log scale polar. Scale is 10 dB per division. Dynamic range is 60 dB.

erating element backed by a totally sealed case. When placed in a sound pressure field, the perfect omni disregards the direction of the sound's origin. A positive pressure (air expanding) at the diaphragm, for example, causes the diaphragm to move inward regardless of the sound's point of origin (Fig. 12). Such a microphone may also be referred to as a "pressure microphone."

So it would be with the perfect omni. Most omnidirectional microphones, though, are not truly omnidirectional. The case of the mike represents a barrier to the higher frequencies arriving from off-axis. So, due to this "case effect," most omnis are increasingly directional as the frequencies get higher. Likewise, the smaller the omni, the more truly omnidirectional it may be. In addition to case effect, energy arriving at the diaphragm from on-axis is reinforced at those frequencies to which the size of this baffle area is significant. This "baffle effect" causes a rise in the microphone's high frequency output, but only with respect to energy arriving on axis.

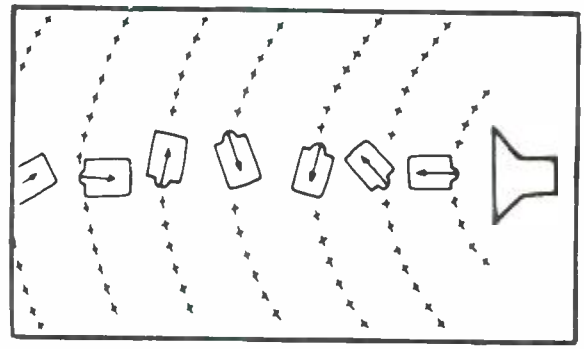


Fig. 12. Omnidirectional microphone principle.

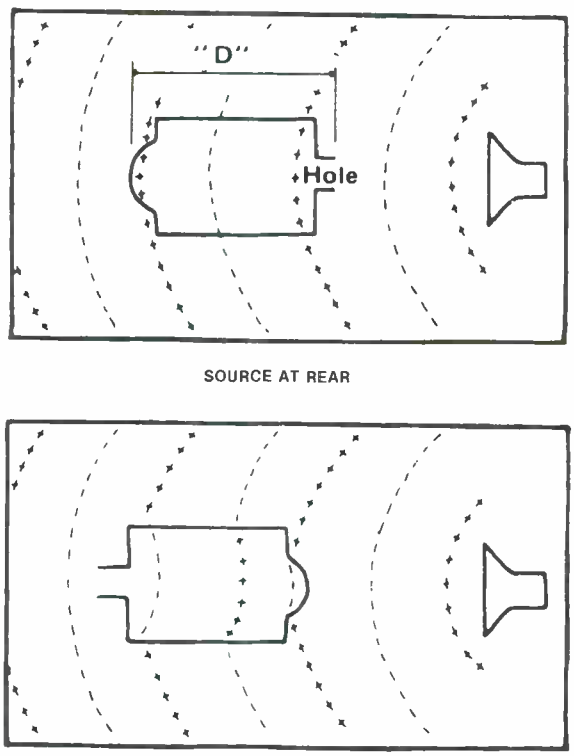


Fig. 13. Single-D cardioid microphone operating principle.

Cardioid Comments

The chart (Fig. 9) may be used to get some idea of how the various patterns should relate to the reference omni with respect to their ability to reject unwanted energy arriving from various points off-axis. A sound source which delivers 60 dB sound pressure level (SPL) to a cardioid on-axis from one foot away will "sound to the microphone" as if it has dropped in level to 54 dB, or been moved to two feet away, when the microphone is simply rotated to position the sound source at 90 degrees off-axis. Here a properly designed cardioid emulates well its mathematical model. At 180 degrees off-axis, however, the cardioid can't live up to its equation. The chart indicates 0 output. In reality, well designed cardioids are capable of significant cancellation at 180 degrees, but typically, more on the order of 20 dB or better.

Still, a 20 dB drop in the level of some unwanted noise may be enjoyed simply by turning the cardioid to face directly away from the noise. That's the equivalent of moving the sound source to ten times its actual distance from the microphone. Not bad.

The 180 degree response curves ("back curve") of many cardioid microphones show their tendency to more closely resemble omnis at both the low and high frequencies. The much more impressive cancellation in the midrange only is just the kind of temptation that sometimes causes a manufacturer to release a data sheet that shows one polar pattern only, and that at some unknown frequency.

Omni versus Cardioid

Compared to the omnidirectional microphone, the cardioid has several characteristics that should be noted:

1. The cardioid reduces the pick-up of ambient noise and reverberant energy. A look at the comparison chart shows that the "random energy efficiency" (RE) of the cardioid is .333 as compared to a RE of 1 for the omni. The random energy efficiency is a measurement that compares a microphone's sensitivity to random, or reverb-

erant energy to its on-axis sensitivity. While this shows the cardioid to be one third as sensitive to random ambient noise as the omni, remember that discreet sound sources positioned at the null of the cardioid will be attenuated to a much greater extent. This will prove true outdoors where sounds arrive at the microphone directly with minimal reflections. Indoors, the advantage of the cardioid's deep rear null is only appreciated when the microphone is situated within "critical distance" of the offending sound source. Up to critical distance, the direct sound is greater in intensity than the reflected energy; after that point, the two remain approximately equal.

2. The cardioid is more susceptible to the problems of "P-pop" (the blast of "plosives" such as "P" and "T" in speech), wind noise and handling or mechanical noise.

3. The cardioid is more complex to design and construct. Due to this fact, expect to pay considerably more, sometimes, for a cardioid microphone than for an omni of seemingly equal audio quality. The cardioid's more complex construction results in the omni often being the more rugged of the two as well.

4. The cardioid offers greater immunity to feedback in most sound reinforcement applications.

5. The cardioid increases the effective "working distance." The comparison chart lists a "distance factor" (DF) of 1.7 for the cardioid. This means that a cardioid microphone has a working distance advantage over the omni of 1.7:1. An ideal cardioid may be used at a distance of 1.7 times that of the omni for a given ratio of desired on-axis signal to ambient noise. A non-linear back curve will, of course, reduce the microphone's advantages in terms of working distance, gain before feedback, and rejection of ambient or reverberant energy.

6. The cardioid exhibits proximity effect. While some designs are quite low in proximity effect, all exhibit some of this bass-boost phenomenon when used close. This may be considered an enhancement in many close-miking applications. Care should be taken, however, to avoid input overload or loss of intelligibility that may result from excessive proximity effect.

Other Patterns

An examination of the chart will quickly show how the three other polars relate to the omni and the cardioid. The hyper-cardioid, for example, combines a tight acceptance angle with superior side rejection and offers the lowest RE. The result is a good pattern for distant miking such as is often required on a boom mount. Most short shotgun microphones approximate a hyper-cardioid pattern.

Notice that the bidirectional pattern offers the best side rejection but with no advantage over the cardioid in RE. Bidirectional microphones are typically ribbons or dual-diaphragm condensers. They are excellent for the pick-up of two sound sources in music or dialogue miking with no phase problems.

Compared to the omni, each of the directional patterns shares all six of the characteristics described above.

LIMITING THE WORKING DISTANCE

Sometimes it is not enough to reduce ambient noise merely through the choice of a polar pattern that offers the lowest RE. In very noisy environments such as may be encountered in an aircraft, on a battlefield, in a factory, or at a sporting event, it may be desirable to differentiate between close sound (an announcer, for example) and distant sound.

Those microphones which offer considerable proximity effect may be used to advantage in these situations. Close-mike the talent and roll-off the low end as needed to flatten the response.

In extreme situations, a noise-cancelling (differential) microphone may be required. The design of the rear ports and back damping systems of the differential microphone causes sound which originates in very close proximity to the front of the diaphragm to arrive in phase at the rear of the diaphragm, allowing diaphragm movement and maximum output. Sound arriving from a distance, however, strikes both sides of the diaphragm with equal intensity and out-of-phase, causing the signal to be cancelled. The noise-cancelling microphone is able then to differentiate between close and distant sound sources. The audio quality of such systems normally limits them to voice communications applications.

Inverse Square Law

The easiest, and certainly the cheapest, way to limit the apparent working distance of a microphone is by simply positioning the microphone very close to the sound source. Inverse square law tells us that every time we decrease the distance between the microphone and the sound source by one half we increase the SPL from the source at the microphone by 6 dB (Fig. 14). Because of the logarithmic nature of this phenomenon, the ambient noise level from more distant sources remains rather constant. As the input sensitivity control of the mixer or recorder is lowered to compensate for the additional 6 dB available from

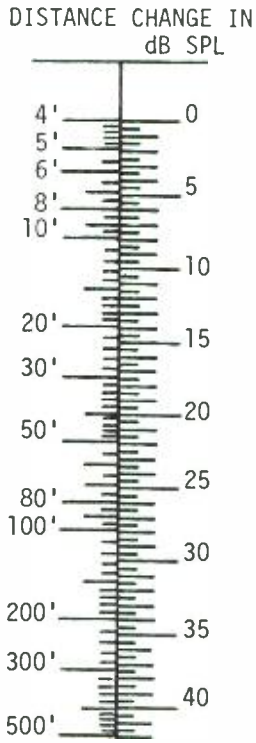


Fig. 14. Inverse square law.

the now-closer sound source, the microphone, in effect, becomes less sensitive to distant sounds.

Headset microphones

Headset microphones benefit from always remaining at a set distance from the talker's mouth. Background noise is reduced due to the use of inverse square law. Omni, cardioid and differential elements are available on headset systems. Cardioids offer the best combination of ambient noise suppression and acceptable broadcast quality.

GOING FOR THE DISTANCE

Shotgun microphones

Effective working distances beyond those afforded by cardioid, supercardioid or hypercardioid systems may be realized through the use of a shotgun or "line" microphone. The line microphone uses a slotted "interference tube" ahead of the element to provide a high degree of cancellation at the sides. Sound waves arriving on-axis are virtually unaffected by the tube. Sound arriving from slightly off-axis, however, is forced to turn and travel down the tube to the element. This results in numerous out-of-phase conditions being set up in the tube, with cancellation increasing as the microphone is rotated to 90 degrees. The length of the tube will determine the low frequency limit to which this cancellation can be effective. Below this limit, it is up to the capsule to offer the directional pattern for the shotgun microphone. All things being equal, longer tubes should maintain their cancellation at lower frequencies than short tubes.

Shotgun microphones tend to be much less uniform in their off-axis response than simpler, more conventional designs (Fig. 15). Even with their multi-lobed polar patterns, however, their very narrow acceptance angle can often save the day.

Shotguns work best outdoors and in controlled acoustic environments such as well designed studios. They do not function properly near reflective surfaces. Distant miking down a hallway will not be greatly assisted by the use of a shotgun microphone. A shotgun microphone pointed toward an open window will "see" all sounds originating on the other side of that window as if they are coming from a source the size of the window. No directional advantage will be realized other than to reduce, perhaps, the level of some nearby off-axis sounds originating from the microphone side of the window.

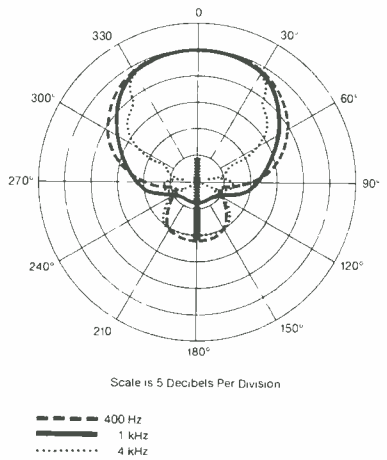


Fig. 15. Shotgun polars.

Acoustic Gain Devices

Shotgun microphones increase working distance by throwing away off-axis energy, thereby narrowing the acceptance angle. Some devices actually increase working distance by providing acoustical gain. Increased acoustical gain means less electrical gain is required and, therefore, less noise. Providing that a satisfactory signal-to-ambient noise ratio may be obtained, the improved signal-to-electrical noise ratio derived from the use of an acoustical gain device will in-

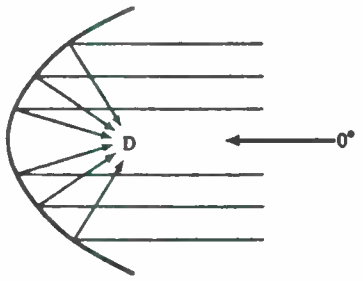


Fig. 16. Parabola principle.

crease the effective working distance of the overall system.

The most commonly used of the acoustic gain devices is the parabola or parabolic reflector (Fig. 16). The parabolic reflector is shaped so that sound is reflected onto a "focal point" a short distance in front of the center-point of the "dish". An omnidirectional microphone placed at this point receives multiple reflected sound waves in-phase which add together to produce significant gain. The response of such systems is very ragged and limited. Low frequency response is limited by the dish diameter. While totally unacceptable for most broadcast applications, the audio quality achieved with the parabolic microphone is often deemed adequate for sound effects pick-up such as at sporting events. In some situations, "acceptable" quality means the best level of performance possible through practical or affordable means.

A second type of acoustic gain device is the horn. Low cost re-entrant paging horns are often used for "talk-back" in paging systems. They can be quite directional and are extremely sensitive. Their audio quality as a microphone, however, is no better than as a loudspeaker. Horns are sometimes used as microphones in surveillance applications where natural sound is secondary to sensitivity and intelligibility. Installed on the side of a building, the small horn is virtually as inconspicuous as a light fixture and is seldom thought of as a microphone. Some horns are built with 45 ohm voice coils, providing higher output to microphone inputs.

Acoustic gain is also realized by using a microphone in the very-near vicinity of a large hard, reflective surface. Omnidirectional microphones may be flush-mounted into the barrier, facing out. In this position the microphone is in a "half-space" environment, or looking into only half the world. The output, for sound arriving on-axis, is increased by 6 dB. As the sound source is rotated off-axis, however, the microphone output drops. At 90 degrees off-axis, the output is down 6 dB, or equal to the omni in free space. The resulting polar pattern resembles a cross-section of a cardioid cut through the microphone at 90 degrees.

See the section on Acoustic Phase Interference later in this chapter for further details regarding surface mounting.

Frequency Response and Distant Miking

Distant miking may result in noticeable, or even dramatic, changes in the spectrum of the sound being recorded. High frequencies, attenuated by the air, may have to be boosted to restore a normal sound. Similarly, high-pass (low-cut) filters may prove helpful in reducing low frequency room reverberation or background noise, thereby extending the useful working distance. If possible, any boost in EQ should be done in the recording process to minimize noise that would be amplified in post-production equalization. Microphones with rising high frequency response or a rolled-off low end will reduce the need for EQ.

SENSITIVITY RATINGS

Certainly, one of the greatest sources for confusion on a microphone specification sheet has to be the sensitivity rating. Several different rating systems are currently in use.

Here are some figures to keep in mind when trying to interpret any of the ratings:

$$\begin{aligned} 10 \text{ dynes/cm}^2 &= +\ 94\ dB\ SPL \\ &= 10 \text{ microbar} \\ &= 1 \text{ pascal} \\ &= 1 \text{ newton/}cm^2 \end{aligned}$$

Open Circuit Output Voltage

Microphones are often specified to have a particular output voltage when looking into an open circuit. In most modern equipment, microphone inputs are at least 10 times the measured impedance of the microphone and may be regarded as an open circuit. Specifications may be given as an actual output voltage or as decibels below one volt at a sound pressure level of 74 dB (1 dyne/cm² or .1 Pa). These ratings are referred to as the "open circuit output voltage rating" or "open circuit sensitivity."

The open circuit sensitivity may be expressed in dB by means of the following formula:

$$V_{OC} = 20 \log E_O - \text{SPL} + 74 \qquad [1]$$

Where: V_{OC} = Open circuit voltage in *dB* (ref 1 *v*/0.1 *Pa*)
E_O = Microphone output in volts
SPL = Actual sound pressure level (in dB) at microphone

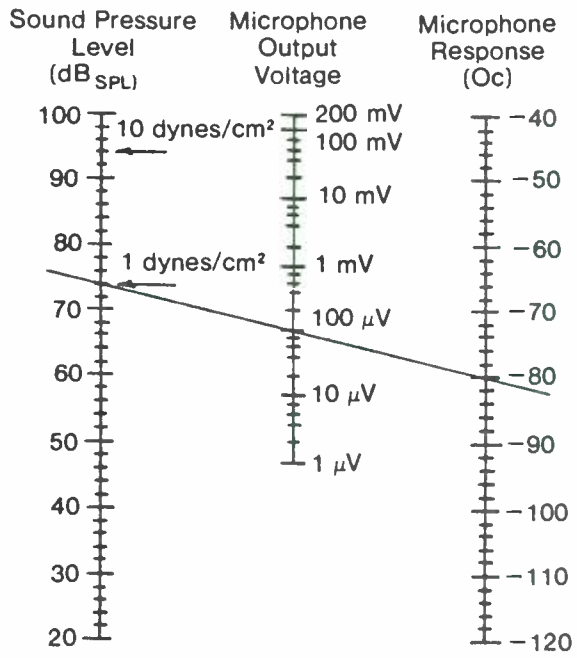


Fig. 17. Nomograph: open circuit voltage rating.

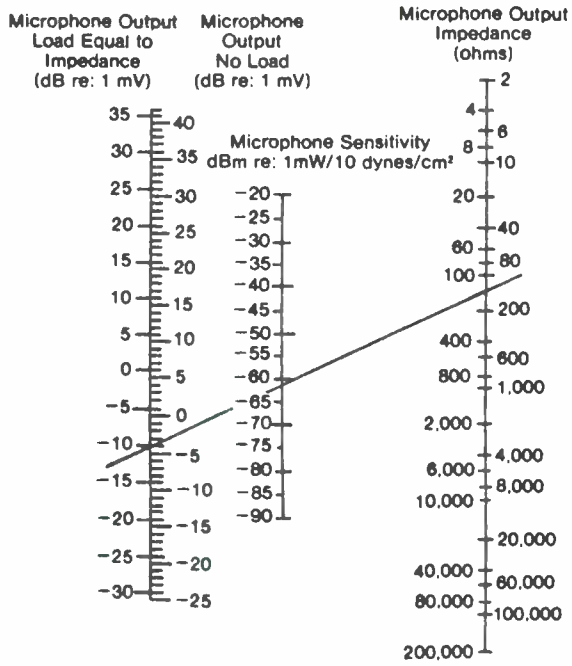


Fig. 18. Nomograph: equivalent power rating.

Power Level

A microphone's sensitivity may also be specified in terms of its output power level. This "equivalent power level rating" takes into consideration the open circuit rating and the actual impedance of the microphone. Specifications given would be in dBm (or just dB) referenced to 0 dB = 1 mW/10 dynes/cm² or 0 dB = 1 mW/Pa.

Calculating the power level rating may be done this way:

$$P_E = V_{OC} - 10 \log_{10} Z + 44\ dB \qquad [2]$$

Where: P_E = Equivalent power level
Z = Impedence of the microphone

EIA Sensitivity Rating

This is one of those "sometimes specified, hardly ever used" specifications. The formula for determining EIA sensitivity is as follows:

$$ESR = V_{OC} - 10 \log_{10} R_{MR} - 50\ dB \qquad [3]$$

Where: ESR = EIA sensitivity rating
V_{OC} = Open circuit voltage in dB
R_{MR} = Center value of the nominal impedance range

For R_{MR} you may use the following table:

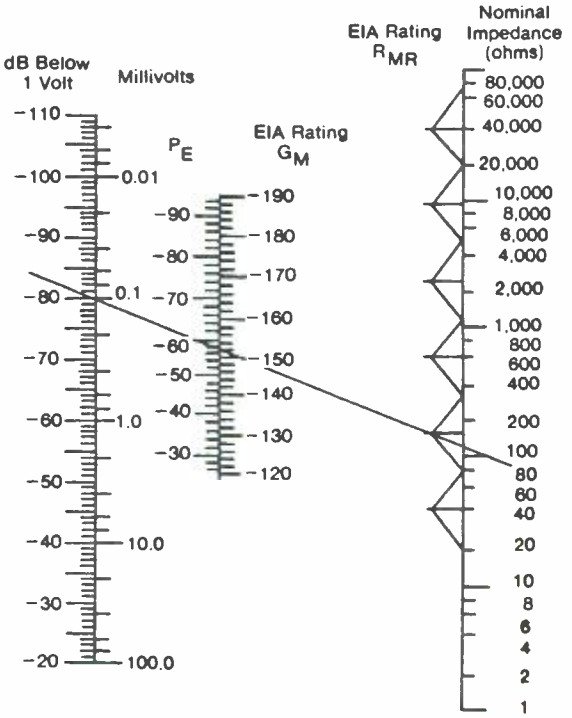


Fig. 19. Nomograph: EIA sensitivity rating.

RANGE		CENTER VALUE
20-80	(In Ohms)	38
80-300		150
300-1250		600
1250-4500		2400
4500-20000		9600
20000-70000		40000

Line-Level Microphones

The line-level microphone incorporates a microphone, preamplifier and power supply into one hand-held package. The system may also include a limiter. Line-level may be required to get the signal above the level of induced noise (see section on Hum Rejection), to overcome resistive losses in long cable runs or merely to level-match to a system that does not provide a microphone preamp at its input. A line level microphone is sometimes preferred over a separate microphone and preamp for simplicity of operation.

Applications may include operation into extremely long lines, into unshielded twisted-pair cable, phone lines, or into line-level inputs such as those often found on microwave transmitters. (Also see 6.1-3 on Telco connection.)

OUTPUT IMPEDANCE

The *impedance* (Z) of a microphone is a measurement of its ac resistance looking back into the transducer. Broadcast microphones are virtually all low impedance, ranging typically from 50 to 600 ohms. Dynamic moving coil microphones may achieve their low impedance by either a low-Z voice coil winding or a transformer. Condenser microphones use an impedance converter circuit to step-down the capacitor's high-Z output.

Low impedance offers the advantages of low susceptibility to hum and electrical noise pick-up and the ability to run relatively long lines with minimal level or high-frequency loss.

Unlike matching power amplifier impedances to speaker systems which may be desired for best power transfer, microphones like to see load impedances on the order of 10 times their internal impedance or even higher. This assures maximum voltage transfer. A microphone that looks like a resistive source of 150 ohms, looking into a load resistor of 150 ohms, for example, will suffer a 6 dB voltage drop as compared to an open-circuit connection.

DYNAMIC RANGE

The difference between a microphone's own "self noise" and the maximum SPL it can handle is its dynamic range. In field applications, ambient noise usually provides sufficient masking to make the self-noise spec of minor interest. The importance of this specification increases, of course, as greater working distances are demanded or ambient noise levels are lowered.

The impedance converter of condenser microphones, like any active circuitry, will create some noise. The degree to which it does so will vary greatly from one design to another. The impedance converter design also determines the "headroom," or maximum SPL that the condenser microphone can handle. A maximum SPL of as much as 141 dB is achieved in several high quality condenser microphones. Such levels may never be encountered by lavalieres worn at a news desk or seldom by shotgun microphones that are more often attempting to pick up weak audio signals.

Dynamic microphones contribute virtually no self noise. When greatly amplified, only the noise of the thermal agitation of air molecules is detected. While this is very low in level, the dynamic microphone does not automatically win the award for first choice in a low-noise system. Because the output level of the dynamic is often lower than that of a condenser system, the user may end up working into the noise floor of the preamplifier in order to provide sufficient system gain.

Properly designed dynamic microphones are practically impossible to drive to audible distortion. The distortion heard when a dynamic microphone is subjected to the lips-touching proximity of a blow-your-brains-out rock and roll vocalist is the clipping of the electronics following the microphone. Outputs of a volt or more may actually be delivered under such abuse as rock and roll or hog calls.

Preamp or amplifier clipping may be avoided through padding the microphone output or adjusting the "trim" (gain adjustment) of the mixer. Be aware that many mixers offer adjustment only after a gain stage or transformer, either of which may then distort before any control is possible. In-line attenuators, or "pads", are commercially available that allow the selection of 10, 20 or 30 dB of attenuation. These plug directly into the microphone line. They will not pass phantom power.

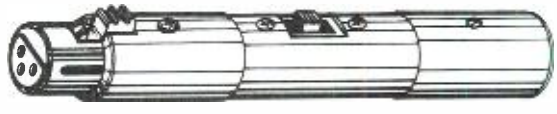


Fig. 20. Microphone in-line attenuator.

DURABILITY AND RELIABILITY

Modern day design and manufacturing techniques have provided the broadcaster with a variety of very durable microphone types. There are a few concepts that generally apply to a microphone design's potential for durability:

1. The moving coil dynamic system should offer more inherent durability than condenser or ribbon designs, although both of the latter systems have been employed recently in prod-

ucts that exhibit impressive improvements in durability.

2. Omnidirectional microphones are more easily built to be very durable than are more complex directional designs.

3. Internally shock-mounted microphones may present a compromise in durability relative to rigidly mounted, nested designs.

Reliability is influenced by a variety of factors including the original design, construction and quality control as well as the care that is taken in the use, transport, and storage of the microphone. Further discussion of this may be found in the last section of this chapter.

VOIDING AND AVOIDING NOISE PROBLEMS

This chapter has dealt already with improving the ratio of desired signal-to-ambient noise. Other unwanted signals include wind noise, "P-pop", mechanical or handling noise, ac hum and RFI (Radio Frequency Interference). The reduction or elimination of each of these can be handled through both proper microphone design and user technique.

RFI problems can usually be traced to a point in the low level circuitry at which the signal leads are unbalanced, Hi-Z or both. Condenser microphones, for example, may sometimes be sensitive to RFI at or around their impedance converter. In such an event, the manufacturer should be consulted for low-pass modifications or information.

P-pops may be reduced through several approaches:

1. Use an omni if possible. Directional microphones are much more prone to P-pop problems than are omnidirectional ones.

2. Position the microphone out of the "ground-zero" area of the breath blast. In an announce application, speak on-axis but at a slight angle to the diaphragm. Stand-ups and hand-held interview miking should be done with the microphone capsule below the axis of the mouth.

3. Use a "pop filter". This is often the same part as the manufacturer's windscreen. Avoid using foam filters that are not designed for the particular microphone model. If such a requirement arises, test the combination carefully for frequency response and directional characteristics before putting it into service. Windscreen/pop-filter foam is specially designed, reticulated foam which comes in a variety of densities. Even very acceptable open-cell foam may be too thick for use on some microphones. Non-reticulated foam (such as "nerf balls") will roll-off high frequency response and alter the polar patterns of directional microphones.

4. Fashion a pop filter. In an emergency, for radio and other off-camera miking, a piece of fabric such as silk may be suspended a short distance in front of the microphone diaphragm. This is often accomplished by using a wire ring for support. The fabric may be stretched loosely over the ring and the ring attached to an arm from the microphone or its support.

5. Use a high-pass filter. Most of the disturbing explosive energy of a P-pop is very low in frequency. Try using a very abrupt high-pass (low-cut) filter in the microphone line. Rolling this energy off before it gets to the board or recorder input will further serve to reduce harmonic distortion at higher frequencies.

Wind noise may be dealt with similarly to P-pop:

1. Omnis are preferred for low wind noise.

2. Use a properly designed windscreen. Most are made of reticulated foam. Superior results with shotgun microphones can be attained by using a well-engineered fabric/mesh cylindrical screen which provides an air space between the material and the microphone (Fig. 21). To handle severe cases (gale-force winds) special socks are available to wrap around the tubular windscreen. While this will result in some per-

Fig. 21. Zeppelin-type windscreen on shotgun microphone.

formance trade-offs, recordings made under such conditions are typically not intended for critical listening. Windscreens must cover all openings to the element: front and rear.

3. Use a high-pass filter.
4. A microphone with a limited low frequency response will help minimize wind noise. Extended response condenser microphones can produce very high outputs of infrasonic energy when panned or when air around them is moved by air handling systems, etc. The result may be preamp overload or undesirable compressor or limiter action. Again, windscreens and/or high-pass filters may solve these problems.

HANDLING OR MECHANICAL NOISE

The problem of mechanical, non-acoustic, noise is one that plagues the user, whether the microphone is hand-held or hardware mounted. The reduction of a transducer's sensitivity to such noise, or the improvement of its acoustic to mechanical-noise sensitivity ratio, starts with the basic element design.

First, omnidirectional microphones are lower in mechanical noise than comparable directional systems. Second, condenser microphones, because of their inherently lower diaphragm mass, are superior in this respect to dynamics. Also, as the size of a dynamic system is reduced, such as in dynamic lavalieres or some small hand-held systems, the acoustic sensitivity tends to go down while the mechanical-noise sensitivity may remain fairly constant.

When the resonant frequency of the microphone's mechanical sensitivity is low, a high-pass filter may be used.

Microphone elements are, of course, often internally shock-mounted by the manufacturer to avoid the transfer of noise from the case to the element. Lowest noise is achieved through the combining of omni or even omni condenser systems with internal shock mounts.

External shock mounts are often employed in stand or boom-mounted microphone applications. Properly designed shock mounts allow excursion on-axis, or perpendicular to the diaphragm plane. Excellent mechanical isolation may result from using an external shock mount on an internally shock-mounted microphone. Provided that the resonances of the two systems are dissimilar, they will stagger, increasing the effective isolation.

Another method of reducing mechanical noise is to raise the resonant frequency of the mechanical drive system. An example would be that of

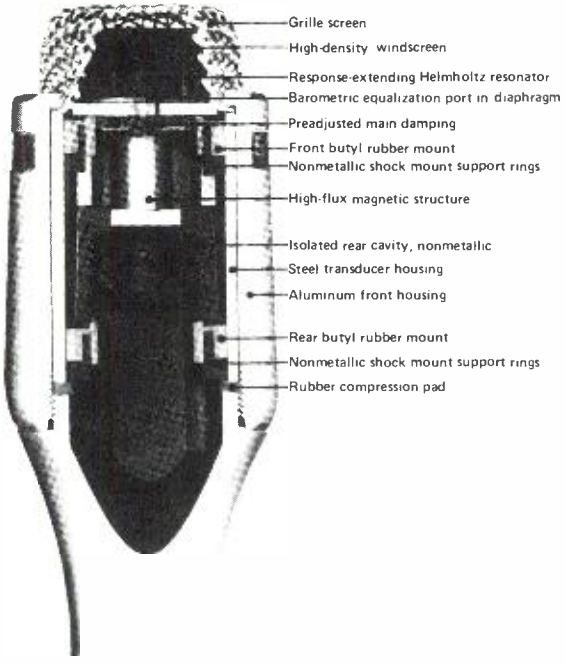


Fig. 22. Cutaway of shock-mounted omni.

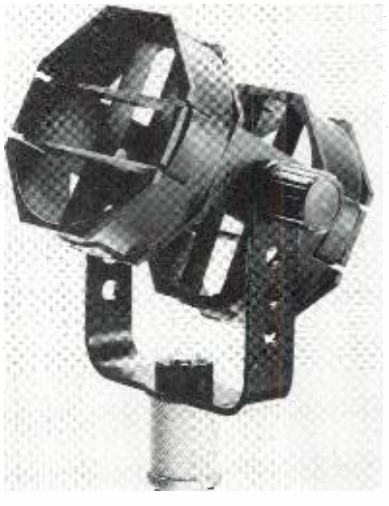


Fig. 23. An external shock mount.

bracing wooden platforms, tables or lecterns to eliminate the very audible "drummy" sound produced when struck. The use of very high-density materials for microphone support systems will result in a higher resonant frequency. A mike stand set onto concrete or into sand gains the advantage of this density.

Mechanical noise transfer to the diaphragm may also be reduced through decoupling the diaphragm from tensile forces, converting these to lateral forces. This may be illustrated as follows:

Select a microphone that has some noticeable handling noise problems and plug it into a talk-out system, raising the gain until the handling noise is evident. Now hold the microphone face up (diaphragm horizontal) with the cable hanging straight down and tap on the cable. You should hear a low thump. Next rotate the microphone 90 degrees so that the cable is hanging at a right angle to the microphone axis. Tap the cable again and the thump should be all but gone.

The mechanical drive that takes place longitudinally on the cable is no longer able to easily drive the diaphragm in the direction of its compliance. Handling noise output, therefore is greatly reduced. This principal may be applied to such areas as your own hardware designs and the dressing of cables as they enter stand or boom-mounted microphones. A loop of cable or a small coiled cord lowers mechanical noise transfer by this method. Direct interconnection of boom cabling and a shock-mounted microphone can create a direct mechanical short between the two, by-passing much of the shock mount's effectiveness. A coiled cord may be employed between these two points to eliminate this direct path.

AC HUM REJECTION

Microphones may also be sensitive to noise induced in them and their cables by electromagnetic or electrostatic radiation. This may be the result of their proximity to power transformers, fluorescent ballasts, high-voltage ac lines, SCR dimmers, etc. The following points should be considered in attempting to avoid or eliminate induced ac hum:

1. Insure that lines are balanced low impedance. The higher the impedance of the microphone, the greater will be the voltage of the electrostatically induced hum. The balanced line insures that nearly equal hum will be induced on each conductor. Little differential is seen, then, at the amplifier input to amplify, resulting in "common mode rejection" of the hum. Pins 2 and 3 of the 3-pin microphone connector should carry the signal, with pin 2 most often "high." This would mean that positive pressure on the diaphragm produces a positive voltage on pin 2. The shield connects to pin 1 (ground).
2. Route cables with caution. If possible, do not run low-level cables near high-voltage lines, avoiding especially long parallel runs of adjacent microphone and ac power cables. When such cables must cross, they should do so at right angles.
3. Use twisted pair cable. Leads should be twisted inside the microphone and out. The virtually identical positioning this provides them within any hum field and the fact that they are out-of-phase with each other will further insure electrostatic hum cancellation.
4. Use well shielded cable. Installed cable may utilize a foil shield as flexibility and low flex "memory" is not a factor. Good stage and field cable, though, normally has a braided shield. Some of the cables which offer the best combinations of flexibility and good shielding utilize conductive cloth or conductive vinyl under the braided shield.
5. Follow good grounding practices, avoiding ground loops.
6. In general, dynamic microphones are much more apt to be sensitive to induced hum than are condenser microphones. The voice coil can be a very effective inductor. "Hum-buck coils" are employed in some designs which lower electromagnetic hum sensitivity by about 20 dB. The hum-buck coil is wrapped around the outside of the motor mechanism and wired in series with the voice coil but out-of-phase. When both coils are placed into an electromagnetic field, equal energy is induced onto each. Because they are out-of-phase with each other, the offending signal is cancelled.
7. Transformers in microphones should be avoided if electromagnetic hum is a possible problem. Some transformers are constructed with hum-bucking characteristics, however, to greatly reduce their hum induction potential.
8. In severe problem situations, operation at line level rather than microphone level may be required.

ACOUSTIC PHASE INTERFERENCE

Another miking problem relates not to sounds that are added to the output, such as popping or hum, but to portions of the spectrum that are greatly attenuated. This change in the microphone's apparent frequency response is due to acoustic phase cancellation. Acoustic phase cancellation may occur when two or more microphones are mixed, or even when a single microphone is subjected to an overdose of reflected sound. Figs. 24A-24E show the severe phase cancellation problems that can result from several typical miking situations.

Although sound arriving at each microphone is identical, originating at the same source, it arrives at the two microphones by paths of varying lengths. This causes a difference in the arrival times and results in phase cancellation of certain

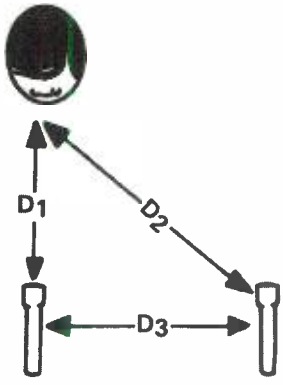


Fig. 24A.

frequencies. The curves given for each of these examples are FFT (Fast Fourier Transform) derived displays of the actual frequency response of the two microphones combined, with respect to a sound source positioned as shown. The FFT analyzer and its companion microprocessor were used to compare the combined output of two matched, calibrated microphones to the output of one of the two microphones by itself. If no phase cancellation occurred, no trace variations would appear on the X/Y plot, as its plot would be a straight line.

It doesn't take much study of the response charts to show that, no matter which way we have oriented the microphones and our sound source, the summed response of the two mikes is awful. These experiments reveal quite graphically what the ear often perceives as a comb-filter or notch-filter effect that sweeps up and down in frequency, and even changes Q, as the variables *D1*, *D2* and *D3* change with the movement of the microphones or sound source. In more subjective terms, the resultant sound may be described as hollow, as if the sound is being forced through an empty cardboard tube.

Unfortunately, situations that cause acoustic phase cancellation arise quite frequently. One classic example occurs on a podium with a pair of microphones, spaced apart to provide on-mike coverage as the speaker turns his head to address all of the audience in front of him. The curves shown in figures 24B and 24D are typical of the problems caused by this approach. If the output of these two microphones is summed and fed simultaneously to a house sound system, there probably will be gain-before-feedback problems, as well. Add the insistent creeping oscillation of a system on the brink of exceeding unity gain to the already intolerable frequency response of the microphone pair, and you'll have the quality of sound that makes the audience check the credits to see who handled the audio.

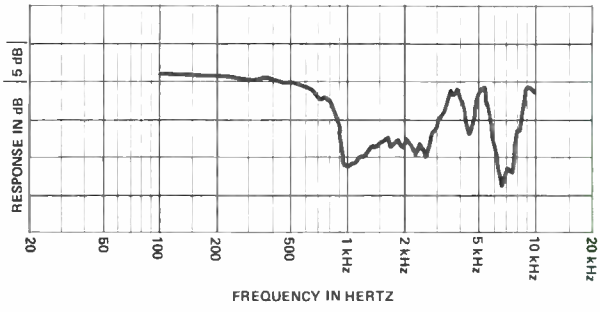


Fig. 24B. $D_1 = 12''$, $D_2 = 21.6''$, $D_3 = 18''$

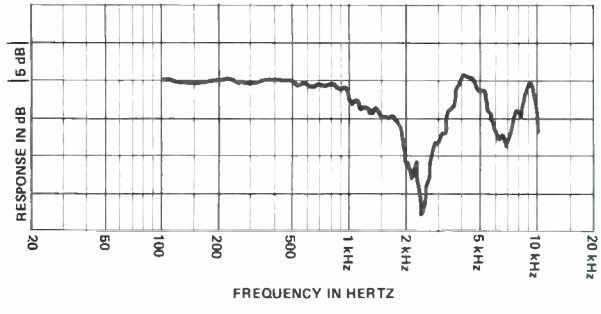


Fig. 24C. $D_1 = 18''$, $D_2 = 21.6''$, $D_3 = 12''$

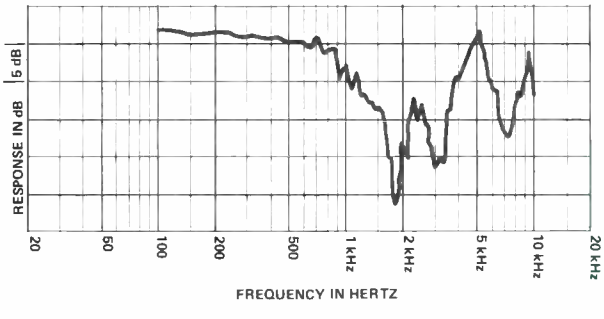


Fig. 24D. $D_1 = 24''$, $D_2 = 30''$, $D_3 = 18''$

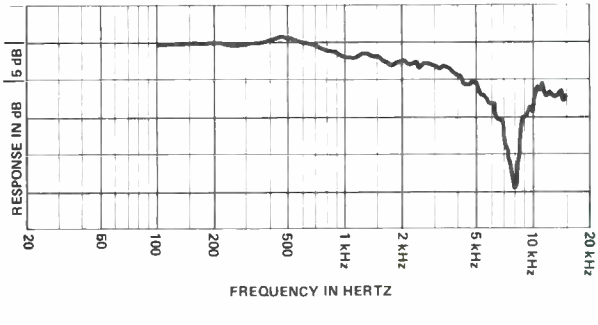


Fig. 24E. $D_1 = 5.6'$, $D_2 = 6'$, $D_3 = 2'$

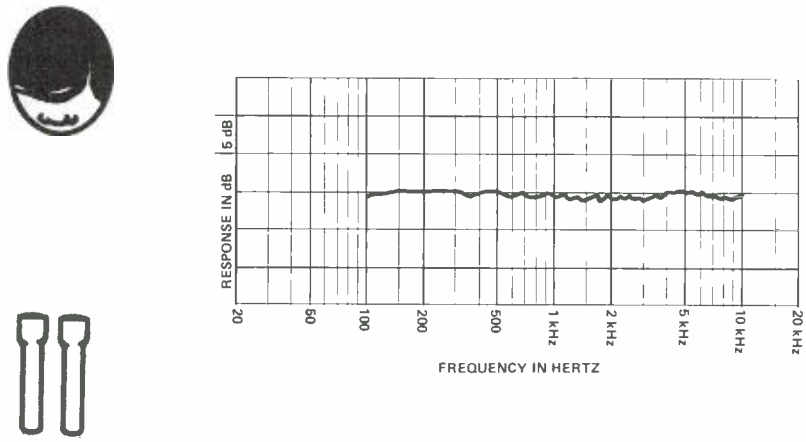


Fig. 25. Redundancy miking.

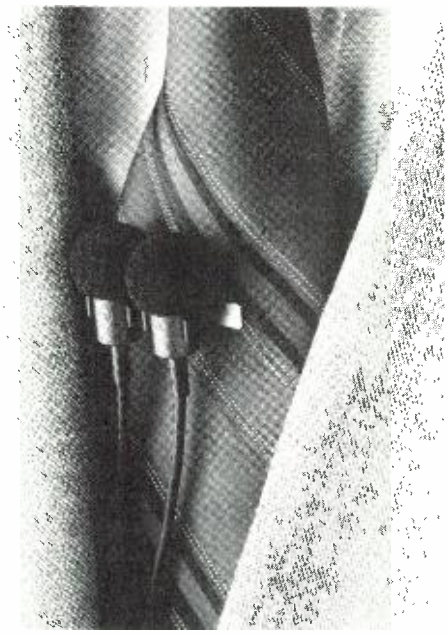


Fig. 25. Redundancy miking.

The simplest solution to the problems caused by this spaced-pair podium miking technique is to use one microphone only, placing it in front of the person speaking and toward the center of the podium. Fig. 25 shows two microphones immediately adjacent to each other. This type of positioning is often employed where redundancy miking is desired for critical applications. Normally, only one of these microphones would be "open" at a time. The second is strictly a back-up system. Sometimes the two mikes are used to feed separate systems, such as for house PA and broadcast. Each may still be used as a back-up for the other.

Adjacent pairs of cardioid microphones may at times be angled inwardly with their axes crossed and their diaphragms closely spaced. This may be done in order to broaden the acceptance angle of the two mikes while still maintaining some cancellation at the rear. The microphones' close proximity allows their diaphragms to occupy nearly the same point in space, thus reducing sonic time path differences. This ensures that negligible phase cancellation will occur should their output be summed. The same formation is often used as a 2-mike stereo pick-up technique, which has the benefit of good mono compatibility.

Obviously, there are many times when the outputs of two or more open microphones must be mixed. How do we then avoid phase cancellation? The phase cancellation problems we have been discussing occur when identical signals, at the same or nearly the same amplitude, are allowed to combine at something other than zero phase angle. We have shown the result of reducing phase angle error by placing the two pickup elements close together. We can also influence the amplitude difference between the two combined out-of-phase signals through careful microphone placement. A good "rule of thumb" to follow in microphone placement is called the "3:1 Ratio Rule."

To eliminate the problems demonstrated in Figures 24A-24E by employing the 3:1 Ratio Rule, *D3* must always be at least three times *D1*. Fig. 26 shows examples of both the violation and enlistment of the 3:1 Ratio Rule. Subjective tests have shown that an amplitude difference of at least 9 dB between the two signals will reduce the phase cancellation to an inaudible level. The 3:1 Ratio Rule is a means by which this 9 dB minimum difference may be approximated quickly in most multiple microphone set-ups.

The amplitude variance desired may also be achieved by judicious use of the mixer's gain or fader controls. Only those microphones in actual use should be opened to their normal operating levels; others should be lowered in level or preferably off. Attentive monitoring on an ac-

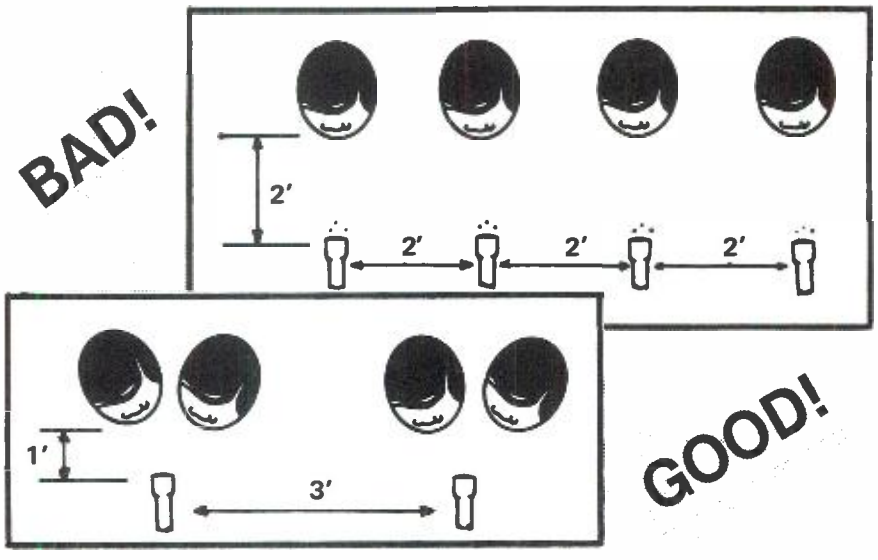


Fig. 26. Violating and obeying the 3:1 ratio rule.

curate control room speaker system will reveal audible phase problems, especially in relatively simple program sources such as speaking voices or most solo instruments.

Acoustic Phase Cancellation with a Single Microphone

Acoustic phase cancellation can also occur in a single microphone system when reflected energy from a nearby barrier such as a music stand, podium, table or floor is introduced at the microphone's diaphragm at a sound pressure level that is within 9 dB of the direct sound. Such problems may be avoided by four different means:

1. Increase the reflected path length.
2. Shorten the direct sound path length.
3. Reduce the reflectivity of the barrier. It may be possible to construct or cover the barrier with an acoustically absorptive material or construct the barrier of an acoustically transparent material. The latter may be used for opaque screens used in chroma keying to eliminate, for example, reflections into a weather person's lavaliere.
4. Position the microphone so close to the barrier surface that the direct and reflected sounds arrive at virtually the same time, causing them to be in-phase.

The latter method also results in a higher microphone output because of the additive effect of the two in-phase signals. As was discussed in the section on acoustic gain devices, the microphone is operating in or nearly in a half-space environment. This barrier miking technique may be employed with omnidirectional or directional elements. The omni may be recessed flush into the surface facing out for best performance. Some of the earliest use of the near-barrier technique was with the Electro-Voice Mike Mouse, an acoustically transparent foam holder which positions the mike inside (usually a cardioid) very close to the barrier, with the diaphragm perpendicular to the surface.

The results of barrier miking will vary due to the following influences:

1. The size of the barrier. (The barrier must be large to support low frequency response.)
2. The size of the diaphragm. (Very small diaphragms may be positioned extremely near the barrier, resulting in less high-frequency cancellation.)
3. The reflectivity and resonant characteristics of the barrier.
4. Ambient noise or reverberant energy problems.
5. Reflections from other nearby reflective surfaces.

MICROPHONE POLARITY REVERSAL

Phase cancellation will also occur if the outputs of two microphones, positioned in the same sound field, are combined with their polarities reversed (i.e. pins 2 and 3 are reverse wired at one end of one cable). The frequencies cancelled, and the degree to which cancellation will occur, will depend upon how far apart the microphones are spaced, how closely matched their frequency

responses are and the relative levels of the two mixed signals. It should be noted that the terms "phase" and "polarity" do not mean the same thing. Phase refers to a time difference. Having noted this distinction, in common usage, the terms "in-phase" and "out-of-phase" are often used to refer to matters of polarity. Most microphones will be wired to what is sometimes called the "RCA pin count" which is:

PIN #1 = SHIELD
PIN #2 = HIGH
PIN #3 = LOW

This conforms to IEC standard 268-12 and 268-4. Refer also to RS-221 paragraph 3.3 which states that the in-phase terminal should be the red (or other than black) conductor and that the out-of-phase terminal shall be the black conductor. The terms "in-phase terminal" or "high" (pin #2) indicate the terminal that has a positive voltage present when a positive pressure is applied to the microphone diaphragm. While there are commercially available devices which use a pulse generator to check for polarity reversal, microphones and their cables may also be checked by simply bringing them together and summing their output while speaking into them from a foot or so away. Two mikes which are "in-phase" will deliver a higher output under such a test; if they are reversed in polarity, the output should drop noticeably.

Polarity Reversal as a Tool

While inadvertant polarity reversal in a mike line can result in some very bad audio, deliberate polarity reversal is sometimes employed as a problem solver.

Reducing Background Noise

A pair of mikes may be reversed in polarity to reduce the pick up of ambient noise. This technique is sometimes employed with two mikes in fixed locations, such as in a press box at a sporting event. If these mikes are brought together, a noise-cancelling or "differential" microphone is created. The talker must now speak into one of the mikes only, virtually in a lips-touching position. Due to inverse-square law, the amplitude of the voice at that microphone will be much greater than at the other, resulting in reasonable output level. Distant sound will be picked up equally well, however, by both elements and cancelled.

STEREO MIKING

When miking for stereo broadcast, it is of utmost importance to provide high quality stereo audio without compromising mono audio quality. This all-important mono compatibility normally excludes the use of spaced-pair microphone techniques involving omnidirectional or cardioid microphones. Coincident microphones can provide good stereo and with no phase cancellation problems in mono. Spaced microphones depend upon a combination of amplitude and timing (phase) differences to provide stereo separation. They do not sum well for mono as the very phase differences upon which they depend, to a great extent, to provide separation result in multiple comb filter effects in the mono mix.

Mid-Side Coincident Technique

The most useful of the types for stereo broadcasting is the M-S or "Mid-Side" microphone. Dependent only upon amplitude differences for stereo separation and imaging, the M-S microphone provides excellent stereo imaging and maintains total mono compatibility. The M-S microphone is a combination of a "Mid" microphone, which is typically a cardioid, a bidirectional microphone and a matrixing network which combines their outputs. Sound originating from directly on-axis of the M-S mike will be picked up by the M element but not by the S, typical of bidirectional systems. As the sound source moves off the center axis, one side of the bidirectional mike becomes "positive" relative to the other and, therefore, adds its output to the M signal with which it is in-phase. The result is a smooth transition from left to right and total mono integrity.

Three cardioid microphones may also be employed to perform the M-S function (Fig. 27). The outputs of the mikes, with one of the two opposing cardioids' polarity reversed, should be sent to a mixer. There the Mid mike may be

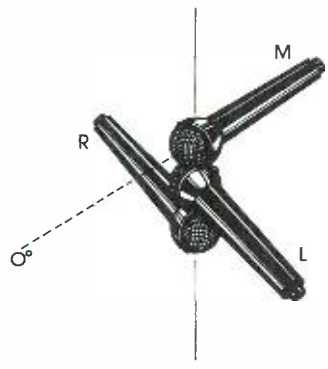


Fig. 27. Three cardioids used as an M-S microphone.

right. The M-S technique offers several control capabilities:

1. Adjusting the relative levels of the M and the S signals will narrow or broaden the perceived stereo image.

2. Panning the M signal off-center may be done to deliberately shift the stereo image. For example, crowd noise at a sporting event may be shifted to appear more closely balanced left and right of a mike position without moving either the mike or several thousand fans.
3. Substituting various patterns, from omni to hypercardioid, for the Mid microphone will affect the apparent mike-to-sound source distance as well as the signal-to ambient or reverberant-noise ratio.

Each of the first two of these controls may be exercised in production or post production: another big bonus.

Blumlein Miking

The Blumlein technique employs crossed bidirectional elements and responds, like the M-S, to amplitude differences to achieve stereo separation. The stereo sound achieved by this approach can be very natural and mono integrity is well maintained. The Blumlein is more sensitive, however, to ambient noise and reverberation than the M-S and placement is critical.

CARE AND FEEDING

Microphones require a certain amount of care in their handling and storage. Here are some basic factors to consider and tips on microphone care. Misuse, or even some attempts to service or clean the microphone, could affect some manufacturers' warranties. When in doubt, ask or return mikes to the manufacturer's recommended service organization for maintenance.

1. Use windscreen or pop filter to protect microphone if it is to be subjected to air-borne contaminates such as dust or smoke.
2. A foam windscreen will also protect a mike from exposure to rain or snow for a surprising period of time. Over time, the cells will fill with water resulting in high-frequency loss and level drop. The foam may be quickly squeezed to reduce the moisture content or a dry screen substituted as required.
3. Foam windscreens will accumulate deposits of dust and other contaminates. The result will be a deterioration of frequency response and, perhaps, even altered polar response. Foam may be cleaned with soap and water. Rinse well to remove all residue. Nondetergent soaps work well.
4. Many mikes may be carefully opened to remove a foam pop filter and sometimes a cloth insert. Do so only in a very clean environment. These filters should be cleaned as above.
5. Avoid allowing dynamic microphones to be set on work benches or other areas where metal particles or metallic dust may be attracted to their internal magnet structures. Very small particles can work their way onto the diaphragm and alter the response greatly. In some cases, the dynamic mike can be opened to reveal the diaphragm for examination. Metallic particles may be *very* carefully removed onto the magnetized tip of a screwdriver. The screwdriver shaft should be steadied on the edge of the mike case and the tip very carefully lowered to attract particles which would likely be held immediately above the voice coil gap.
6. Avoid subjecting electret condenser microphones to high temperatures. This means do not store in the trunk or glove compartment of a car left in the sun on a hot day. Also avoid leaving the electret mike on a boom very close to hot lights. The result may be a loss of charge on the capacitor element and a drop in level.
7. Avoid moisture with all mikes but especially with condenser microphones.
8. If given a choice between using mercury or alkaline batteries to power a microphone, remember that mercury cells die much more suddenly than alkalines. The gradual drop in level with an alkaline can be a life saver; no one likes surprises. Mercury batteries also drop in output level in cold weather. Furthermore, mercury batteries may give off a gas that can corrode the contacts.
9. Avoid unnecessary mechanical shocks. Store in clean padded enclosures.
10. Moving a condenser microphone from a cold environment to a warm one may cause noise problems from condensation.
11. Avoid moisture in cables and connectors, particularly where phantom power is being used.

SUGGESTED READING

For further information on microphones, the author suggests the following sources:

Audio Cyclopedia, Howard M. Tremaine, Howard W. Sams & Co., 1974

Sound Recording, John Eargle, Van Nostrand Reinhold Co., 1976

Microphones: Design and Application, Lou Burroughs, Sagamore Publishing Company, Inc., 1974

Microphones—2nd Edition, Martin Clifford, Tab Books, Inc., 1982

Layman's Guide to Microphone Specifications, James Long, Audio Magazine, August 1969

The Microphone Handbook, John Eargle, Elar Publishing Company, Inc.

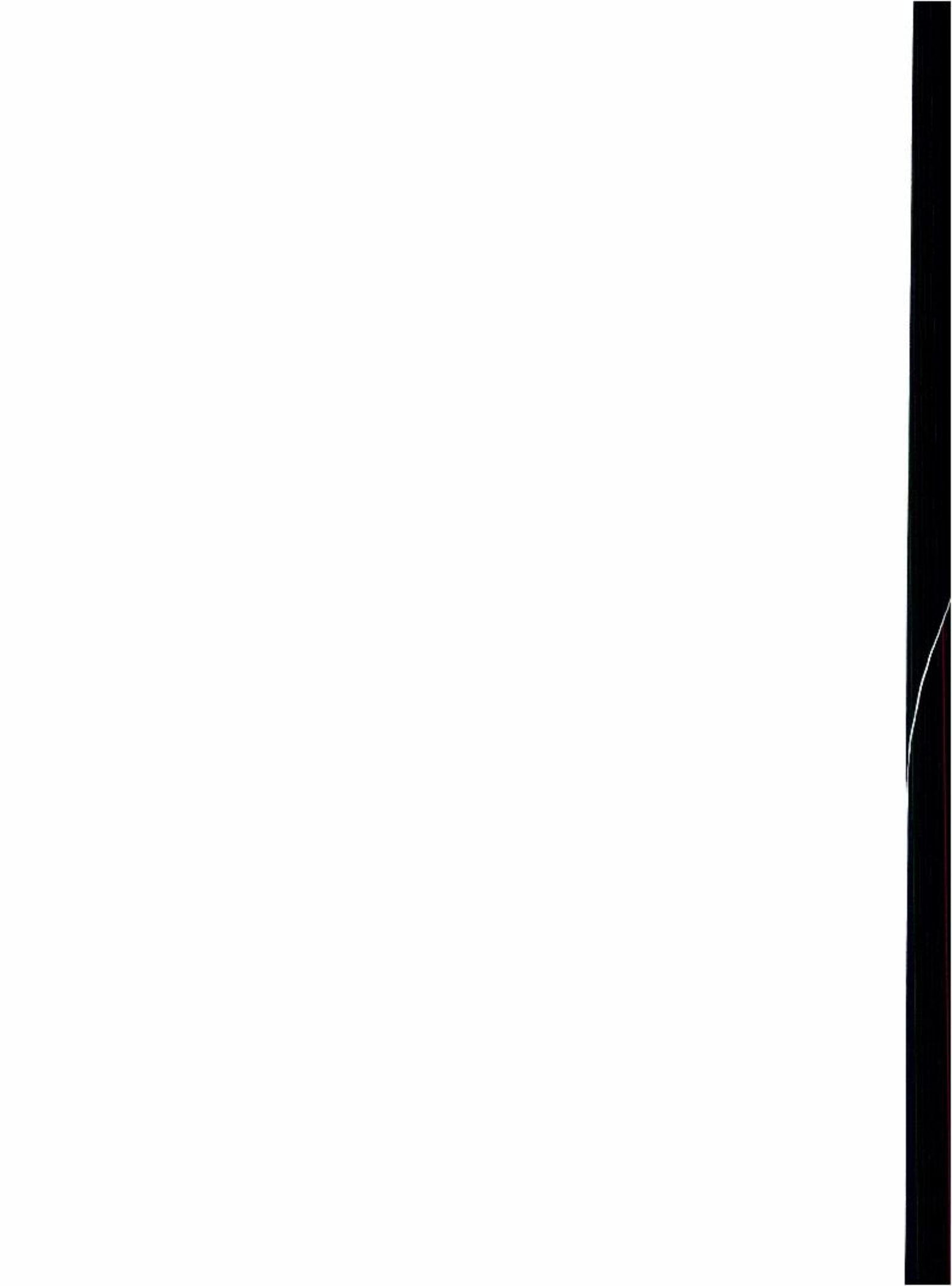
The Recording Studio Handbook, John W. Woran, Elbar Publishing Company, Inc., 1982

Microphones, Jon R. Sank, J. Audio Eng. Soc., Vol. 33, No. 7/8, July/August 1985

Modern Sound Reproduction, Harry Olson, Van Nostrand Reinhold Co.

Sound System Engineering, Don and Carolyn Davis, Howard W. Sams & Co.

Microphones: An Anthology of articles on microphones from the pages of the "Journal of the Audio Engineering Society", Audio Engineering Society



Chapter 1: Radio Field Production
Chapter 2: Microwave Electronic News Gathering
Chapter 3: Television Field Production
Chapter 4: Telephone Systems and Interfacing

SECTION 6: REMOTE PROGRAM ORIGINATION

6.1

Radio Field Production

Jerry Whitaker
Editor
Broadcast Engineering Magazine
Overland Park, Kansas

Radio stations have used the remote location broadcast for decades to bring the listener an added sense of realism and excitement. Although the concept of the remote—as it is better known—has not changed substantially over the years, the means to accomplish the task has been quantum leaps in performance, ease of operation and reliability. Radio Electronic News Gathering (RENG) systems of today can be configured to provide virtually any degree of sophistication required by the station. As with any other area of broadcasting, the key to a successful RENG system is thoughtful planning.

PLANNING THE NETWORK

The importance of careful planning of a RENG system cannot be over emphasized. The network should be configured based on the precise needs of the station. All persons that will be involved in the use of the system should be consulted to determine just what type of arrangement will be needed. Whether a station's format is "all news" or, "AOR," all persons in the news, production and engineering departments should sit down and define the requirements of the network. Whatever is heard at such gatherings, resist the urge to be negative when someone asks for a level of performance that is not practical. Hear everyone out. Even though the engineers present at the meetings may know that it is impossible to provide every reporter on the staff with a separate frequency that can be received at the studio from anywhere in town, at least listen to what the users would *like* the system to do. The realities of station economics and the laws of physics can be explained after the desires of the participants have been outlined. Many—perhaps most—RENG systems were built on a piecemeal basis, as needs dictated and economics allowed. The lack of a unified plan has often lead to RENG systems that are cumbersome to operate and—in the long run—more expensive than necessary to build for a given level of performance.

The size and layout of the station's market will have a substantial effect on how the RENG network is designed. A system intended to cover a sprawling urban area of 10,000 square miles will be configured much differently than a tightly clustered urban center covering 2,000 square miles. The number of stations in the market that are involved in RENG activity may also affect how a system is designed, and what types of equipment are used. Stations in major metropolitan areas may find that few, if any, frequencies are available for RENG activity.

Additional information for this chapter was provided by Richard A. Rudman; Engineering Manager, KFWB Radio; Los Angeles.

Program material can be returned from the field to the studio though either of two common routes—wired telephone lines or wireless transmission systems of various types. The route back to the studio will depend upon a number of factors, including the location of the event, the availability of telephone lines, the amount of set-up time provided and the duration of the broadcast.

Wired vs. Wireless

Until the 1960's, the word "remote" was rarely spoken without reference in the same sentence to "the telephone company." Wired systems, either using the dial-up network or leased broadcast loops, provided the vast majority of interconnections from remote broadcast sites to a station's studio facilities. Since that time, however, radio systems have assumed an important role in remote activities because they inherently offer greater flexibility and generally provide the user with a higher-quality audio link.

Radio systems are ideally suited for broadcasts of relatively short duration from a variety of locations (during the course of a week's time). Meetings, speeches and sporting events, however, are probably best handled by a wired arrangement. The amount of frequency congestion in the origination area will also have an effect on which method a station will choose for the greatest reliability. Urban areas in which secure RPU channels are difficult to find may be best-suited to a wired link.

The amount of lead-time given the station before various events that need to be covered will also have a significant effect on the route taken by the program audio back to the studio from the remote site. Broadcasts that are scheduled weeks in advance are obvious candidates for use of a telephone company loop. Spot news events, on the other hand, do not lend themselves to planning days in advance, let alone weeks in advance. In such applications, therefore, a radio system is most practical.

The cost of telco facilities must also be considered. Unless the loop is to be left in place for a long period of time, installation charges can become prohibitive, especially if high-performance equalized lines are needed for the application. Many stations are able to justify the cost of a RENG radio system based solely on the telco savings that can be anticipated.

This discussion does not mean to imply that stations should choose between *either* a wired link or a wireless system. Large-scale systems are often built using both interconnection methods, either as various links in the chain or as back-up protection, in the event of a partial system failure.

WIRED SYSTEMS

Wired communication systems for news, sports or programming can take a number of different forms, from basic telco equalized loops to sophisticated single or multi-line frequency extension systems using the dial-up network. An equalized line offers the user a simple, reliable link to the studio. The drawbacks include inflexibility, installation lead-time and installation or rental costs. Using the dial-up network gives the user a greater degree of flexibility than with standard equalized loops, however the level of performance (when a bandwith extension system is *not* used) leaves a great deal to be desired. The most popular way around this problem is through the use of a 2-line frequency extender system, as illustrated in Fig. 1.

There are a wide variety of extension methods, each with a different way of accomplishing the task. Generally speaking, however, audio from the remote source is split into two frequency bands by a filtering network. The higher frequency components are shifted lower by a conversion circuit for application to the telephone company dial-up network. The lower frequency components are shifted upward by a second conversion circuit and applied to a second telephone line.

At the studio demodulator end, the two signals are frequency-shifted back to their original values, filtered and re-combined to form the output of the system. Variations on this method include the use of single or multi-band compressors, variable equalization and compandor circuits. The use of audio compression at the transmitting (remote) point, and reciprocal expansion at the receiving (studio) end, can provide a substantial reduction in apparent line noise.

An interesting application of a single-line encoder/decoder is shown in Fig. 2. Audio from a news or sports story is recorded at high speed on a two-speed tape recorder. When the material is fed to the station, the low speed is used and the recorder output is fed through a single-line bandwidth extension system. At the studio end, the feed is recorded on the low speed of another 2-speed machine. When the program material is played back on high speed at the studio, an effective doubling of frequency response at the high end is achieved. With this arrangement, it is thus possible to squeeze a signal bandwidth of 100 Hz-5 kHz through a single dial-up telco line. Companding circuits, if used in the bandwidth extension unit, will also improve the line's apparent signal-to-noise (S/N) performance.

Setting Up a Wired Remote

If a wired remote is chosen for a particular broadcast, the station has a number of options

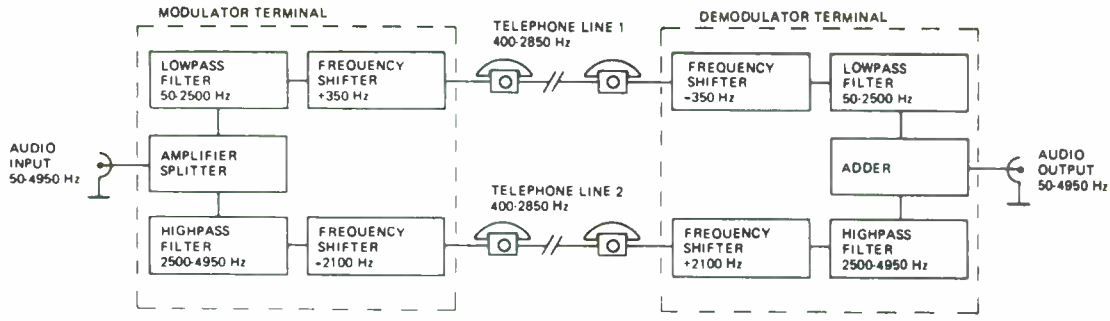


Fig. 1. The basic two-line frequency extension process for dial-up telephone links. (Courtesy of C. N. Rood.)

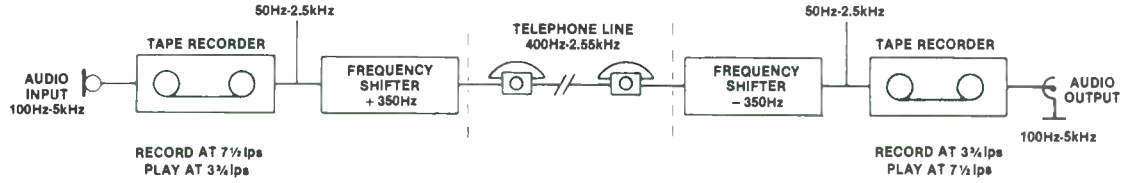


Fig. 2. A frequency doubling technique using 2-speed tape recorders and a single-line bandwidth extension system. (Courtesy C. N. Rood.)

in terms of equipment and configurations. The decision on how to originate the remote location programming will depend upon the requirements of the particular broadcast. Some generalizations can be made, however, that apply to most events.

A program transmitted back to the studio via a standard dial-up telephone company line—without any bandwidth extension—will usually be brief in duration, if for no other reason than the poor audio quality typical of such an arrangement. Spot news reports are common examples of this method of program return.

Small, battery-powered mic-to-line amplifiers are available to drive dial-up telephones through direct connection to the *tip* and *ring wires* of the phone company cable or through clip leads at the handset microphone pins. The direct connection method of coupling is preferred over the handset connection because the former by-passes the telephone hybrid coil assembly with its associated level loss. The broadcaster's motto when it comes to dealing with telco equipment is usually, "the more you can bypass, the better off you will be."

A broadcast transmitted to the studio over one or two dial-up telco lines using bandwidth extension equipment can provide impressive audio quality. Reasonably flat frequency response from 50 Hz to 5 kHz is possible using a two line system.

The equalized broadcast loop is probably the most popular method of relaying lengthy remote programming to the studio. Some stations prefer to order unequalized lines and adjust the loop themselves for the required frequency response. This procedure can be effective on relatively short telco lines. Generally, however, any audio loop that goes through more than one exchange should be left to the phone company, which has had decades of experience in making miles of twisted pair cable sound decent.

If a station decides to equalize the line and not rely on telco, equalization should be applied only at the studio (receiving) end. Applying frequency selective boost to a telephone line input can raise components of the signal to a point that will cause crosstalk into other lines or clipped audio due to the action of network protection devices.

The receiving equipment for a wired remote broadcast should be given careful consideration. Sophisticated telephone interface equipment is available today from a number of manufacturers. This hardware can ensure that maximum audio fidelity is recovered from the line. Some new generation interface equipment includes automatic gain control circuits, equalization and dynamic noise reduction systems.

Remote Site Equipment

The audio equipment used at the site of the remote will vary as widely as the types of programs broadcast. Fig. 3 illustrates a typical application for either a wired or wireless relay system.

A four channel audio mixer is used to mix the sources and drive the telco loop, phone or RPU transmitter. Careful attention should be given to the connection of the mixer output to the telephone line. A phone coupler should be used be-

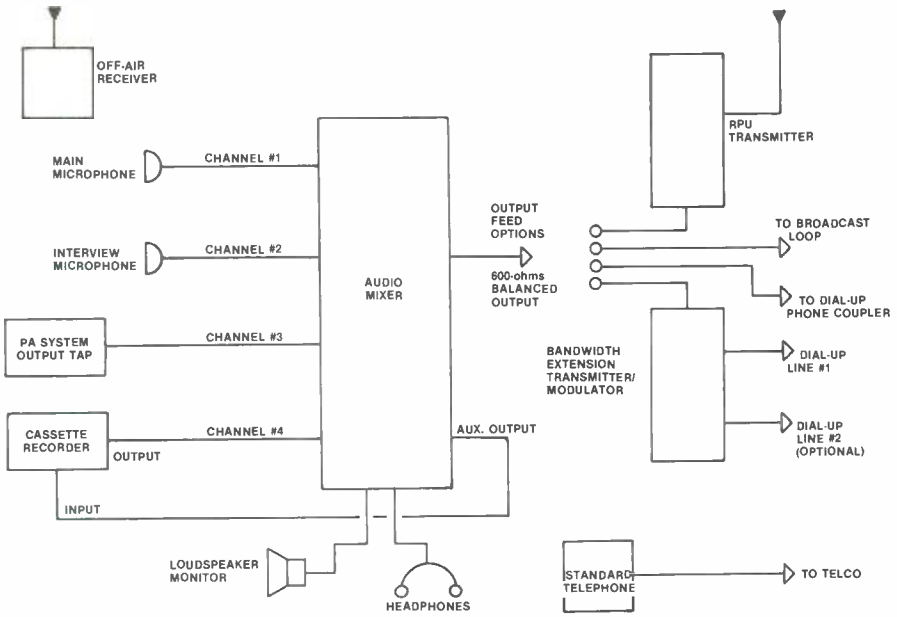


Fig. 3. A typical equipment configuration for a medium scale RENG broadcast.

tween the mixer and the telephone unless the mixer is specifically designed to work directly into a *hot dial-up line* (one with dc voltage across it). This caution applies to a connection made either to the phone line tip and ring wires or to the telephone set through the microphone terminals.

As shown in Fig. 3, two microphones are used —one for the announcer and another for interviews. An output is taken from the local PA system to pick up audio from meetings, speeches, music or whatever. A cassette recorder is often useful at a remote broadcast because it gives added flexibility to the remote crew. The recorder input signal can be taken from an auxiliary output on the audio mixer, allowing interviews or material from the PA system to be mixed and recorded for later use on the air.

A tone oscillator is useful in setting up the remote broadcast. Most mixers designed for remote applications include an oscillator that can be switched on to the program channel. This feature is especially useful when a telco line is employed to return program audio to the studio.

Having the proper monitoring facilities is important to the success of any remote broadcast. A loudspeaker and set of headphones should be provided for the remote crew. It is often desirable to have several headphones available for use by personnel at the remote site. Not all portable mixers can support a loudspeaker and multiple headphone outputs, and so a separate power amplifier and headphone booster may be needed.

An off-air receiver is a requirement for nearly all remote broadcasts. The receiver gives the remote crew a way of checking the total link and allows easy cueing of talent at the event.

A separate dedicated telephone set is suggested for complicated remote broadcasts. The phone provides an easy means of communicating with the studio. It can also serve as a backup line for program audio in case the RPU system or telco loop should fail.

WIRELESS SYSTEMS

RENG has come a long way since the narrowband walkie-talkie days, when a 5 watt "portable" unit would be as big as a briefcase and weigh 35 pounds. Today's gear is small, lightweight and can deliver excellent audio quality. Stations can now go into the field for news and special event programs and maintain studio-like sound. The audio quality of remote broadcasts is more important now than ever before, because radio station transmission systems and consumer receivers are constantly improving. Further, the listening audience is becoming more discriminating and demanding of news operations. Today's competitive marketplace requires more than just sound from the field. It demands clean audio with good frequency response and low distortion. TV news has shown the public that this is possible, and has conditioned consumers to expect it.

Radio channels typically used for RENG work are used on a shared basis, and so receipt of a license is no guarantee of unlimited interference-free operation. Indeed, an unused channel is the

exception—not the rule—in most larger urban areas of the United States. The frequency coordination process is a complicated procedure that requires careful thought and planning, and generally a great deal of lead-time. Broadcasters in a given geographical area rarely have to decide whether they wish to become involved in frequency coordination efforts. Usually the need for coordination is painfully obvious to all persons involved in RENG activity in the region.

The main driving force behind coordination efforts has been the Society of Broadcast Engineers, which has set-up a National Frequency Coordinating Committee to encourage and support local coordination efforts, and to provide whatever support might be needed in this regard. The subject of frequency coordination is discussed in detail in Section 1. Spectrum congestion is a sad fact of life to many stations engaged in RENG today. Users must recognize that coordination is vital to the reliable operation of remote broadcast systems, since spectrum congestion will no doubt become worse in the future, rather than better.

Licensing Procedures

RENG work is done on two primary bands of frequencies set aside by the FCC for Remote Pickup Unit (RPU) operation. A number of frequency groups are allocated near 150 MHz and 450 MHz. Some assignments are also made on frequencies in the 25 MHz region. A particular broadcast station is not restricted to a maximum number of RPU systems that it may put into operation. The needs of the station and the budget available for equipment purchase are, instead, the major controlling factors.

Most RENG activity is currently centered in the 150 MHz and 450 MHz bands. In these slices of spectrum, three major license classifications exist—Automatic Relay Station (ARS), Base Station and Remote Pickup Mobile Station.

ARS systems are designed to receive program material on one frequency and retransmit on another. In this way, the average area of the RENG system can be extended considerably.

Base stations are, as might be expected, fixed-position transmitters used for communication between the central point and one or more remote points. Base stations may, in the event of emergency conditions, be used as a program relay channel for Emergency Broadcast System information.

Remote Pickup Mobile Stations consist of vehicle-mounted and portable (hand-carried) transmitters. They are usually licensed as a system in conjunction with a principal Base Station, or Stations. Remote Pickup Mobile Station licenses generally specify a minimum and maximum number of mobile transmitters allowed in the RPU system. Standard divisions include from 1 to 4 stations, from 4 to 12 stations, from 10 to 20 stations and from 20 to 50 stations.

The Commission's Rules require that the transmitter power for a RPU station be limited to

a level necessary for satisfactory coverage of the service area. In any event, not more than 100 watts of transmitter power output will be licensed. RPU transmitting equipment operating onboard an aircraft is normally limited to a maximum transmitter power of 15W. A Mobile Station consisting of a hand-carried or pack-carried transmitter is restricted to not more than 2.5W power output.

All RPU transmitting equipment must be type accepted by the Commission and checked each year (for units with more than 3W output) for frequency accuracy, deviation and RF power output. FCC Rules also require that RPU transmitters rated for 3W or greater must be equipped with a circuit that will automatically prevent modulation in excess of the authorized limits. In other words, an audio limiter must be built-in to the unit.

There are virtually no operator requirements for the use of a unit in the RPU service. Any person designated by and under the control of the licensee of the station may operate the equipment. An operator's license, as detailed in Part 13 of the Commission's Rules, is not required.

Building a RPU System

In view of the serious spectrum congestion problems that exist today in many areas of the country, any RPU/RENG system should be designed to be as spectrum-efficient as possible and—equally important—to be as immune to undesired transmissions as possible. Even if the system will be operated in an area that currently does not have a spectrum congestion problem, there is no guarantee that such a problem will not surface in the near future. In any event, a well engineered system is also a spectrum-efficient system.

The first rule of spectrum-efficiency is to use only the effective radiated power (ERP) necessary to do the job. There is no justification for putting 15W into the air when 5W will provide the desired (or acceptable) signal-to-noise figure from the receiver. Ideally, all transmitters in a RENG system would, therefore, be equipped with continuously-variable power output stages. The operator at the remote site would then run the transmitter with only enough power output to reach the required S/N figure at the receive (studio) point. With some types of units this method of operation is possible, but in the majority of cases, continuously-variable power output transmitters are not available. User modification of existing equipment is not an acceptable solution, since such work would most likely invalidate the transmitter's FCC type acceptance.

A more logical solution, therefore, is to purchase RENG transmitters of several different power levels operating on the same frequency (or frequencies). All of the popular RENG broadcast equipment manufacturers offer units with different power output levels. With some equipment, a low-power transmitter is used and an optional power amplifier module is added between the transmitter and the antenna to give the needed RF output.

Directional receive and transmit antennas are a good idea for both an efficiency and coordination standpoint. The use of a pair of high gain antennas makes it possible to achieve a much greater ERP for the same transmitter power. Of equal benefit in a crowded urban area is the elimination of any non-essential radiation. Through the use of directional transmit and receive antennas, stations can establish more secure channels by placing the radiated energy where it will do the most good (from the transmit end), and rejecting unwanted signals from other directions (at the receive end).

A simple and sometimes effective coordination tool is cross-polarization. Two stations on adjacent frequencies may achieve as much as 25 dB isolation through the use of different polarizations of transmit antennas, matched by like polarization at their respective receive antennas. Cross-polarization results in varying degrees of success, depending upon the frequency of operation and the surrounding terrain. Line-of-sight paths usually will provide good results, but urban centers with their highly-reflective buildings, generally cause polarity shifts in the transmitted signal that may significantly reduce the benefits of cross-polarization.

Path Engineering for Fixed Stations

Careful path engineering should be performed prior to any licensing work to determine if the proposed locations of Base Station and ARS installations will be able to achieve the desired results without using excessive amounts of transmitter power. There is much more to path engineering for a RENG system than simply pointing the transmitting and receiving antennas at each other (when directional antennas are used) and turning the equipment on. Base Station and ARS systems are fixed-position installations that cannot always be located in the best possible geographic locations because of space availability problems, excessive construction or site rental costs, or local/federal licensing difficulties. In such cases, the required path is not the ideal path and the link will have to be engineered around the fixed points.

The site selection process for repeaters and receivers should also take into consideration the RF environment in which the equipment will be working. Multi-user locations, such as the World

Trade Center in New York City or Mount Wilson near Los Angeles, are very good talk-out sites, but terrible receive sites. For such situations, a remotely-located receiver (in the case of a repeater system) should be considered. The two sections of the ARS station would then be tied together with telco facilities.

The use of a telco loop to feed a remotely-located transmitter introduces several familiar problems, such as noise, crosstalk, distortion (if repeated several times), limited frequency response and installation/service delays. In some arrangements, the use of a telco loop to the transmitter (or receiver) is the only economical way to complete the link. Although such a hybrid system is not the ideal configuration, it will get the job done.

Planning for any RENG system should begin with an accurate, detailed U.S. Geological Survey (USGS) map covering the proposed path. Note should be made of any natural obstructions or Fresnel clearance obstructions (such as mountains, hills or vegetation) or man-made obstructions (such as buildings, water tanks or transmitting towers) in the proposed path. The transmitting and receiving antennas should be plotted so that a minimum of .6 Fresnel Zone clearance is obtained over 4/3 earth. Information on obtaining USGS maps may be found in the chapter on Information Sources in Section 1; Fresnel zone clearance is covered in more detail in the chapter on Microwave Engineering in Section 4.

When planning a RENG path, a profile drawing of the transmitting and receiving antennas, the terrain and any obstructions in between should be made on graph paper set to 4/3 earth radius. The use of such graph paper will compensate for the curvature of the earth and the normal refraction of VHF and UHF frequency signals when determining Fresnel Zone and obstruction clearance. Simple height above sea level is insufficient to determine whether a natural or man-made obstruction will interfere with the RENG signal on a long-distance path. Once a proposed path has been drawn, a visual inspection should be made of the area for any problems that could degrade the performance of the system. Particular attention should be paid to items not documented on the USGS maps, such as unforeseen hills, high-rise buildings or point obstructions, such as radio towers.

The terrain from the transmitting antenna to the receiving antenna must be examined not only for obstructions, but for reflection possibilities as well. A large body of water will usually cause problems for a RENG system operating in the UHF frequencies. If the water is an even number of Fresnel Zones from the direct path, signal attenuation will likely occur at the receiver. Temperature changes and tidal conditions will also have an effect. Likewise, thick vegetation or forested areas can be reflective to RF signals when wet, creating a similar (but not so troublesome) problem. Generally the solution to reflection problems is to change either the transmitting or receiving antenna height or to employ a diversity reception system, if a long-term solution is needed.

Determining the Fade Margin

A gain and loss balance sheet should be computed to determine the *fade margin* of the proposed system. An adequate fade margin is vital to reliable performance of the system because a link that is operating on the edge of the minimum acceptable receiver quieting will encounter problems later down the road. Normal component aging in the receiver or transmitter can cause a loss in received signal level and thus degrade the system performance. Likewise new construction near the transmitting or receiving site can degrade the path, resulting in poor performance. Atmospheric conditions, usually severe weather in the area or ice on the transmitting or receiving antennas can also cause sharp fading, and even a complete loss of signal, if an adequate fade margin above minimum receiver quieting is not provided. The RENG system fade margin can be computed by using the following equations:

$$G_s = G_t + G_{ta} + G_{ra} \qquad [1]$$

Where: G_s = total system gain (dB)
G_t = transmitter power output (dBm)
G_{ta} = transmit antenna gain (dBi)
G_{ra} = receive antenna gain (dBi)

The values for G_{ta} and G_{ra} are gathered from the antenna manufacturer's literature.

(Note: $dBi = dBd + 1.1\ dB$, approximately.) The value for G_t is given by the following formula:

$$G_t = 30 + 10 \log P_o \qquad [2]$$

Where: G_t = transmitter power output in dBm
P_o = transmitter power output in watts

Next, the system losses are computed:

$$L_s = L_p + L_l + L_c + L_m \qquad [3]$$

Where: L_s = total system losses (dB)
L_p = path loss (dB)
L_l = transmission line loss (dB)
L_c = connector loses (dB)
L_m = misc. loses (dB)

The values for L_l and L_c can be determined from the manufacturer's literature. Fig. 4 shows typical loss values for ½-inch foam-filled transmission line. A reasonable value for connector loss with components normally used in ½-inch transmission line installations is 0.5 dB. The value for L_p can be found by using the following formula:

$$L_p = 36.6 + 20 \log F + 20 \log D, \quad [4]$$

Where: L_p = the free space attenuation loss between two isotropic radiators (dB)
F = frequency of operation in MHz
D = the distance between the antennas in statute miles

Now, the fade margin can be calculated:

$$Fade\ Margin\ (dB) = G_S - L_S - R_m \quad [5]$$

Where: G_S = total system gain (dB)
L_S = total system losses (dB)
R_m = minimum signal strength required for target S/N (dBm, a negative number)

G_S and L_S are determined by the equations previously shown. R_m (receiver sensitivity) is determined from the receiver manufacturer's specifications. If the manufacturer gives a receiver sensitivity figure in microvolts, the following formula can be used to convert to dBm:

$$R_m = 20 \log \frac{V_r \times 10^{-6}}{.7746} \quad [6]$$

Where: R_m = minimum required signal strength (dBm)
V_r = Receiver sensitivity (microvolts)

R_m can also be found by using a communications receiver test set, available at most commercial and industrial communications radio service shops.

In order to predict accurately the performance of a RENG radio link, the value of R_m must be determined carefully. Many receiver manufacturers specify V_r for 20 dB of receiver quieting. This level is a convenient reference point; however, it should not be used for fade margin calculations. For maximum system performance and reliability, the fade margin determination should be made based upon the signal level required to provide the minimum acceptable receiver signal-to-noise performance.

The recommended fade margin for a 150 MHz band RPU system is at least 10 dB plus 2 dB for each 10 miles of line-of-sight path distance greater than 10 miles. At 450 MHz, the fade margin should be increased to a minimum of 15 dB plus 3 dB for each 10 miles of path distance greater than 10 miles. These fade margins are designed to limit periods of performance degradation of the radio link to 1% or less during worst-case environmental conditions. The fade margin assumes transmit and receive antenna clearance above the ground and all obstructions of 50 to 100 feet.

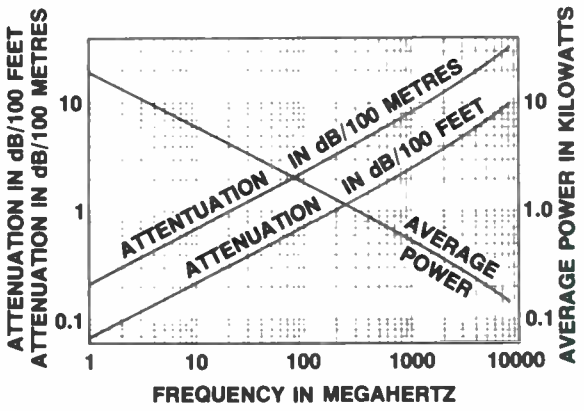


Fig. 4. The attenuation and power handling ratings for 1/2-inch foam dielectric coax. (Courtesy of Andrew Corp.)

While it is important to provide an adequate fade margin, needlessly high fade margins should be avoided because of the spectrum congestion problems that may result. Variable power output transmitters give the user the ability to adjust for an optimum fade margin, while keeping radiation toward other stations at a minimum.

Other Planning Considerations

Path engineering for remote-location broadcasts is seldom done for RENG activities because of the transient nature of such events. Rough estimates should be made, however, of the geographical areas of interest before attempting remote feeds. It is well worth the time spent to conduct a coverage survey of the primary areas of interest for RENG acivity when planning an overall system to determine which locations provide good or marginal performance. A little planning and work ahead of time will save many problems (and probably dead air) once the system is put into operation.

For base or relay installations that, for one reason or another, cannot use frequencies in the RPU bands for program or control data interconnection, there is often an alternative to the telephone company audio loop back to the studio. Private common carriers in many markets are installing competitive audio circuits, which can be leased. If the RENG installation is co-located with

a television relay station, it may also be possible to back-haul the RENG audio on one of the TV microwave system's subcarrier channels.

The selection of receiving sites must be made with care, keeping in mind the area of coverage required of the receiver. The best location for a RENG system is not always the highest building in town. Placing a receive antenna at a high elevation in a metropolitan area can result in poor performance of the system in the downtown area, since the gain of many omnidirectional vertically polarized antennas decreases as the antenna is raised above the transmitting point. Tall buildings are excellent for point-to-point relay transmissions, but are generally unsatisfactory for wide-area coverage in a metropolitan region.

An inexpensive installation option is available to AM broadcast stations that do not want to erect a separate RENG transmitting tower at the main transmitting site. An isocoupler can be installed at the AM tower base that will pass the RPU transmitter frequency with good efficiency (90% is typical), while at the same time presenting a high impedance to the AM band energy. Isocouplers are available in various frequency and power ranges. Installation of these devices may change the base impedance of the AM tower slightly thus an engineering consultant should be contacted before installation work begins.

Every effort should be made to locate the receiving antennas of a RENG system as far away from high power transmitting antennas as possible. This should be attempted regardless of the frequency separation between the receive unit and the suspect high power transmitting antenna. Failure to achieve adequate separation may require the installation of filters of various types on the receiver front-end.

In order to keep system losses to a minimum, a low loss transmission line should be used, such as the 1/2-inch foam-filled coax shown in Fig. 4. The advantages of using a low loss line are illustrated in Table 1. The two ends of the transmission line (at the receiver and transmitter) are probably the easiest parts of the hardwired system in which loss can be introduced, and so care should be taken to install the lines and connectors according to good engineering practice. The line should not be bent in a smaller radius than that recommended by the manufacturer. Excessive bending can cause a kink in the outer conductor of the coax, reducing the power handling capability of the line and (more importantly in most cases) changing the characteristic impedance of the line at that point. This will result in increased VSWR (and therefore, power loss) at the transmit end, and greater signal loss at the receive end (if bent there).

The transmission line and connectors must be made watertight if exposed to the elements. Each connector should be sealed with a silicone dielectric compound and then wrapped with good quality tape. Unless this is done, rain may eventually work its way into the connector and cause signal loss or VSWR problems. The line should be grounded (using a recommended grounding kit) at the point where it leaves (or enters) the equipment building and where it starts its climb up the tower (unless the vertical distance to the antenna is less than 10 feet). This will prevent any high voltage transients caused by lightning from entering the equipment building, and thus the RENG equipment. A short length of flexible coax is generally used on each end of the two transmission lines for connection to the equipment and antennas (when 1/2-inch or larger coax is used).

TABLE 1. Typical cable loss for popular types of transmission line. Note the poor performance figures for RG-58/U. LDF4-50 is 1/2-inch foam-filled line, LDF5-50 is 7/8-inch line and LDF7-50 is 1-5/8-inch line. (Chart courtesy of Scala Electronics.)

TRANSMISSION LINE LOSS COMPARISONS

L = Loss in dB per 100 feet
E = Approximate power transmission efficiency of 100 foot length

	150 Mhz		450 Mhz		950 Mhz	
	L	E	L	E	L	E
RG-58/U	6.0 db	25%	12.0 db	6.3%	20 db	1%
RG-8/U	2.5 db	55%	5.0 db	31%	9 db	13%
LDF4-50A	0.85 db	83%	1.7 db	67%	2.5 db	55%
LDF5-50A	0.48 db	90%	0.9 db	85%	1.55 db	71%
LDF7-50	0.28 db	94%	0.56 db	88%	0.88 db	84%

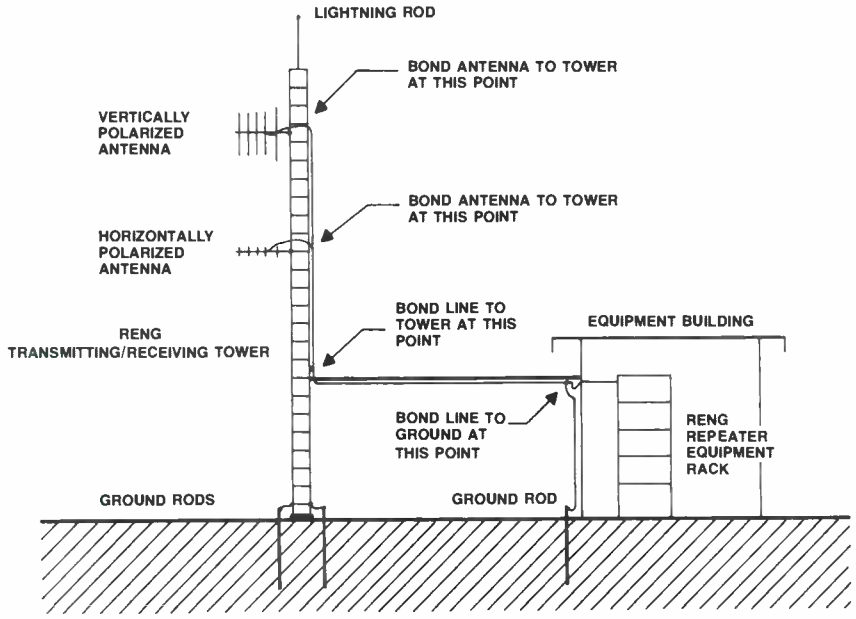


Fig. 5. The recommended installation practices for RENG antennas and transmission lines.

This "pigtail" is normally no more than 18 inches long. See Fig. 5.

Antenna Considerations

The selection of an antenna for use in a RENG system is an important decision because of the effect the antenna has on system performance and spectrum usage. The usual RENG antenna has, until recently, been the omnidirectional vertical whip with a small amount of gain. Many system planners, however, are now being forced by interference concerns to use directional antennas with moderate amounts of gain. The low power levels commonly used with RENG equipment and the RPU band frequencies make it possible to economically achieve increased effective radiated power (ERP) through the use of high gain transmit antennas. The use of high gain antennas also concentrates the radiated signal where it will do the most good, and minimizes radiation in directions that may adversely affect the RENG activities of other stations in the same, or nearby, communities.

The omnidirectional base station antennas commonly used in the 150 MHz and 450 MHz bands are vertically polarized units with 4 to 6 dB gain. Electrical beam tilt is sometimes available. Depending upon the manufacturer, up to 20 degrees downtilt can be provided on 150 MHz antennas, and up to 11 degrees is common for 450 MHz omnidirectional units. Large amounts of beam-tilt are normally used when the antenna is to be mounted on a structure that is substantially above the surrounding terrain, thereby improving the antenna's close-in coverage.

The typical directional RENG antenna is a medium gain 5-element Yagi. Such a unit provides about 9 to 10 dB gain over a reference dipole, with a front-to-back ratio of approximately 14 to 18 dB. Fig. 6 shows the radiation pattern for a commonly-used 5-element 150 MHz Yagi. This particular antenna measures 40″ × 40″ × 4″ and weighs 8 pounds. It is, thus, small and light enough to be used on remote broadcasts. It is also suitable for permanent installations using either horizontal or vertical polarization. These antennas may be stacked in two and four bay arrays (with suitable phasing harnesses) for additional gain and directivity.

Most Yagi antennas are made to match the specific frequency requirements of the user. Multiple frequency operation using a single antenna is possible with reasonable VSWR numbers, though, as long as the operating frequencies are not removed from the cut center frequency by more than 1 to 2 percent.

A recent addition to the RENG user's bag of electronic tricks is the broadband log periodic antenna, which can be used on any channel within a wide band of frequencies. Such antennas provide a smooth pattern with minimal sidelobe radiation and a high front-to-back ratio (typically 25 dB in the 150 MHz band). Nominal gain for 150 MHz operation is 7 dB. Units can also be stacked to provide additional gain and directivity. Such antennas are usually larger and heavier than the familiar Yagi, however they allow use of the antenna for virtually any frequency within the specified band at low VSWR levels (a maximum of 1.5-to-1 is typical). Fig. 7

shows the radiation pattern of a log periodic antenna designed for use in the 450 MHz band. Horizontal or vertical polarization is available. The antenna shown in Fig. 7 has a gain of 8 dB and a front-to-back ratio of 35 *dB*. Such a unit is, thus, ideally suited for operation in areas with high spectrum congestion.

Just as a TV or FM broadcast antenna must be protected against icing problems, so should antennas used in RENG applications. Although antenna de-icers are not used in RENG installations, a radome is often available for an antenna to protect it from damage or degradation in performance due to snow, ice or salt spray.

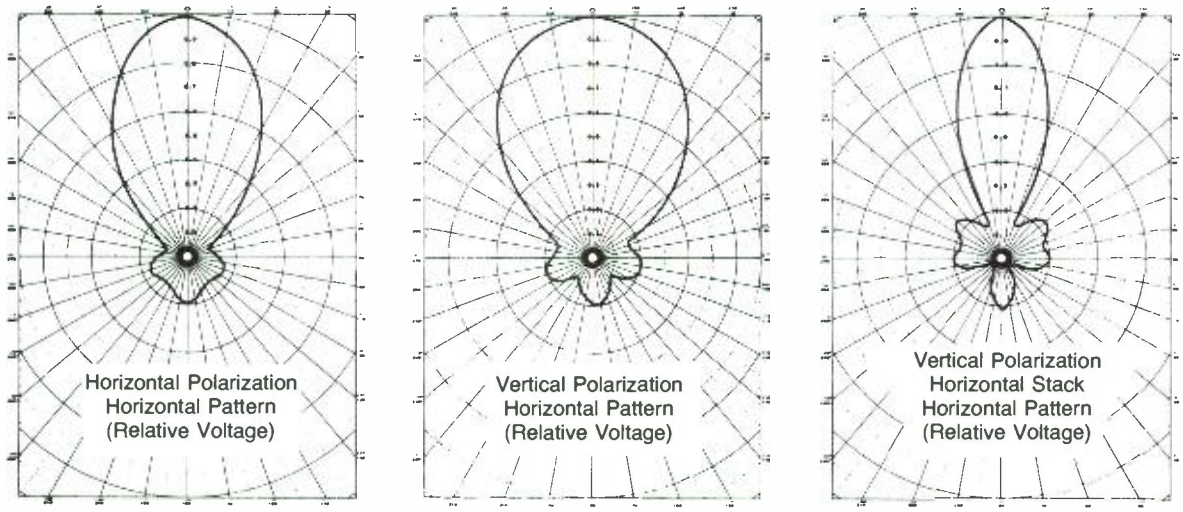


Fig. 6. Radiation patterns for the CA5-150 5-element yagi antenna made by Scala Electronics for use in the 150 MHz frequency band.

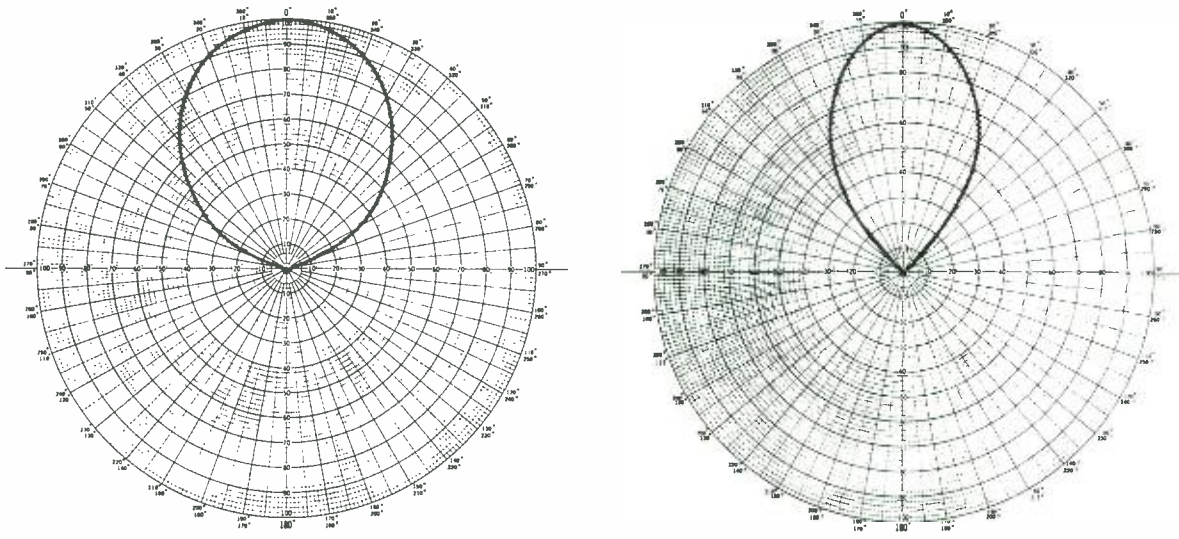


Fig. 7. The radiation patterns for the Scala CL-400 broadband log periodic antenna, designed for use in the 450 MHz RPU frequency band. (Courtesy of Scala Electronics.)

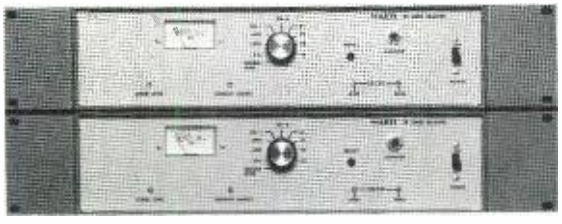
Transmitter-receiver Considerations

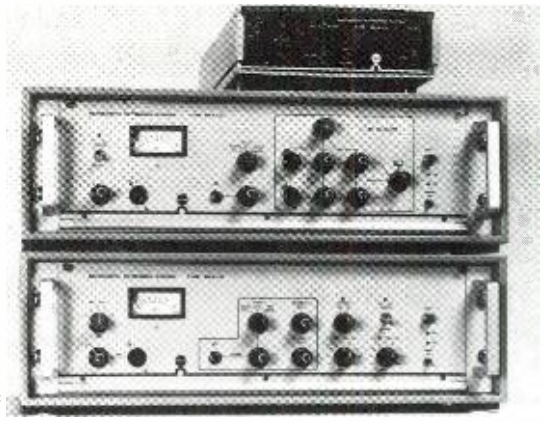
Whatever the configuration of the planned RENG system, there are several important points that should be considered. Most of these items apply to receiving equipment, which usually present the greatest problems to a system designer. Transmitting equipment must also be selected with care, but the receiving links in a RENG system are the ones most often subjected to conditions that may make good performance difficult.

A receiver should be selected that has sufficient dynamic range and headroom to allow the system to deal with strong adjacent-channel signals, as well as very weak and very strong co-channel signals from transmitters in the network. A receiver with inadequate headroom will clip and yield distortion. Wide dynamic range active devices should be used in the receiver front-end, such as gallium arsenide field effect transistors (GAsFETs).

The need for a preamplifier or cavity preselector network ahead of the first RF stage should also be considered. RF preamplifiers can add sensitivity, but they can also cause overload conditions in the presence of medium-level co-channel signals. Preselectors are often necessary at mountain-top or antenna farm locations because of the high-level RF signals present at such sites. It is not uncommon to have a 1 kW land mobile paging transmitter operating in the 454-455 MHz range located nearby a RPU band receiver that is working in the 455-456 MHz frequencies. High power FM or TV transmitters can also cause desensitization of the receiver front end, unless adequate bandpass filtering has been included in the receiver design.

The locations commonly used for relay sites are seldom ideal from an environmental standpoint. They are often inaccessible during portions





of the year, very hot in the summer and very cold in the winter. For this reason, equipment that is rugged should be selected, if downtime is to be minimized. Temperature extremes can also cause problems for frequency-determining elements, as well as accessories such as cavity filters, preselectors and preamplifiers. Since relay sites are often difficult to reach, equipment should be designed for easy maintenance, preferably through module replacement. A spare stock of modules should be kept at the site so that the system can be quickly returned to operation. The defective module can then be serviced at the studio, or returned to the factory for repair. It makes little sense to haul a truck full of test equipment up to a remote site whenever a problem occurs. It is not cost-effective either.

Regular performance tests should be made of the RENG system, just as an engineer would do with any other important chain of equipment at the station. Regular checks and measurement often allow the engineer to spot problems that could cause a total system failure if left unattended. If trouble is experienced with a piece of receiving equipment, the possibility of interference from other services should not be overlooked. A spectrum analyzer is invaluable for such work.

System Configuration

The requirements of users will vary greatly from one station to the next and from one market to the next. There are, however, several standard system configurations that can be modified to fit the requirements of most users. These range from the simple point-to-point program relay system common in many small-scale operations, to complicated multi-point relay installations with automatic signal quality voting circuits.

Fig. 8 shows the basic RENG program relay system in which one (or more) transmitter(s) on a particular frequency is (are) used in the field, and a single receiver is located at the studio. All

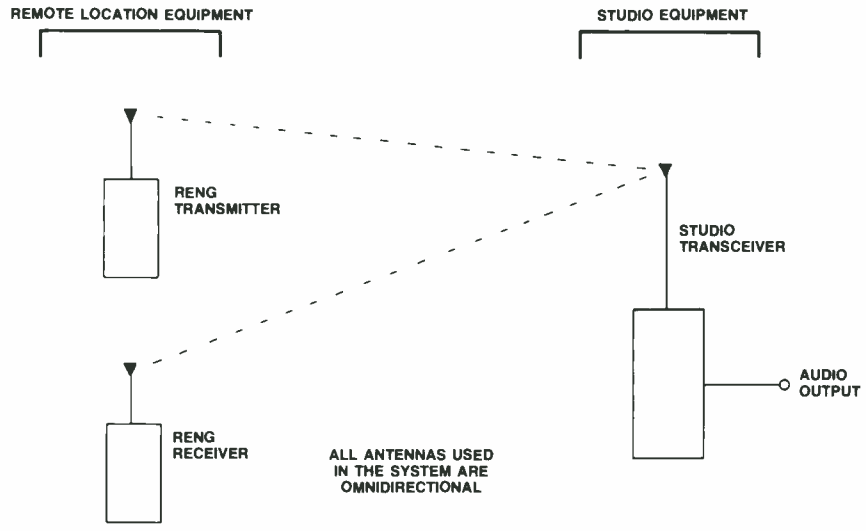


Fig. 8. The basic RENG program relay system using a single hop from the remote location to the studio.

antennas used in the system are omnidirectional. While there is much to be said for system simplicity, such an arrangement is not practical in an increasing number of urban areas because of spectrum congestion problems and the need to cover large geographical areas.

The system configuration shown in Fig. 9 overcomes the geographical coverage area problem through the use of an Automatic Relay Station. The range of a RENG system can be greatly extended through the use of an ARS. Such systems also make it possible to use lower power transmitters in the field, since the transmitter at the program origination point need only be powerful enough to reach the ARS site. This often allows the use of smaller and lighter remote transmitters, usually hand-carried or pack-carried units. The arrangement shown in Fig. 9 will satisfy the requirements for wide area coverage and is sufficient for radio markets where spectrum congestion is not a problem. Because all antennas in the system are omnidirectional, however, the con-

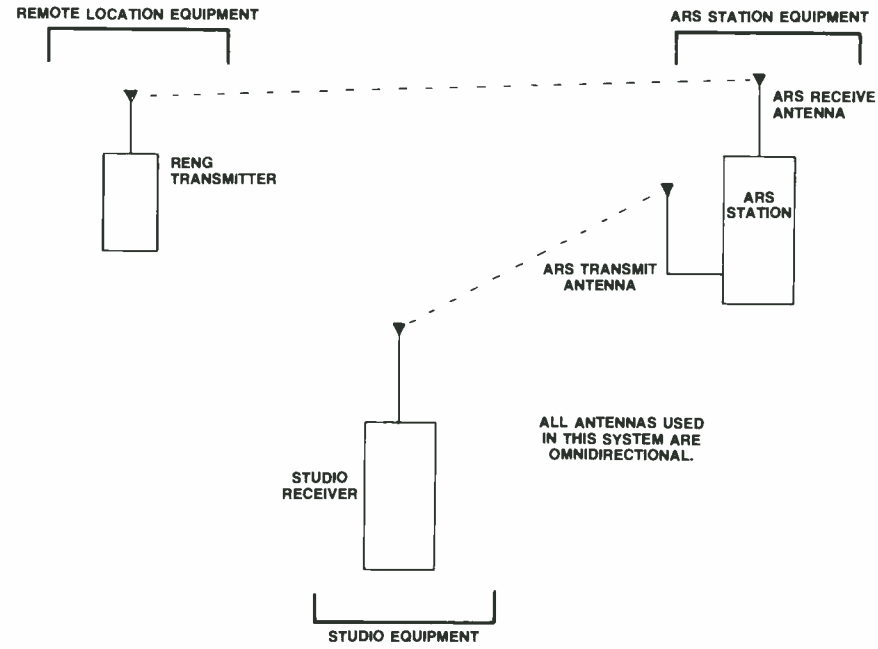


Fig. 9. The basic RENG program relay configuration using an ARS station between the remote location and the studio.

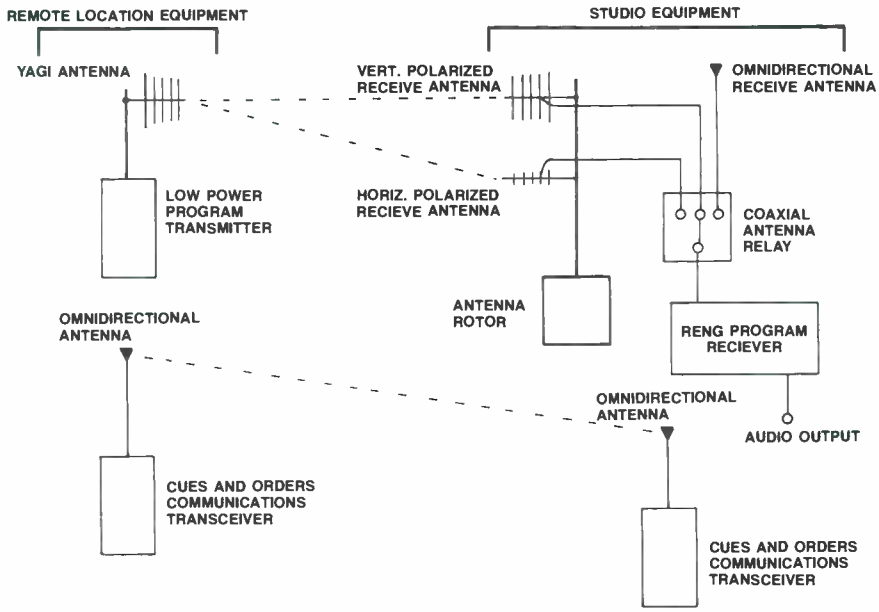


Fig. 10. A high-performance two-point RPU system designed for operation in frequency-congested areas.

figuration is not suitable for use in larger urban areas which are experiencing frequency allocation problems. For such applications, a more sophisticated approach is needed to RENG activity.

Fig. 10 shows a high-performance two-point RENG system designed for operation in spectrum-congested areas. At the remote site, two transmitters and two antennas are used. The communications transceiver is used to set-up the program audio link and to relay cues and coordinating information. The low power transmitter and its associated directional transmit antenna are used to relay the program signal to the studio. At the studio site, a communications transceiver, feeding an onmidirectional antenna, is used for set-up information, cues and coordination work. The multi-antenna receive system is used for program audio pickup.

The "cues and orders" radio system shown in Fig. 10 is used for general purpose communications not requiring wide frequency response and a high signal-to-noise ratio. The lower power program relay transmitter and directional receive and transmit antennas provide a secure and quiet channel, without causing interference to other RPU band users in the area.

Between remote broadcasts and when beginning the initial set-up procedure for a remote, the omnidirectional antenna is patched into the broadcast-quality RPU band receiver at the studio through the coaxial switch, K1. Once contact has been established with the remote crew, one of the directional antennas—which are mounted on a common mast driven by a remote-controlled antenna rotor—is switched into the studio receiver. The polarization of the transmission from the remote site is planned before the remote crew leaves the studio. Selection of either horizontal or vertical polarization is made during the frequency coordination process, or at the discretion of the user. Engineers may find that a particular polarization may yield better results from certain geographical areas, and in such cases, that polarization would be chosen. Once the proper antenna has been selected, the antenna rotor is adjusted for maximum received signal strength. The studio operator then talks the remote crew into the best position for its Yagi transmit antenna. At this point the antennas are locked-down and the link is ready for the remote broadcast.

If a variable power transmitter is used at the remote site, or transmitters of various power levels are available, the transmitter power would next be adjusted to the point necessary to achieve the required S/N performance at the receiver. After power output adjustment, the antennas on both the receive and transmit ends should be checked again for correct positioning.

While this process may be time consuming and require the purchase of additional equipment, it will assure a high quality, secure, RF link from the field to the studio. This system will also result in a minimum of unwanted radiation to other RPU band users.

Fig. 11 shows a high-performance, secure-channel Automatic Relay Station. The same antenna selection and positioning procedure is used in the ARS installation as was used in the two-

point system of Fig. 10, except that the antenna switching and positioning work is done by remote control. The link for this remote control system can be a subcarrier on the main station broadcast signal, a separate dedicated radio link, a dial-up telephone patch or a leased telco data or voice loop. A standard broadcast transmitter remote control system is used, with the common channel on-off/up-down functions performing the necessary switching and positioning work at the ARS site. For stations with multiple site capability on the main transmitter remote control system, the ARS remote points can be simply treated as other "transmitter sites" and controlled as such from the master unit.

A monitor receiver is included at each ARS installation to inhibit activation of the ARS transmitter if a transmission is already in progress on that frequency. As shown in Fig. 11, the control commands are received over a subcarrier receiver from the main station transmitter. The relay station logic interfaces the remote control unit with the receive antenna coaxial switch and the antenna rotor control box. During set-up, the telemetry section of the remote control unit provides an audio FSK signal that is sent back to the studio control unit via a telco line or the relay (ARS) transmitter, as shown.

The SCA, omnidirectional program, monitor and relay transmit antennas are all fixed in position. Only the directional receive antennas, one set for horizontal polarization and the other for vertical polarization, are movable. An arrangement such as that shown in Fig. 11 will provide maximum flexibility and minimum risk of program audio disruption.

In a system where two or more of the ARS stations shown in Fig. 11 are used, an arrangement such as that shown in Fig. 12 may be implemented. The studio remote control unit is used to determine which of the ARS stations is allowed to repeat the program traffic. Those stations which will not be used to repeat the program material would be instructed by the studio operator to remain inactive. For multiple site ARS operation, as shown in Fig. 12, individial directional receive antennas, or a single directional receive antenna mounted on an antenna rotor, may be used to receive the ARS traffic at the studio.

For protection against system failure, an equalized telco loop can be installed between each ARS point and the main studio. With this backup provision, an equipment failure in the relay gear would not interrupt a remote broadcast.

One of the problems sometimes experienced with ARS equipment is the possibility of a desired signal opening the system, and an undesired signal keeping it open after the desired traffic has ended. This can occur if the tone burst method of repeater keying is used. For example, a valid tone burst signal unlocks the ARS system and then undesired noise or traffic holds the channel open after the desired traffic has ended by prohibiting a loss-of-carrier indication from the receiver. The ARS will thus be stuck open until the level of the interfering signal drops to a point that allows the receiver to squelch and generate a loss-of-carrier command to the ARS system logic. In order to maintain positive control over the system, a means should be provided to override the ARS logic by remote control from the studio.

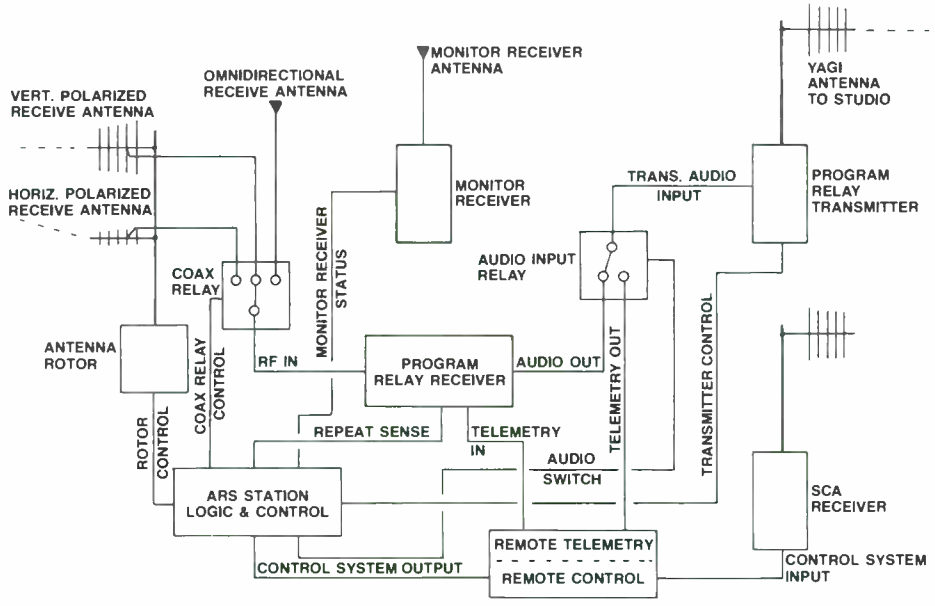


Fig. 11. A high-performance secure-channel ARS station with remote control of system functions.

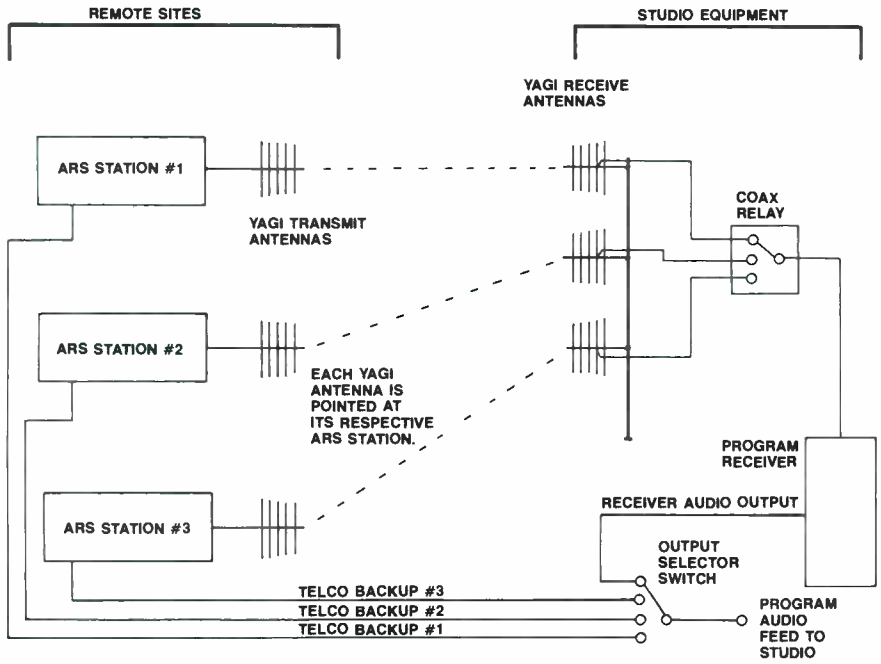


Fig. 12. A multiple site ARS network feeding a central studio control point. Note each ARS station is also connected to the studio via a land line for backup protection.

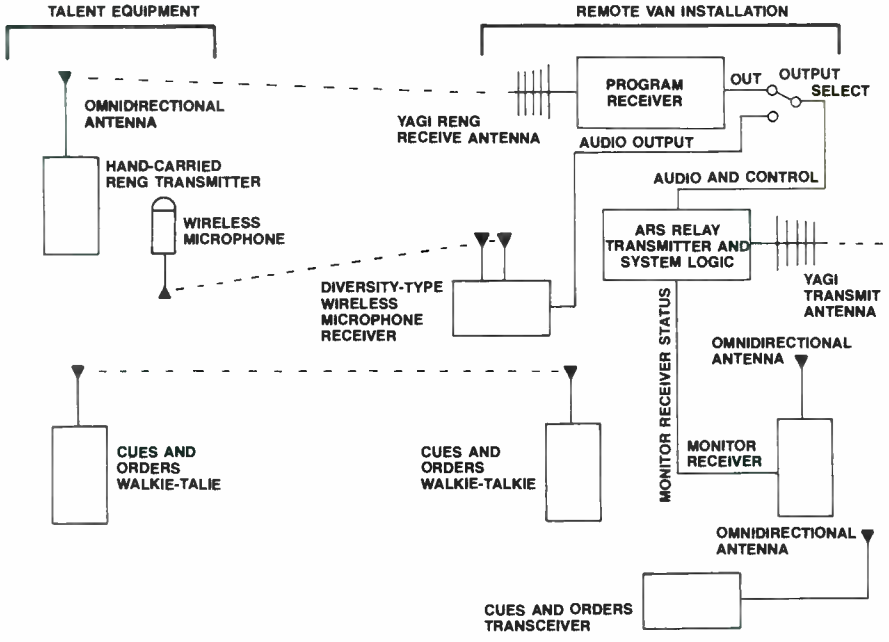


Fig. 13. The use of an ARS system at the event site for added range and talent flexibility.

Fig. 13 shows some of the ways the remote location program audio can be transmitted. As mentioned previously, the communications transceiver is used for cues and orders from the studio location. The program channel signal can consist of a hand-or pack-carried transmitter, which directly feeds the studio receiver or one or more ARS systems. Fig. 13 also shows a repeater station configuration that can be used when a high-power transmitter is required to reach either the studio or the ARS relay point. The use of a repeater—configured as a standard ARS station—in a car or van outside the remote location also gives the talent at the event greater flexibility, since a small hand-carried transmitter can be used, rather than a larger unit with antenna and power cables attached. This arangement is also ideally suited for use with a wireless microphone, which gives the talent an even greater degree of flexibility. The receive antenna at the remote van can be either an omnidirectional unit, or a Yagi. The system shown in Fig. 13 includes a monitor receiver to prevent ARS transmission over traffic already in progress.

There is a limit, of course, to the number of times a signal can be repeated and still maintain good audio specifications. Moreover, each added hop in the path between the remote site and the studio increases the chances of a spurious signal interrupting the remote feed. Each additional hop also increases the complexity of the system and the vulnerability of the link to equipment failure. The design goal for any RENG system should be to keep the arrangement as simple and direct as possible, while still providing talent flexibility, backup protection and high performance.

Wireless Microphones

The use of wireless microphones to free-up the talent at a remote broadcast is gaining popularity with stations involved in RENG activity. The advantages to the talent are obvious: complete freedom of movement and nothing to carry around but a microphone and air monitor receiver. There are no controls or meters for talent to worry about. The range of a wireless mic is somewhat limited, but a properly designed system for remotes that are more-or-less stationary can provide simple set-up and coverage of an event.

The receiver used in conjunction with the wireless microphone may use either diversity or non-diversity reception techniques. A non-diversity receiver is used where multipath cancellation is not a problem, such as in open areas or when conducting fixed-position interviews. If, on the other hand, the wireless mic is to be used in several places and the possibility of multipath cancellation exists due to nearby reflective objects, a diversity receiver is recommended.

The diversity receiver uses two antennas, located in different areas of the event site. A minimum separation of 20 feet is usually recommended. The receiver automatically selects the stronger of the two signals for demodulation. The switching of RF sources occurs silently without any "squelch type" noise bursts.

Many wireless microphone systems include audio companding circuits to extend the dynamic range and lower the apparent noise floor. A properly engineered wireless microphone system can be treated by engineering personnel as essentially a piece of wire between the microphone and the audio console input.

Remote Cues and Orders

Communications with a remote crew from the studio can be accomplished in one of several ways. The simplest method is an over-the-air cue in which the talent simply listens to the station's air signal and takes his (or her) cue from the studio announcer or a pre-recorded introduction cart. Other methods include use of the station's subcarrier signal for cueing information or a separate, dedicated, radio link specifically used for cueing instructions, either from the remote truck (as shown in Fig. 13) or from the main studio.

If a station needs a more sophisticated intercommunication system, a trunked 800 MHz radio system can be considered. A 5 or 10-channel trunked repeater acts like a small telephone exchange in which the number of users (telephones) exceeds the number of channels (trunk lines). Telephone system theory is used to predict the busy level that can be expected during periods of heavy radio traffic. Three minute time-out timers are usually included in mobile transmitters to enforce time limits.

These trunked systems can tie into the regular telephone system at hilltop repeater sites or at trunked base stations. Broadcasters interested in 800 MHz trunked radio should contact their local area land mobile operator to see if such a system is available.

In certain situations, a station may be able to design and license a UHF business radio system for dispatch and coordination of RENG crews. These systems offer the user the luxury of not encountering a busy signal, as may occasionally happen in a trunked system. As with the trunked network, no programming is allowed on a UHF business radio system.

One of the problems often encountered when carrying remote broadcasts on an automated station is the need to have an operator stand-by during the broadcast to trip the automation system to the next event when the talent at the remote site gives the proper cue. The simplest way around

this problem is through the use of a sub-audible tone that is high enough in frequency to not interfere with the ARS sub-audible tone that may be used for repeater equipment, and low enough in frequency so that it does not interfere with normal program audio. For example, in a system where the ARS access sub-audible tone is 25 Hz, an "advance system" control tone of 45 Hz could be used. In order to prevent premature automation system trip commands, the program audio input to the remote location transmitter would be passed through a high pass filter to remove any audio components below about 60 Hz. At the studio, the receiver audio output would run through another high pass filter to remove any control tone signals from the automation system program channel feed.

In Conclusion

A RENG network should be planned and constructed with long-term service and frequency coordination requirements in mind. Areas that currently do not experience spectrum congestion problems may encounter them in the near future. It pays, therefore, to design a system that is spectrum-efficient and relatively immune to interfering signals. It is always easier—and cheaper—to do the job right, the first time.

6.2

Microwave Electronic News Gathering (ENG)

Daniel J. McCarthy
M/A-COM MAC
Burlington, Massachusetts

INTRODUCTION

Electronic News Gathering (ENG) and Electronic Field Production (EFP) are standard operating networks in most broadcast stations. Rapid advances in equipment and system designs have contributed in making fast coverage to on air possible and opened the doors for more and better field operations.

Close cooperation between the news department and the engineering department is now demanded and the technology is there to assist.

This section of the *Handbook* will address the microwave portion of News and Field Productions. Other support equipment, Vans, Cameras, VCR's and the like are covered elsewhere.

FREQUENCY CONSIDERATIONS

Microwave bands available for the Broadcast Auxiliary Service in Television Remote Pickup applications are the same as in fixed link service; i.e., 2 GHz (1990-2110 MHz) plus the non-exclusive, shared band 2450-2500 MHz, 7 GHz (6875-7125 MHz) plus frequencies shared and coordinated with common carriers in the band at 6425 to 6525 MHz*, and 13 GHz (12.7-13.25 GHz). Analysis of the options is similar to the discussion in the STL sections of the Handbook, plus some additional considerations.

The 2 GHz band has been the predominant selection because of overall path performance, antenna design, transmitter power, receiver sensitivity and general reasonable electro-mechanical configurations.

In comparison, the 7 GHz Band can be supported; however, propagation through adverse path conditions, trees, etc. is more difficult and corresponding antenna configurations with narrower beamwidths make path alignment more difficult. Band D (13 GHz) is proportionately more difficult than 7 GHz.

These interrelationships for remote performance will be more evident as one becomes aware of the following arguments.

Some additional considerations for band selection that should be reviewed are as follows: Which band is in service for STL Relay operation in your neighborhood region? How far away are you planning to go with your remote system? What STL Relay activity is present in these areas? Which mechanical configuration can you support? Which mode of operation is planned, i.e. News Gathering or Planned Field Production?

Obviously, mutual interference with other participants in the same band must be considered. Channels 8, 9, and 10 of the 2 GHz Band (2450-2500 MHz) are available on a shared, non-exclusive basis. The shared users at this time include microwave radar ovens, industrial heating

*Not available for Broadcast Auxiliary fixed link service.

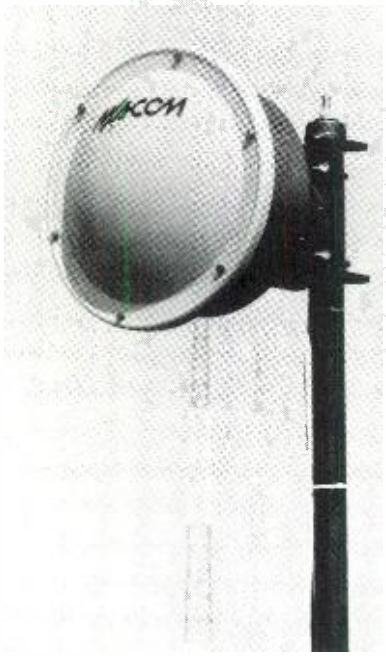
systems and medical diathermy, etc. This means broadcasters can license for operation in this band and equipment is available; however, if any interference is realized in generation, the FCC will not take any action to alleviate the interference.

Systems have been used successfully in these channels. Selection of a receive site in a remote area is possible. Narrow beamwidth antennas can be employed and acceptance of some interference in limited azimuth positions can be tolerated.

RECEIVE SITE SELECTION

Receive site selection is an analysis encompassing the full spectrum of broadcast operations. Some considerations are as follows:

Downtown site—high rise building: How will it support local urban activities, hospitals, court houses, city hall, mayor's office, school committee offices, police stations, parks, etc. Do not forget the path for relay back to studio. Discussions with the News Department and Production Department should be conducted to identify other important points of potential interest. Roof top configurations can play an important role in the selection of the class of receive antennas. Naturally, the building management restrictions relative to aesthetic factors, as well as window washer activity, fire and helicopter access, structural integrity and a host of other factors all bear on these considerations.



23 GHz ICR Transmitter. (Courtesy M/A-COM MAC)

Quadrant selectable horn antennas have been used successfully in many downtown sites that have demanded invisible installations. Antennas can be finished in the color of the building, they can be flush mounted on penthouse walls, parapet corners or mullions. If visibility and profile integrity are not the overriding issues, a stub tower installation on the roof top can support any of the available ENG antennas. Specifics of these antennas will be discussed in a later section.

Internal installations on high-rise buildings have been constructed with special attention to the type of glass the antenna must look through. Leaded glass must be avoided. Tinted glass, depending on technique used in tinting, should be checked closely for propagation loss.

The selection of high rise building relative to other stations in town can be a problem and an aid. All stations on the same roof present a conflicting situation relative to mutual interference. At the same time, it can be a compatible situation for pooling activities with subsequent distribution to each station over its respective relay.

TRANSMITTER TOWER

The TV transmitter tower is probably the most universally used ENG receive site. It is not necessarily the first site, but eventually it emerges as the most logical. Typically, the tower site provides the long range performance.

Depending on tower load budget, antenna selection can range from the earlier four quadrant horn or omni antennas, both approximately 13 dBi gain, up to the higher gain, 26 to 29 dBi, steerable reflector antennas.

Two basic tower configurations have emerged over the years. The most prevalent configuration places the antenna with low noise amplifier at the highest available position on the tower, with the RF and control lines run down to the receiver and control system in the transmitter room. The received signal is then coupled back to the studio over a duplex channel with the STL.

A second configuration places the antenna, along with a tower mounted repeater box at the highest point. In this configuration, only control line or VHF/UHF radio control is coupled to the repeater and the output is coupled to the fixed relay antenna for routing back to the studio.

Some considerations for tower systems are: tower loading, lightning protection, icing conditions, elevator or climb, and environmental extremes. Tower sites, with their associated long range capabilities, can support regional interchange of news.

A projection of receive site height versus horizon distance is plotted in Fig. 1.

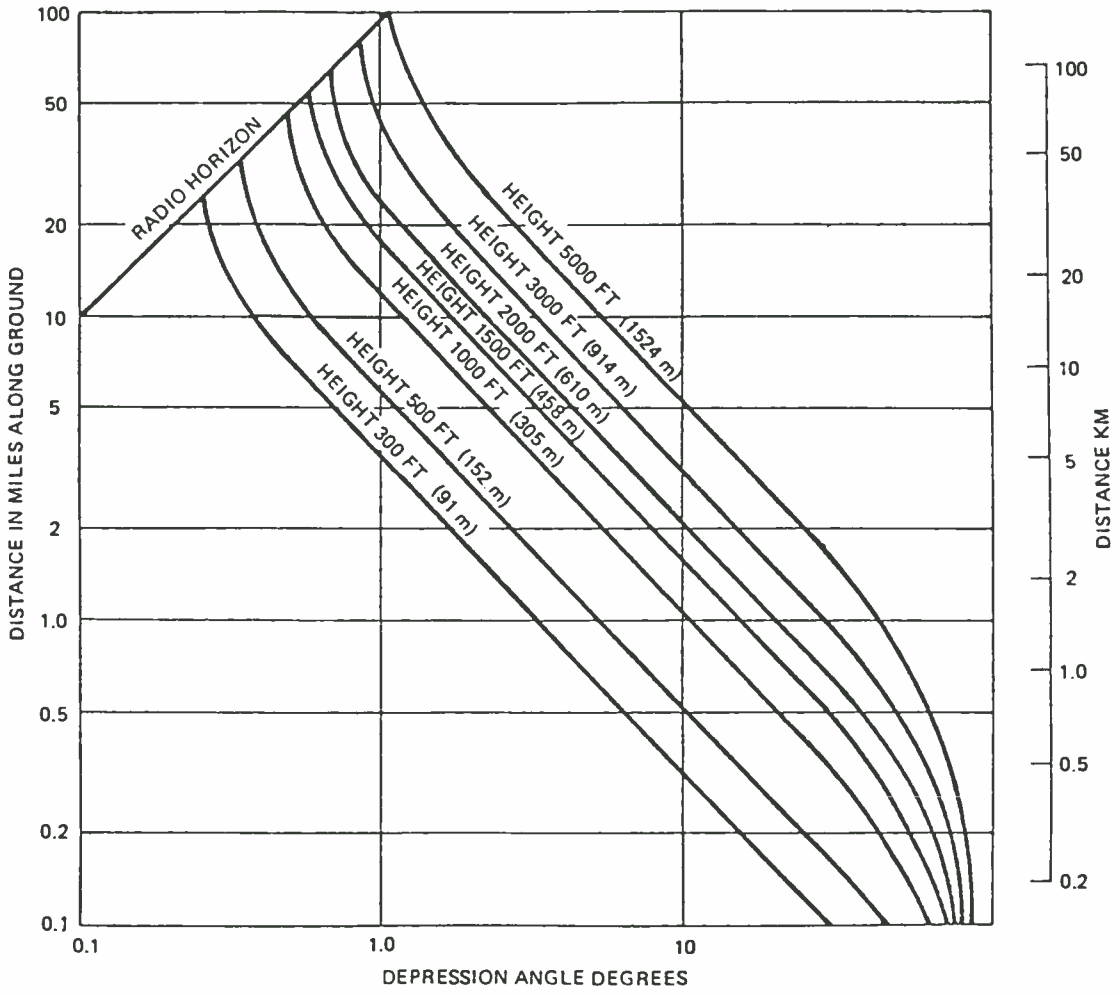


Fig. 1. Conversion of antenna angle to distance miles for different antenna heights.

THE ENG VAN

The ENG Van is a study in the evolution of human engineering. Each van design reflects changes peculiar to the people involved. We will restrict our discussion to the microwave content.

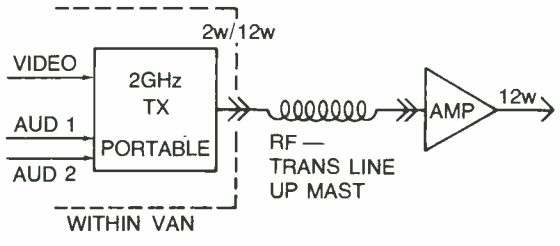
Transmitter systems at 2 GHz take a number of approaches, all aiming to provide the maximum 12 watts allowed by the FCC for mobile input to the transmitting antenna.

Maximum flexibility is provided by the following Block Diagram A. This configuration allows for full power at the antenna on the van mast as well as full power when the transmitter is removed from the van and used externally, e.g., on a roof top for a more direct shot to the receive site.

A second configuration is detailed in Block Diagram B. This configuration is used for a more economical design when the transmitter is expected to remain devoted to the van and only employed as a separate portable on rare occasions.

A third configuration represents the earlier van designs and is detailed in Block Diagram C. Essentially, all the basic transmitter-amplifier

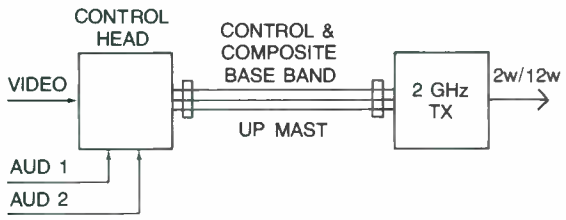
Block Diagram A:



Typical Van Tansmitter Configuration

Typical ENG Van. (Courtesy M/A-COM MAC)

Block Diagram B:



Block Diagram C:

systems cover the standard seven channels plus offsets (½ channel frequency up or down) of the 2 GHz band and operate from either +12V to +31 VDC or 115 VAC.

Various telescoping masts have been employed ranging from 15 feet high to greater than 50 feet. Many operators in (metropolitan) environments feel the shorter masts are just as effective to get above local traffic and to set up a reflective "bounce" path. The taller masts have proved effective in treed areas, enabling the antenna to get up to the thinner portions of vegetation.

Typical van-transmitting antennas are detailed in Table 1. Gain, wind load, mast stability, and stored configuration are some of the considerations.

TABLE 1
Van-Transmitting Antennas at 2GHz

Single Disc Rod — 18 dbi — Circ. Pol. — 6.1″×6.6″
Dual Disc Rod — 21 dbi — (2 Element) — 6.1″×22″
Golden-Rod — Dual — 21 db — 4.25″×20″
Quad Rod — 24 dbi — (4 Element) — 6.1″×54″
Silhouette — 20 db — 20″×30″
2-Foot Parabola — 19 db — Circ. Pol.
4-Foot Parabola — 25 db — Circ. Pol.

The interrelation between van and receive site is obviously important. We have noted that multiple channel (frequency agile) equipment is employed to help avoid interference among users. Multiple polarized antennas are also used to assist in this interference avoidance as well as helping self-generated interference to our own signal.

Circular polarization has been promoted for many years as a technique to reduce multipath signal reception which in turn generates many ghosts in a conventional video system. The basic theory shows that if a transmitted signal is launched from a "right circular" polarized antenna, a corresponding "right circular" polarized receive antenna will couple the incoming signal to the signal input receiver at maximum power transfer.

Conversely, if a transmitted signal is launched from a "left circular" polarized antenna, a "right circular" polarized receive antenna will accept this signal at a dramatically reduced power transfer efficiency, on the order of 20 dB below the correct mode.

A characteristic of circular polarization is that *"right circular"* wave reflecting off a reflective surface will become, effectively, a *left circular* wave. As described above, this reflected wave, as a multipath signal, is now reduced dramatically at the receiver front end, helping to make a cleaner desired signal. This antenna performance is used constructively in ENG operations. In one sense, "multipath", the undesired reflected signals, is reduced by the polarization isolation of the receive antenna. In the opposite sense, intentionally reflecting, or "bouncing", the signal is used to reach the receive antenna from blocked van positions. In this mode the receive antenna is switched or tuned to the opposite circular polarization from the transmitting antenna, optimizing the input.

In contrast, a "linear" polarized signal, be it horizontal or vertical, has no reversal of apparent polarization when reflected off a reflective surface. This passive discrimination of circular polarization has been a vital ingredient in ENG operations. Fig. 2 is a graphic display of the benefits of circular polarization.

Most receive site antennas are configured with continuously variable polarization or switchable polarization, right circular, left circular, horizontal, and vertical. This design flexibility allows the studio operation to optimize the reception.

The basic function of the ENG/EFP microwave van is to couple the remote camera origination back to the studio. Another function that often occurs is as a repeater van. Some consideration in configuration should be given to this use. There are a variety of combinations that allow a van to be used as a repeater. A typical mode is to extend the position of the cameraperson beyond the hard wired video/audio lines by the use of a 13 GHz mini portable. A small 13 GHz transmitter with 3 inch horn antenna allows the cameraperson to extend the coverage over one mile from the van. Obviously, alternate antenna sizes are available that further extend these possibilities. Another van repeater configuration is as a 2 GHz in-band repeater. Situations arise that call for long distance coverage which in turn requires the employment of two vans in tandem.

In this mode, care must be taken to provide sufficient isolation to the receiver system. The unknown conditions of relative positioning of receive antenna to transmitting antenna can be a problem.

13 GHz Mini Portable. (Courtesy M/A-COM MAC)

Consider a configuration wherein the optimum receive antenna position ends up looking right at the outgoing transmitting antenna. Front end overload will severely limit the receive path range. The latest receiver designs have addressed interference rejection with some dramatic improvements, however this adverse proximity to high power transmitters will most likely require selective channel filtering. Both transmitters and receivers need this filtering.

The transmitters typically employ wideband power amplifiers to support high power along with full band frequency operation. These amplifiers produce an undesirable noise level across the full bandwidth therefore acting as a noise generator to the nearby receiver. Channel filters must be employed, one tuned to the

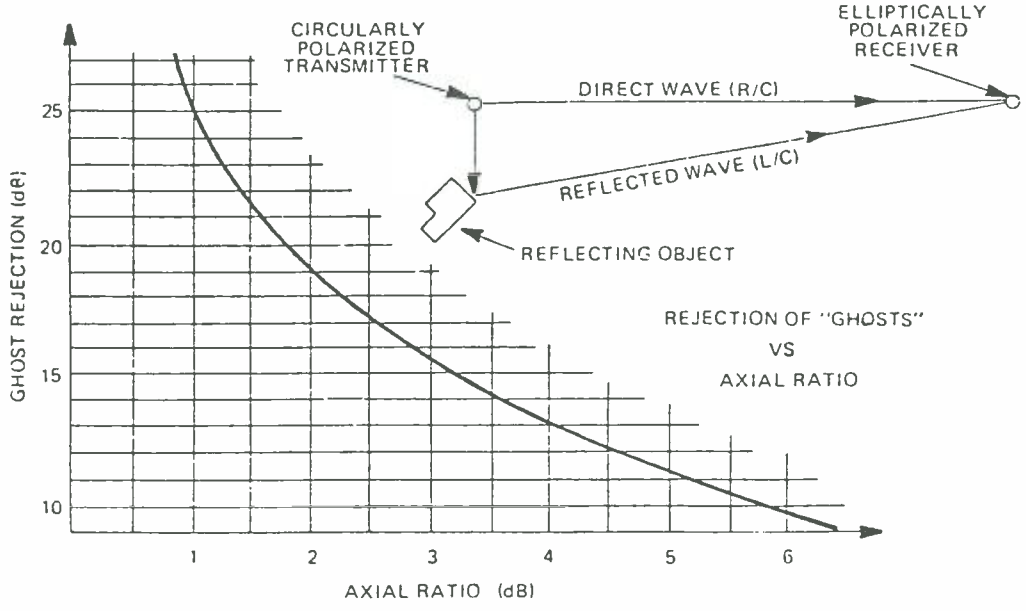


Fig. 2. The benefits of circular polarization.

transmitter frequency to limit out-of-band noise, and one to the receiver, to reduce the unusually high level of interference signal to the receive signal. This reduces the frequency agility somewhat, but is a reasonable compromise under these adverse configurations.

The 13 GHz mini portable system mentioned above has been joined by new system combinations at 38 GHz. At this high-frequency, compact transmitters have somewhat limited range, approximately one mile with reasonable performance and horn-type antennas. This flexibility is valuable in cutting the umbilical cord to free the cameraperson from the van. With proper choice of antenna, these signals can also be "bounced" when line of sight is not possible.

Full van-type vehicles have been the primary remote vehicles for the early news gathering systems. In a conventional van configuration, the microwave content is typically a mini portable 13 GHz system, comprising a comera cable extension, a 2 GHz transmitter, a 30- to 40-foot telescoping mast and a circular polarized transmitting antenna.

The "news car" concept is another type of remote unit. This is a streamlined vehicle similar to the film car of earlier days. In the news car, the microwave content is basically a 2 GHz low-power/high-power transmitter, a tripod or short bumper mount, manual telescoping pipe, and a small transmitting antenna. The combination allows for quick and simple set up, by snapping the antenna to the transmitter and then to the tripod, or by putting the transmitter in the trunk to a coaxial line to a quick-connect antenna on a pipe mount.

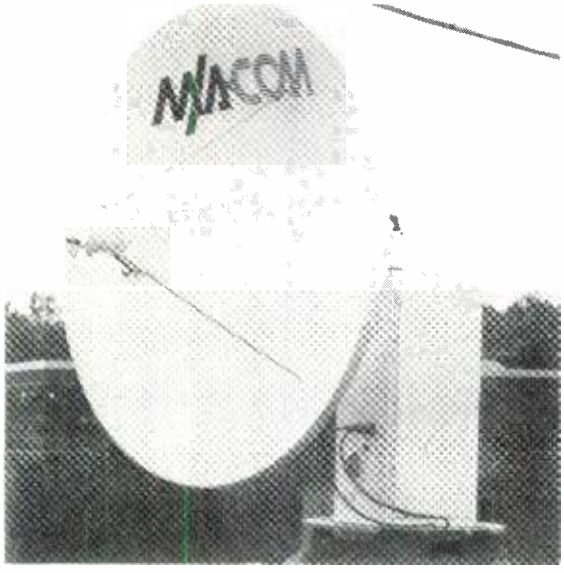
CENTRAL RECEIVE SITE

ENG central receive design configurations employ a variety of antennas; some of these are as follows:

a. Omni-directional dipoles—6 to 13 dBi
b. Quad horn-switched 90 degree sector—13 dB per sector
c. Directional nominal gain—16 to 20 dB
d. High gain steerable—22 to 24 dB
e. Higher gain—narrow beamwidth steerable and auto-track—25 to 29 dB
f. Dual band 2 and 7 GHz or 2 and 2.5 GHz directional—steerable 22 to 25 dB

The omni class of antenna can be varied in gain versus length with corresponding reduction in vertical beamwidth. Omnis serve the necessary functions and allow for essentially lower cost, low wind load and simpler installations. The inability of the omni to reject multipath or interference is a drawback. A relatively clean receive site—high tower, flat terrain—coupled with clear, narrow beamwidth, transmitting antenna positions can support the omni configuration.

The quad horn-switched 90 degree sectors provide the full complement of polarization selection (horizontal, vertical, left circular, right circular) along with direction discrimination. The multiple, four separate quadrant elements allow for a variety of installation configurations. They can be grouped in a cluster, as on a tower, or separated far apart, as on the corners of a roof top. This flexibility of placement along with the



Superscan™

Miniscan™

selectable sector discrimination has led to wide use in downtown, high rise and roof top installations. Bounce (reflected) shots are easier to set up with horn antennas, versus steerable, since only one antenna, the van, is essentially panning and the studio observer has the ability to select the optimum polarization and sector. Control systems with quad horn antennas provide two-way control command and confirmation feedback of sector (N,S,E,W) polarization, (H,V,RC,LC) receiver AGC and frequency channel.

High gain, steerable antennas combine the standard antenna technologies of aperture (size) and phasing (numbers of elements) to provide the higher gain, 20 to 29 dB. This higher gain dramatically increases system sensitivity (double range per each 6 dB increase). However, the narrower beam width and panning at both ends of the path introduce some complexities in optimum path alignment.

REMOTE CONTROL

Remote receive sites require control from the studio. The control systems are typically designed to operate over standard voice circuit lines (Telco 300-3400 Hz), 2 wire and/or 4 wire. If subcarrier capacity is available over existing microwave paths (STL/TSL) then the control circuits can be carried on these networks. Some standard telephone lines can exhibit noise conditions creating false inputs to and outputs from the control system. Care should be taken to note this, as opposed to assuming there is a fault in the antenna system.

The control functions from the studio vary somewhat versus the class of receive antenna, but basically are: Antenna direction—Azimuth and elevation in steerable systems, Quadrant (N, S, etc) in sector systems. Polarization—Right Circular/Left circular Horizontal/Vertical or any in between mode on continuously variable systems. Other functions provided are Frequency Channel selection and AGC indication of Received Carrier Level.

Studio observation of optimum receive signal on a video monitor and speakers is conventional. Maximum AGC feedback is not always synonymous with optimum video/audio.

INTERFERENCE AND CENTRAL RECEIVERS

Rejection of interference from other originating systems has been addressed by suppliers and operators: Local frequency coordination and planning are a must. Planned antenna polarization can help. Diverse receive site selection is possible. In most markets an optimum common site usually emerges and interference grows.

Receiver design has evolved focusing on rejection of undesired signals while preserving the desired signal to the extent possible. The essential compromise that has emerged is reflected in the common baseband loading of standard color video with audio subcarrier at 4.83 MHz. This close-in subcarrier frequency has led to narrow IF bandwidth designs. Naturally, the ability to pass multiple subcarriers suffers under these limitations. Variable bandwidth control is effective in supporting configurations that call for field production as well as news gathering.

Remote Van Positioning Considerations:

Line of sight from the transmitting antenna to the receiver antenna is the desired optimum configuration. Many situations preclude this, and trial and error situations must be evaluated. The studio controller is an active participant in this activity. Quadrant awareness of the geographical terrain relative to the remote vehicle position is obvious. Topographic overlay mapping of the area with respect to the receive site antenna has been successful. Trial and error experimentation along with recorded results has been very effective. Computer inventory with recall coordination has been implemented at many stations.

Bounce shots can be a solution to a blocked path. Any reflective surface can act as a beam redirection. It is helpful if the van crew is aware of their relative elevation to the receive site. The reflected signal can be considered similar to a handball trajectory—the angle of incidence determines the angle of reflection. Exaggerated elevation of the van antenna can easily cause the reflected signal to pass high over the receive antenna. Multiple bounce conditions can be set up; however, energy disbursement loss must be considered and long range success is doubtful. Fig. 3 presents an effective configuration versus respective antenna gains; note this assumes no obstructions.

AIRBORNE CONSIDERATIONS

Helicopter use by news departments for video coverage can be supported by standard ENG microwave hardware. The helicopter used as a camera platform transmitting to the studio and as a long range microwave repeater platform, can be readily implemented.

Omni antennas (see photo) have been mounted below helicopter frames with varying degrees of success. The omni (360 degrees) patterns coupled with adverse terrain, high hills, buildings etc., result in troublesome multipath. Steerable and

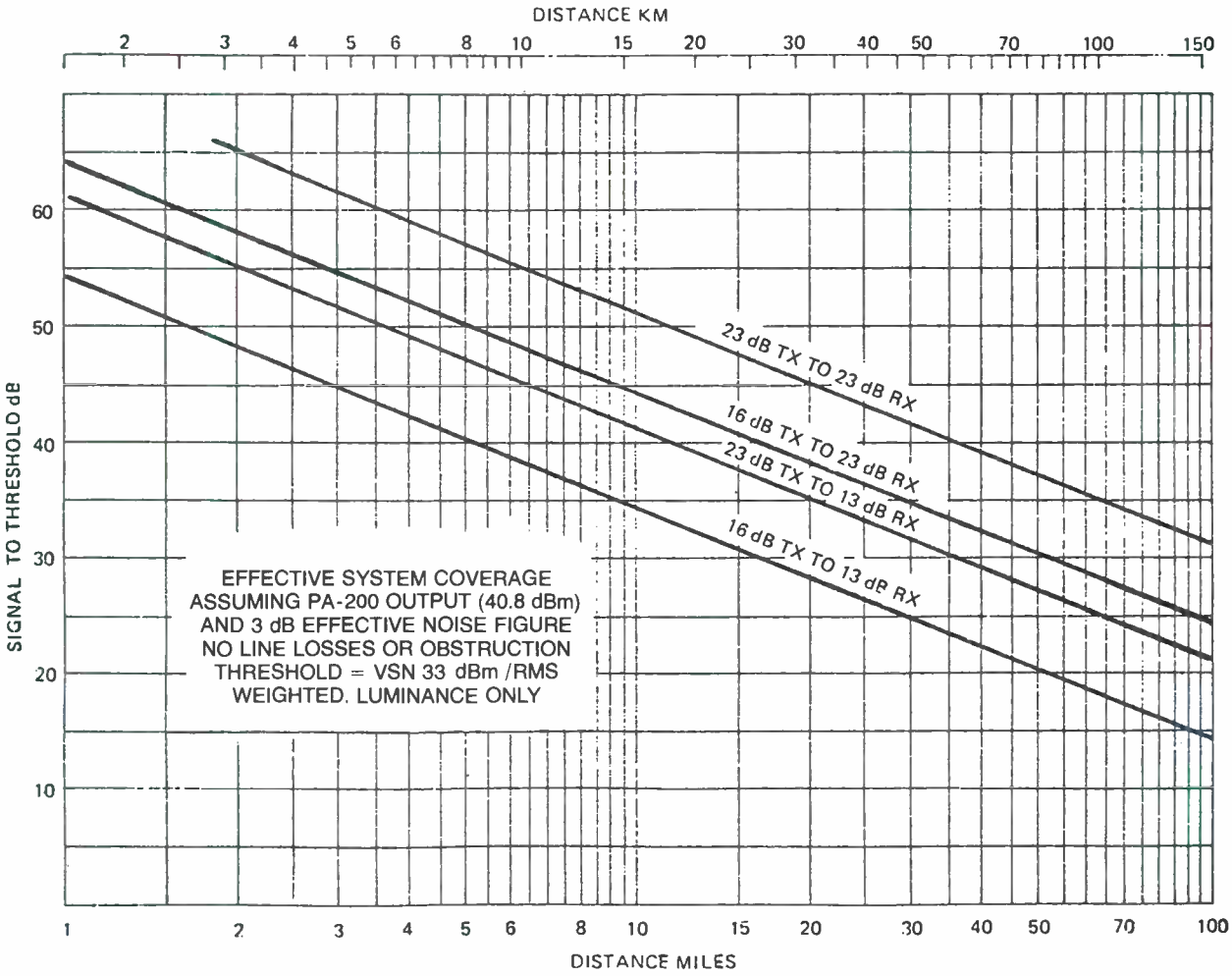


Fig. 3. Effective system coverage.

autotrack receive antennas help reduce this problem but do not eliminate it.

Examination of the omni patterns and the interrelation of gain and elevation patterns demonstrates other performance characteristics that must be addressed. Nominal gain, omni designs (4-6 dBi) have relatively narrow elevation angles resulting in dramatic drop-off of signal strength when the helicopter executes a relatively sharp-angled turn.

Directional transmitting antennas can dramatically reduce the multipath problems prevalent in the omni antenna. Steerable high gain, directional airborne antennas are available with sophisticated automatic steering and/or manual steering. The manual steering configurations require constant attention and relative bearing inputs.

One class of automatic steering system employs a magnetically stabilized gyroscope. A Horizontal Situation Indicator (HSI), coupled to the gyroscope can be set on the correct bearing, steering the directional transmitting antenna to the receive site. As the helicopter maneuvers about this setting, the system automatically holds the directional antenna on the preset bearing. The set antenna bearing will be effective with no further update until the aircraft moves so that the antenna beamwidth falls off the receive site. A manual reset of the new bearing must be initiated at this time.

Skypod-Airborn Antenna System. (Courtesy M/A-COM MAC)

A further sophistication of this steerable system can be implemented with the incorporation of a microcomputer and Loran-C or Omega navigation network. The navigation system provides a continuous update input to the HSI correcting the relative azimuth on a full time basis. Receive site coordinates can be entered in the minicomputer and the system programmed to hold the directional antenna to the required bearing.

Fig. 4 is a nomograph of respective antenna heights for helicopter and receive site versus distance. It should be noted this is based upon a 4/3 earth radius and represents a grazing condition. It also assumes a smooth intervening terrain. Terrain roughness will result in the need to elevate site end points.

Bell Jet Ranger helicopter in flight with retractable antenna mount extended.

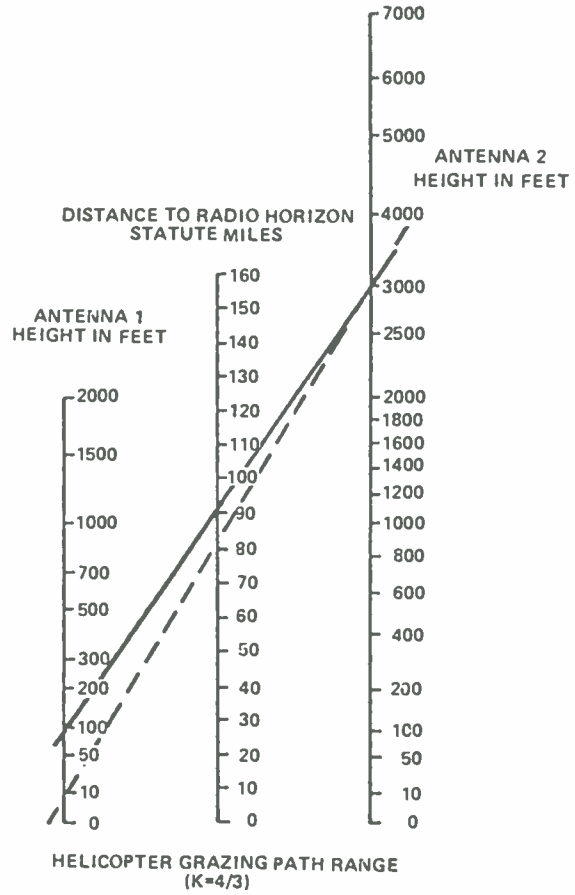


Fig. 4. Helicopter grazing path range (K = 4/3).

Reference:
Forbes, E. J., *An ENG/EJ Handbook*, Microwave Communications Company, Burlington, MA, 1980.

6.3

Television Field Production: An Overview

Carl Bentz
Television Editor,
Broadcast Engineering Magazine
Overland Park, Kansas

Television made a major change in our lives. We no longer had to be content with listening to Ted Mack's Amateur Hour; suddenly the contestants were in our living room. Our imagination could paint the scene as the Lone Ranger met Tonto in a radio studio cottonwood grove; but the magic of TV, through film, proved beyond a doubt that Silver was a magnificent white horse. The excitement of a tie-breaking World Series homer was unquestioned from the radio commentator's voice; however, seeing the action live from the stadium in New York brought new meaning to the game.

Not only has 'remote' taken us from the studio, it has taken us across town, across the country, around the world and into space. The ultimate ENG experiences to date must include the closeup images of Saturn's rings and the sight of Earth and men working in the cargo bay of the Space Shuttle. What better TV coverage than showing such far reaching successes of mankind!

What is Field Production?

Whether we call it ENG, EFP, OB or remote, the concept of field production is the same. Escape the confines of studio walls. Find, and take advantage of, the reality of the outside world.

ENG (electronic news gathering), the simplest means, overcomes our dissatisfaction with talking-head newscasts. We see the first place marathon runner cross the finish line; the biggest catch of a local fishing contest pulled in; the result of a neighborhood effort to aid the elderly. We experience the terror of fires, tornados, war, etc. Our preference is to see it from a live camera via microwave to the studio. But we are content to see it by tape-delay during a regularly scheduled time, so our favorite weekly series is not interrupted.

The demands on ENG equipment are dictated by the needs for immediacy and flexibility. The

Fig. 1. The JVC ProCam series offers lightweight, easy operation, even by unskilled ENG operators. (Courtesy JVC)

Fig. 2. Philips LDK-6 automatic camera family includes compatibility and adaptability to any use. (Courtesy Philips)

equipment must be rugged, easily portable and easily set up and used. The news director is interested in having useable pictures and sound in a hurry. The subtleties of gamma and signal-to-noise are of little importance, particularly in the case of a live news feed or where the footage will only be used one time. Simplified controls and automatic circuitry save time and reduce the chances for error even though they may not produce the best quality under all conditions.

EFP (electronic field production) expands our view. Whether the program is one of the soaps or a documentary feature, being there, even by TV on tape, is better than staying inside the studio. EFP is not bound to videotape; it can be live. Production, however, suggests that post-production may follow the shooting.

EFP crosses a hazy boundary into outside broadcasting (OB), as we televise live remotes. We expect the pagentry of the New Year's Day Rose Bowl Parade; political conventions; a Presidential Inauguration; the Super Bowl game; or a royal wedding. Seeing is believing. Immediacy enhances and satisfies our interest to share happiness and sorrow with our fellow man.

Here the demands on the equipment are for ruggedness and flexibility, but performance quality is more important than with ENG. News production may accept noisy pictures with poor color balance and distorted sound if the content is urgent and the exposure is brief. For longer segments or full-length programs, particularly where considerable expense is involved in acquiring rights, setting up and post production, producers and sponsors are looking for close to studio quality. On the other hand, there is usually more time, in EFP, to set up and adjust equipment to achieve good quality. If equipment is highly automated, it may be desirable to have overrides allowing manual tweaking for optimum performance.

What does field production offer to the station? Viewer satisfaction is one thing, but the visibility of the TV crew at an event heightens the station's committment to, and involvement in, the community. The station becomes more a part of the locality and increases the community's acceptance of the station and its products—communications and programming.

Planning for Field Production

Because preparing for remote capabilities is a major step in station growth, planning is essential. Obviously a primary concern must be budgeting. Management will want the most for the least, but cost effectiveness and reliability are critical. Both personnel and equipment considerations will bring all station departments into the final decisions. Programming and production may know what they want to do, but it will be up to engineering to make it work, to the sales department to earn extra revenue, so that accounting can make payments on the new equipment and perhaps new salaries.

The planning phase considers pie-in-the-sky dreams, as well as down-to-earth realities and limitations. Compromises will be required, and, from them, decisions made on the proposed extent of field production activities and the preferred approach to acquiring equipment.

Who will operate what equipment? Labor agreements may dictate that engineering staffers handle all camera and recording operations. In other stations production people may do some of the technical work. But one question remains—are there enough people now on staff to handle extra assignments?

To what extent is remote operation expected? Do plans warrant purchasing a production vehicle? Should the purchase be a customized system? The bigger the remote vehicle, the more sense a

Fig. 3. Midwest Corporation custom design for TCS Productions. (Courtesy Midwest)

custom system makes. Outfitting a vehicle takes time, and splitting the station staff between construction and regular duties may not be feasible. There are many companies that are well versed in building to given specs. All choices may be left to the buyer, or standard packages of equipment may be offered.

To Lease or To Buy

Leasing might be a more practical approach to start with. It could allow a trial period, so to speak, to check out production concepts and feasibility of remote activities for your station. Keep in mind that if you own your own, you are also responsible for continuing equipment maintenance, upkeep of the vehicle itself and the financing of the system.

Leasing costs for production equipment will vary with area of the country, availability of the equipment and the size of the system needed. A ball park price for a complete 40-foot van, including six or more cameras, several VTRs, all audio and video switching equipment and monitoring, will average about $13,000 per day. In general, a price of $600 per equipment item is a guide line. Still-store systems will possibly be more. The daily amount covers a 10-hour day and takes into account an operating crew of from 18 to 20 people.

The purchase of a turnkey production system will be expensive. The simple ENG super-van configuration is commonly priced from $100,000 to $250,000. If the purpose is strictly ENG, perhaps a 4-wheeled vehicle would be a better solution. Protective containers for the camera, recorder and microwave wave system could be installed, still leaving room for the camera operator, a microwave technician and the reporter/talent.

The stepvan or straight truck system will include more equipment and is geared more toward full production, i.e., several cameras with CCU control positions, several recorders, monitoring equipment, audio and video switching systems and perhaps microwave for going on the air live. Costs of such systems will start upward of $150,000 and could surpass $500,000.

Fig. 4. A transportable elliptical system from GEC-McMichael. (Courtesy GEC-McMichael)

The 40-foot van trailer is the epitomy of production units, and carries a fitting price tag. Except for actual floor space, it is a studio on wheels and requires an equipment complement that resembles or exceeds a normal studio. Vans similar to those used by the major networks will have multi-million dollar tags for a complete studio vehicle with multiple cameras, audio and video recorders, audio and video switching, appropriate audio, pulse and video distribution amplifiers, audio and video monitoring equipment and sufficient air conditioning to cover the heat rise of equipment and personnel.

Making the Mobile Unit Mobile

The cost of the 40-foot van system will probably not include a tractor to transport the system from one production site to another. Tractors may be leased on short-term plans for an average cost of $116 per day or more economical long-term bases. The leasing plan usually includes any emergency or normal mechanical repairs, licensing and taxes required for the tractor.

Alternatively, the tractor could be purchased ranging from the mid $60,000 to mid $70,000s, for a cab-over unit including a sleeping berth for those trips that require a long haul situation. Used tractors may be found in the $30,000 to $45,000 range and could probably provide the required service. Maintenance, operation, licensing and taxes for the tractor must be included in any plans for purchase.

Keeping the mobile unit in top operation requires a maintenance plan. The plan followed by ABC Sports, for example, involves over-maintenance of the fleet of 18 tractor/van production systems. In 1984 terms, the cost of the program is a ballpark total of $200,000 for the entire fleet. Each of the #362 Peterbilt tractors is rated to handle loads to 80,000 lbs gross weight, so the load presented by the 68,000 lb van systems offers no difficulties.

A reliable driver is also a must. Again referring to the ABC Sports organization, a driver must prove a 250,000 mile successful driving experience. His record must be spotless and involve all types of driving conditions, including all four seasons and preferably all areas of the country. Because the driver is in charge of a multi-million dollar package of equipment, he must have a highly professional attitude. The success of the network's sports programming is dependent upon the remote vehicles being in place at specified

times. It is the driver's duty to have the equipment there—on schedule.

Lease-Outs Aid Financing

If you decide to buy, leasing the system to others could provide aid in financing it. The status of owning your vehicle and the convenience of not having to arrange for a leased system are plus factors. If you consider allowing others to use your system, however, two additional questions need to be answered. Will the truck need a staff on lease-out assignments? Will the equipment complement make the truck desirable to others?

If the plans include live remotes, the remote van will require microwave systems to feed signals back to the studio. Some type of 2-way communications is required in the truck for cueing purposes. New subcarrier applications for TV would allow cueing to be provided through multiple aural subcarriers of the station. Frequency coordination is important, particularly in larger markets, and should be part of the planning process (see the chapter on Frequency Coordination in Section 1). Depending on how remote the production location is, transportable uplink and satellite reception capability could be employed. An alternative might be to contract for a common carrier service through one of the newly formed "bypass" microwave companies.

It quickly becomes obvious that planning for remote operation requires answers for four basic questions. What is desirable; what is feasible; what is acceptable; and what is affordable?

Selecting Equipment

Shopping for remote equipment is just as critical as purchasing for the studio. Signal quality is a major consideration, but cost, unfortunately, has some control over quality. The equipment should be as simple to operate and maintain as possible, particularly since non-technical personnel could be involved. Logic suggests compatibility is desired between the new remote items and existing studio equipment.

Cameras

Probably most stations already have one or more basic ENG systems (one camera, one portable video recorder), which see hard treatment in the news department. If all cameras are the same brand, perhaps even the same model, maintenance expense and operator confusion will be reduced. Identical recorders will avoid format interchange problems, large parts inventories and extra operator training time. This approach provides compatibility between ENG systems.

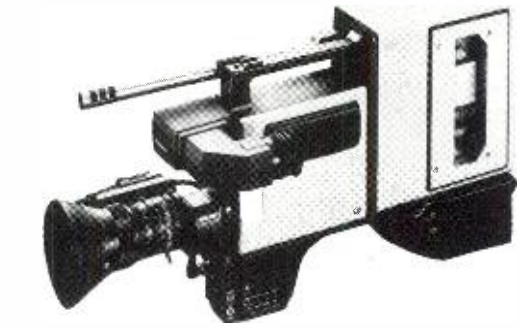


Fig. 5. The Panasonic RECAM and Sony Betacam products include complete systems of cameras, recorders and editing equipment. (Courtesy Panasonic, Sony)

What kind of equipment do we want in our remote system? Nearly any camera could be used for remote production. Other sections of this handbook will give specifics on different products. But let's look at few of the factors which may determine the choice.

- Pickup type—Plumbicon or Saticon tube or CCD
- Three tube or single tube with striped faceplate filter.
- Optical format—½", ⅔", 1" or 1¼"
- Configuration—hand-held, tripod mounted, pedestal mounted.
- CCU/remote panel—required or option.
- Output signal—composite or component video. (PAL, NTSC, Betacam, M, Lineplex, etc.)
- Link to production control—coax, triax, multicore, fiber optic, microwave or none.
- Automatics—black/white balance, iris, registration, centering, etc.
- Detachable recorder unit.
- Digital memory of setup parameters.
- Computer setup system.

- Viewfinder diagnostics.
- Available lens systems.

Some Camera Specs Specifically:

Sensitivity is defined as that amount of light falling upon the scene to be televised (i.e., a standard test chart) that produces an output video signal of 1V peak-to-peak (p-p) including sync or 0.707V p-p non-composite. The value may be given in foot-candles (lumens per square feet) or lux (lumens per square meter), where 1 fc = 10.76 lux (1 lux = 0.0929 fc). The sensitivity specifications should include the lens f/stop, the scene reflectance percentage and the video gain setting. The color temperature of the light on the scene is typically specified at 3200 K.

A data sheet for the Philips LDK-614 ENG camera lists 1300 lux, f/2.8 and 60% reflectance. The incident light falling upon a scene (or test chart surface), 1300 lux, which reflects 60% of that light toward the camera, with a lens set for f/2.8 and video gain at 0 dB, should produce a standard TV video signal.

Maximum sensitivity (or minimum illumination) goes a bit farther. ENG cameras include a video gain control. Actual gain figures vary, but 0, +6, +12 dB and 0, +9, +18 dB are common values. We now are given the amount of light with an f/stop, reflectance % and gain figure, all of which still give the standard video output signal.

For the Panasonic AK-3010 camera head, sensitivity is 2000 lux, 89.9% reflectance chart, f/4.5 and 0 dB gain for standard operation. Under low light conditions, the maximum sensitivity is rated 24 lux, f/1.4 and gain at +18 dB, still using the 89.9% reflectance chart.

Fig. 6. Wireless microphone equipment attaches to the camera to free talent and camera operator from microphone cabling. (Courtesy Panasonic)

It should be noted that in the two examples, the reflectance is different. The camera rated with a 60% figure should be more sensitive than that with the 89.9% value, if the other parameters are the same. Recall that as the lens setting moves from f/4 to f/5.6, the relative aperture is getting smaller, or less light is entering the camera. The larger the number in the "f/" rating, the more sensitive the camera. Finally, the smaller the lux value (which may be estimated to be foot-candles x 10), the more sensitive the camera.

Color temperature of the incident light will have some effect on the output signal level, but its primary effect will be upon the white and black balance. Color temperature is based upon a rather esoteric concept from physics. The color temperature is that temperature to which an "ideal black body radiator" must be heated to radiate a specific color of illumination. The greater the degrees Kelvin specified for color temperature, generally the more blue the light becomes. For example, some idea of the variation is seen in the following color values. Actual numbers will vary from reference to reference, but these serve as indicators.

Candle flame	— 1,850°K
Sunrise	— 1,900°K
500W incandescent lamp	— 2,960°K
TV studio lamp	— 3,200°K
Photographic flood lamp	— 3,400°K
White fluorescent lamp	— 4,500°K
Average 12-noon sunlight	— 5,350°K
Daylight fluorescent	— 6,500°K
Blue sky	— 11,000°K to 25,000°K

Color monitors will also be factory aligned in accordance to color temperature. One common "white" value is noted as D-6500, meaning that a white raster is equivalent to a 6,500°K average daylight white. Some monitors are set for a white reference C, which is approximately 7,000°K.

ENG cameras must be capable of handling a much wider range of lighting conditions than their studio cousins. The camera that goes to the baseball park may need to shoot a segment in full sun, then another in the shade. On the way back to the station, the assignment might require working in an interior artificially lighted area. For an idea of the variation, consider the following lux values.

Full sun	— 100,000 lux
Overcast at noon	— 10,000 lux
Interior by window	— 1,000 lux
Interior work area	— 100 lux*
Full moonlight	— 0.2 lux

*(Artificial light, considered the minimum for working, closely lighted)

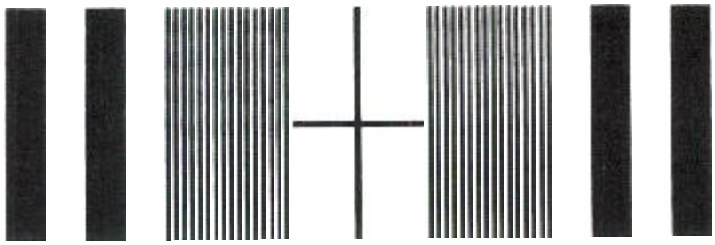


Fig. 7. Modulation depth test chart.
(Courtesy Telecommunications Industries Ltd.)

Again, reference sources will no doubt vary on the luminance values for any given situation, due to the many subjective variables that will come into play.

In order that the camera can begin to accommodate the possible range of light conditions, two types of filters are available in the camera's optical system. First, color filters compensate for the color temperature of the incident light. One will allow a studio light temperature to be changed to daylight color; another, for outdoor use, converts light to the 3200K studio condition.

Neutral density (no color) filters are included to compensate the wide range of illumination. Some are rated by a percent density. Others are graded by a logarithmic scale. In conjunction with the auto iris feature found on most cameras, the neutral density filter allows the camera to better handle wide illumination variations.

Horizontal resolution can be confusing, as specified by the manufacturer. Typically the value is given for the green channel only. The specs should indicate if the values are given for a camera with no enhancement applied or with detail circuits active. The specification may be noted in TVL (television lines at center of screen) or in % depth of modulation. Depth of modulation compares the ability of the camera system to respond to segments of a test chart that are equivalent to frequencies of 5 MHz and 0.5 MHz, i.e., a comparison between 400 TVL and 40 TVL. If the amplitude of the waveform produced by the pattern shown on the modulation depth chart marked 5.0 (a value "b") is compared too that from segments marked 0.5 (a value "a"), then

$$\text{Depth of Modulation} = (b/a)\text{x}100\%.$$

Recorders

Video recorders also offer a great deal of variety. (As this material is written, there has yet been no agreement as to a standard 1/4" format. The 1/2" format remains divided between Beta and M.)

- Portable or mounted use.
- Format—1" B or C, 3/4" U-matic, 1/2" Beta or M and 1/4" Lineplex.
- Recording format—Composite video, color under or component video.
- Confidence heads.
- Playback electronics.
- Field editing accessories.
- Weatherization
- Battery or ac operation.

For EFP material planned for post production, the 1-inch B and C formats continue to hold ground. Although the 1/2-inch system quality rivals the larger formats, 1-inch retains an edge in picture quality. Portable recorders are available in B and C, 3/4" and 1/2" formats.

In the production vehicle, 1-inch, 3/4-inch and 1/2-inch systems are found. The two larger types are more popular, probably because they are more established and have included dynamic video head tracking features for a longer time. Dynamic tracking, with appropriate timebase correction, allows the still frame and both forward and reverse slow motion features, which are of prime interest in sports coverage.

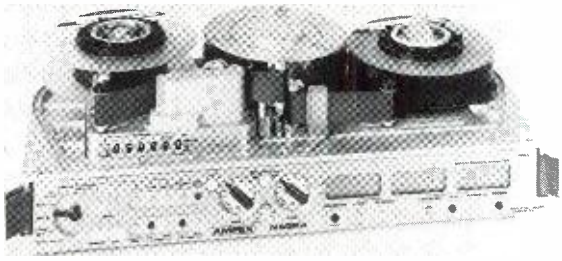


Fig. 8. The Ampex/Nagra VPR-5 system uses lightweight alloys for critical framework stability. Extendable reel support arms allow longer play-time reels, if the machine is used in a van. (Courtesy Ampex)

Other Recording Media

In any size production vehicle, the magnetic disc medium is possible, occasionally with effects capabilities. Ampex in the US and TEAC in Japan (for the Tokyo Olympics) developed disc-based slow motion products which doubled as still-frame storage units.

With floppy disc technology, the Arvin/Echo EFS-1 videodiscassette unit allowed much less expensive still-frame pictures and stepped slow motion during Monday Night baseball games in 1976. Several models later, Precision Echo continues the dual-sided, discassette concept to store 200 images per disc side in a table-top package.

As rigid Winchester disc technology shrank in size, the higher density medium allowed digital disc recording techniques to appear in the Abekas VSP42 Video Slide Projector (later the A42). The rugged system, requires only a few rack units of space, stores 100 frames, expandable to 300 frames, and provides a streaming cassette system for off-line storage. At NAB '84 the A42 was shown with a companion A52 video production effects unit designed around the same limited space feature. Other such systems may be expected in the future.

Other hard disc-based systems, generally requiring larger spaces, are available from ADDA, Ampex, ASACA, Harris Video, MCI/Quantel and NTI.

Film continues to play a role in production for television. While Sony, Ikegami and others have developed interesting products for HDTV applications, film presently maintains an edge in production, particularly for prime time TV presentations. The name of Arriflex is one of the best known for film cameras in the US. A recent introduction by Aaton/Zellan, Clear Time Recording, allows time code information to be printed directly on the film. With multiple cameras involved, this system makes post production editing much easier without the use of slating.

Switching, Etc.

With multiple camera systems, video switching is a must. Every switcher manufacturer offers several system sizes, one of which should work nicely in a vehicle. Most are composite video products. Grass Valley Group and Shintron were the first to introduce component video switching systems in small formats that allow mixing of both types of video signals. Plan for an effects section with at least the typical wipes, keys, etc. Remember that inputs should be available for all possible cameras as well as other sources. You may want to use roll-ins from video tape, the still store and even a graphics system.

Audio, too, must be controlled. Whether the need is for simple or automatic mic mixing, up

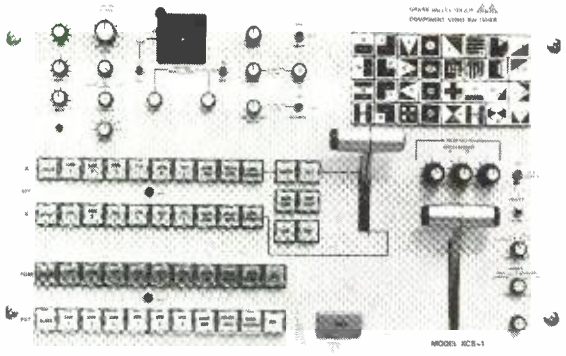


Fig. 9. The GVG 1LTV and 1XTV component video switchers differ little from this developmental model introduced at NAB '83. (Courtesy Grass Valley Group)

to a multi-track recording system, the range of products is unlimited. Even with the approval of stereo aural TV broadcasting, the choice should not be limited, as most mixing consoles offer at least a stereo mix.

Audio facilities should include recording and playback capability. For extended periods, reel-type units may be preferred. Voice over announcements will probably be added for cartridge systems. With improvements in head technology, cassette systems have found some popularity. Studer and TASCAM systems have both been used in production systems, including network vehicles.

A compact disc player would probably be preferred over phono equipment, if the desired material is available on a CD disc format.

Titling is often desirable for the remote event. A variety of character generators provided the basic TV typewriter function. The choices may allow simple type faces in various font sizes to special characters and logos. Other systems require that each face/font size is loaded into the generator memory. Free form electronic graphics systems and graphics options, tied to video disc-based still stores add the flexibility of incorporating a variety of titling and other graphic extras from the remote site.

Interfacing through special data buses on switchers, character generators and graphics systems for digital effects units allow a variety of image manipulations to be accomplished in real time during the production. Try to imagine a remote event without flips, tumbles, spins, compressed images, etc.

Timebase correction is necessary if any inserts from videotape are planned. Many 1-inch tape machines include a system TBC, but other tape formats may require external units. Both composite signal units, and others specifically for the M and Beta component formats are on the market.

When a source provides a signal that does not require time base correction for use into the remote switcher, perhaps the frame synchronizer is more desirable. Cameras operating via individual microwave links to the central production van might be connected to the switcher through individual synchronizer units. Not all synchronizers offer feedback signals commonly used for timebase correction. Check the specifications closely to make sure the operation you want will be possible.

Synchronization of audio may also be required on signals from external sources where the video has been highly processed, i.e., from satellite linked sources. Such audio synchronizers will more commonly be used at the studio location to make the necessary correction prior to airing the signals.

Modern equipment allows an entire production system to be driven by the sync from one of the portable cameras. Still, a master sync generator, including auto-switchover to a backup generator is advisable in the production system. A reliable system will cover all bases with redundant functions.

Distribution, monitoring and test equipment are musts. The plans should include audio, video and pulse DAs, good quality audio and video monitoring units and sufficient waveform and vector monitors for video. Along with single function systems, several manufacturers offer units with switch selection of waveform and vector functions. Such a dual purpose product may be important where available space is critical.

Signal generators and vertical interval test signal insertion allows automatic correction systems to correct video signals whose parameters fall outside of preset limits. Source ID functions may also be provided by the test generators. With appropriate decoders on the video monitors, the origin of each camera's signal is automatically noted on the video monitor screen in the production vehicle.

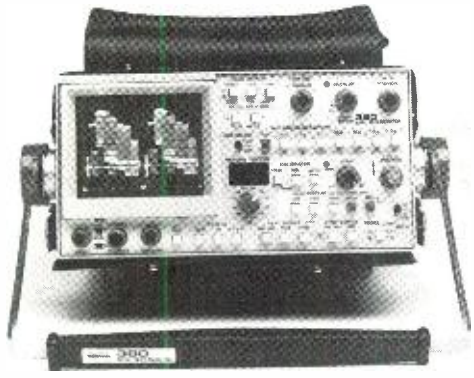


Fig. 10. TEK offers portable signal monitors that offer test oscilloscope as well as waveform and vector functions. (Courtesy Tektronix)

Fig. 11. Wireless microphone systems may double for audio and for intercommunications needs. (Courtesy HM Electronics)

Inter-communications between various areas within the vehicle and with the staff members outside is essential. The intercommunications may include a link to the local telephone system.

Microwave equipment should also be considered. Armed with a portable microwave transmitter, even the single camera ENG system can go on-air live from the scene to good effect. A choice in microwave frequency bands is available. Most systems are in the 2 GHz band, which covers from 1.990 to 2.110 GHz. Increasing use of the 7 GHz band (6.875 to 7.125 GHz) has been found, as microwave paths become more congested in major markets. In both the 2 and 7 GHz spectra, a secondary band is available on a shared basis with other services.

The 13 GHz band is also available, but has seen limited use for ENG. That frequency is more commonly used between fixed locations, such as STL and intercity relay functions. Prior to determining which microwave bands to operate for remote production, it is wise to find out what fixed services are involved in any given area. Special path arrangements may be required for getting the EFP signal back to the station.

If the production plan might involve helicopters, as has been done at auto racing, additional microwave systems, with auto tracking antennas, could be suggested. Satellite uplinking is also desirable when events of network interest are to be covered.

Human comforts must be considered. Not only is heating and cooling advised to make the operators' production time more pleasant, the equipment requires environmental control for best

results. The vehicle may be used in all weather extremes, so insulation is valuable. The insulation will also be important in keeping external noise from interferring with activities inside the vehicle.

Working space, both for operation and technical needs, must be provided. Operators that must function in cramped quarters will not work efficiently for long periods of time. Cables, no matter how well prepared, when forced into insufficient space, will fail at the most inconvenient time. The space needed for technical reasons also allows good circulation of cooling air in and around equipment.

On board power for equipment operation may not be essential. At nearly any event for which a 40-foot trailer is scheduled, power should generally be available. It is possible, however, that local power might not be available at setup time. As a result, a small portable or integral power generator could prove most helpful in getting all systems checked out. A backup generator is advisable, in case the local power fails. The portable can be the primary power supply for out-of-the-ordinary locations where commercial power is not available.

For smaller vehicles, some type of power source may be required. News does not occur in close proximity to a power distribution panel! For ENG, be prepared with plenty of fully charged batteries for cameras and recorders. For small EFP systems, plan ahead. If the event is scheduled, local power will probably be available. But not always.

Using an integral power generator does present problems. In a small vehicle, an inverter, providing ac from the vehicle battery is possible, though the purity of the ac power waveform is often questionable. Most equipment no longer requires highly pure sine wave ac power at exactly 60 Hz, but every attempt should be made to provide proper power, rather than betting against fate.

For larger systems, a gasoline-powered engine system is preferable. The engine, however, is also a source of noise. Special care should be taken in insulation, if the generator is a part of the main vehicle. The generator should be mechanically isolated from other parts of the vehicle, to avoid conduction of noise. Alternatively, the power generator could be a tow-along unit that could be separated from the main vehicle.

Connections into and out of the vehicle should be provided at a convenient location. All ports should allow quickly connected, but secure, fittings for each cable. The panel should be permanently well labelled, so fast setups can be done with a minimum of effort, time and interconnect errors.

Outfitting the production vehicle is perhaps more demanding than setting up a new studio. The most capability within money and space

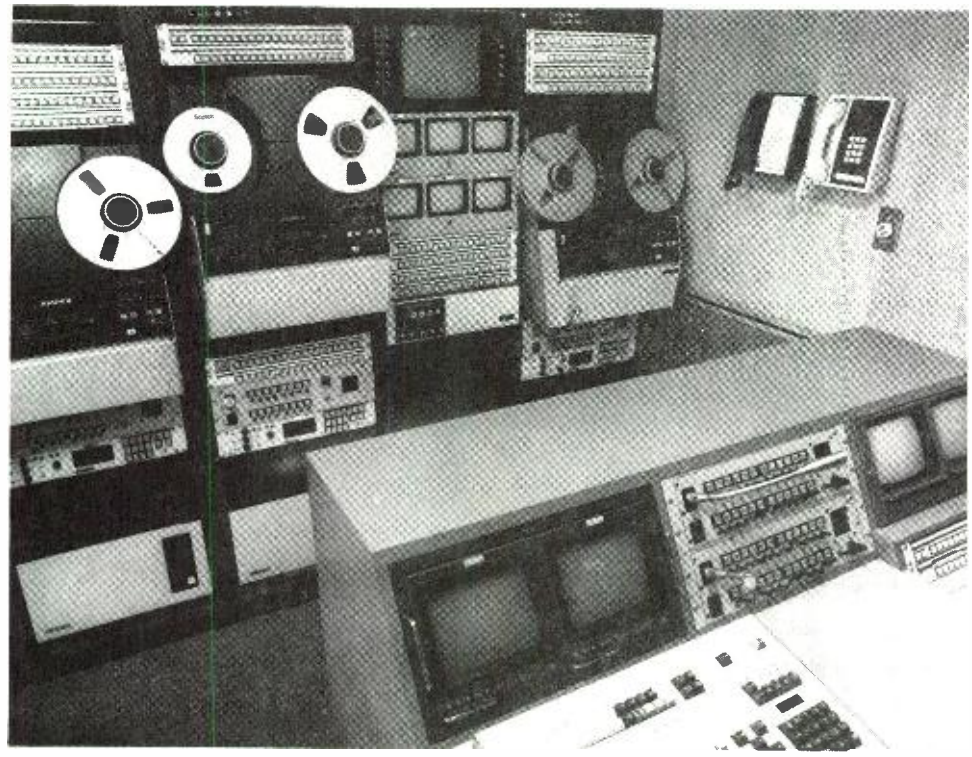


Fig. 12. Typical production control area in a medium size vehicle.

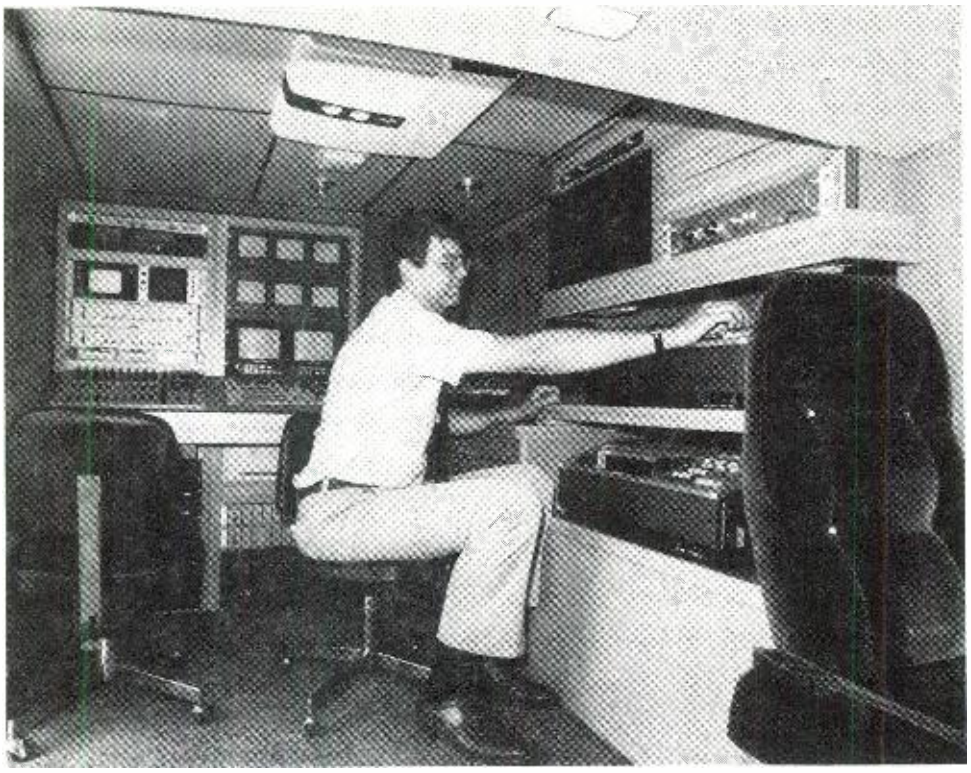


Fig. 13. A production system in a smaller vehicle can still be versatile.

limitations is the ultimate aim. Some degree of compatibility with existing studio equipment should be attempted. The facilities needed to meet the field production expectations will not be planned overnight.

Operation, Tips and Techniques

Preparing for a Remote

With the production vehicle ready and the date of the event set, many small items will still require attention. A checklist is one suggested method to make certain that everything is on schedule. Another good approach to any production is an operations manual. The manual, like the script for a play, includes all information that is pertinent to the production. A copy of the manual is provided to each member of the production staff.

As a case study, the Table of Contents from the July 4, 1984, WGBH/Mugar Productions "Live from the Esplanade," carried on PBS, gives a good example of making certain the annual Boston Pops Concert went smoothly from the television point of view.

Table of Contents

- Program Order/Timings
  A program log
- Schedule
  Calendar of all events involved with the production
- Contact List
  Telephone numbers of all individuals connected with the production
- WGBH Fax Orders
  Station equipment that will be needed for the production
- Camera Positions
  Layout of production area, showing camera locations with lens and support equipment for each location
- Production Microwave
  Special camera microwave equipment needed, locations, special conditions.
- Transmission Microwave, Uplink, Rain, Transmission Contingencies
- Microwave link assignments, satellite transponder assignment, times, signals to be transmitted, what happens if it rains!
- Communications
  2-way radio, wires intercoms, etc.
- Helicopter
  All arrangements for helicopter with cue sheet for chopper crew and camera

- Who is where
  Production staff assignments
- Food & Transportation

The production involved five cameras in and around the Hatch orchestra shell. In addition the layout included one at the Prudential Tower (about ¾ mile away), one on a boat in the Charles River beside the Esplanade park area and one in a helicopter made available by station WNEV-TV7, Boston.

The crew had to work around tens of thousands of spectators gathered for the annual orchestra performance. The scheduling had to meet with the PBS network timing. Helicopter activity was restricted in time and place by local ordinances and required special coordination.

The major items in the equipment complement for this production included:

In the audio remote vehicle—

- Mixer—API 40inX24out
- ATRs - Otari MTR-90 24-track and Ampex ATR-100
- Monitors—UREI and Aurotone, driven by RTS and Bryston amps
- Lexicon 224 reverb
- dbx limiters
- Dolby-A noise reduction systems
- Mics—Schoeps, AKG VR2 and others

In the video remote vehicle—

- Cameras
  — 4 Ikegami HK-312, with triax, equipped with three Fujinon 16-1 lenses and one Canon 40-1 lens
  — 4 Ikegami HL-79D cameras with EFP lenses
- Switcher—CDL CD480
- Video Effects—Quantel DPE5000SP
- Synchronizers—DVS
- Camera microwave—M/A COM 2 GHz
- VTRs—Sony BVH2000 playbacks and BVH500A overlapped backup recording
- Video monitors—Barco CM55 and Conrac
- Audio mixer—NEVE 20in
- Intercoms—RTS, HME wireless mic, 450 MHz walkie talkies, standard business telephones
- Transmission microwave—M/A-COM 2 GHz and 12 GHz systems

A cooperative effort between WGBH and other Boston TV stations (WBZ, WCVB and WNEV) helped to make the production successful. Not only was equipment shared, but microwave channels were made available to WGBH through a frequency coordination effort between the four stations. With only seven 2 GHz channels available for the Boston stations, arrangements allowed only the WGBH operation to use the frequencies during the televised concert.

In providing the information on the production, the engineer-in-charge stressed that cooperation between the various segments of the production and the other local TV stations was the key to a successful event.

On-Air from the Air

Going live from the production site may be only part of the requirement. Such was the situation handled by WHIO-TV7, Dayton, OH, for the International Air Show. Opening ceremonies and five hours of live coverage were provided, as well as a 1-hour documentary within three days of the event.

WHIO has carried the event previously, so parts of the preparation were not new. Special needs included two 150kW diesel generators, telephone lines, scaffolding and the remote vehicle. Equipment included items borrowed from other Cox broadcast stations and rental arrangements.

One major problem encountered during air show production was RF interference. In addition to microwave at the site to bring signals from two portable BVP-330s and one helicopter mounted BVP-3 camera to the production truck, an assortment of communications frequencies were required for the aircraft. Also, microwave carried signals to WHIO for the life feed. Two other stations also covered the event. Add to all those radio systems, radar adding its own touch of pulsed signals!

The syndicated documentary material was taped on another day of the event, simplifying production problems. In addition to activities in the air, special arrangements were needed for interviews. To achieve the most natural sound, a special audio system was used to record the aircraft on a separate audio channel for later mixing into the final program.

For Other Field Productions

Such efforts would hardly be needed for a simple ENG feed into the news, but EFP and OB events require the added planning. For a dramatic production, camera and mic locations would typically be included in a technical copy of the script. Camera movements and shots should be noted according to directorial edicts. Any changes from original plans during rehearsals should be noted as well, to make the final shooting go smoothly.

In OB production such as the WGBH example, convention coverage, sporting events or a space shuttle launch, the basic placements may need to give way to circumstances at the time. Still, all possible pre-planning is a good idea.

Conclusions—Combatting Murphy

One of the greatest difficulties in any field production attempt is getting around Murphy's law and its many corollaries. "If it can go wrong, it will!" It is up to the engineering department to be prepared for all of the inevitable problems. Equipment redundancy is one possible solution. A full complement of test equipment for any eventuality is another.

There is, however, no solution as a propos to avoiding trouble as good planning. Care in decision making toward the remote equipment and compatibility with the studio system will ease possible equipment failures. Keep in mind that a studio camera could become a last minute sub for a defective ENG camera, even with a greatly reduced portability and flexibility.

If the primary remote recorder goes down minutes before the event begins, have another recorder available. A lesser quality machine is preferred to no machine at all. Keep contingency equipment in top condition. The primary equipment only fails when the possible backup systems are not in top condition!

Make sure that everyone involved in the production is prepared for failures. The production handbook or a check list helps. More experienced groups may find a rehearsal unnecessary, but an inexperienced crew could benefit if problems occurred (on purpose) during technical rehearsals. Finding the time for such rehearsal luxuries is seldom possible, but a 'rigged' run-through could pay off.

A complete signal flow chart of the production system should be conveniently located in the vehicle at all times. The staff should know the system without referring such a layout. In the heat of trying to get around a failure, however, the signal map can save valuable time. The smallest item causes the greatest amount of trouble the most number of times, so the more comprehensive the equipment layout and interconnection diagrams the better.

Whether you are in the planning phase or under the stress of a complicated production, stay calm and logical. Panic situations cannot be averted by panicked staffers.

The comments in this section are intended to be only an overview of the world of TV field production. Hopefully some of the comments will give an insight into aspects that you have not considered for your particular needs. Many additional excellent products are available besides those mentioned or pictured. Other sections of this handbook will aid in making decisions for your system.

Best of luck in your endeavours and happy TV field production!

6.4

Telephone Systems and Interfacing

Chapter 6.4:
Part I: Interfacing to the Dial-Up Network
Part II: Telco Audio Program Service

Part I: Interfacing to the Dial-Up Network

Steve Church
WHK, WMMS
Telos Systems
Cleveland, Ohio

Why are the people who run local TV news so concerned with avoiding the dread "talking head" — that is, the anchor simply reading a story into the camera? Because they've discovered that *being there* is better. The same is true for radio, and most often that means "The Telephone Company" and its lines will be involved. Many stations make listener call-ins an important format element. News departments rely extensively on "phoners" to get reporters and newsmakers on the air in a timely fashion. And, despite the recent complications resulting from AT&T's breakup, equalized phone loops are still an important means of moving high-fidelity audio from place-to-place for broadcast use.

INTERFACING TO THE DIAL-UP NETWORK

Introduction to the Switched Network

In order to make the best use of phones on the air, it is helpful to understand how the telephone system works, so that we have an idea of what we can expect from a typical dial-up circuit.

The phone pairs provided us by the phone company are known officially as "subscriber loops." On standard subscriber loops, the phone company specifies a frequency response of 300 to 3,000 Hz. In the not too distant past, when all local calls were connected at the exchange by relay contacts, better frequency response was likely to be had on many conversations. Long distance calls, though, have almost always gone by way of band-limited microwave or satellite links so frequency response on them has never been better than the promised 300 to 3,000 Hz.

Even on local calls, however, the latest generation exchanges convert the phone audio to digital using devices called CODEC's (CODer/DECoders). As with any analog signal to be digitized, anti-aliasing filters must be used to limit frequency response to less than one-half of the sampling rate employed. Since phone CODEC's use a sampling rate of 8 kHz, response is absolutely limited to less than 4 kHz. In practice, filters with steep cutoffs above 3.4 kHz are used, and these are the limiting factor with regard to phone line audio response.

A current-limited dc voltage and the conversation audio appear together on each phone pair. The dc leaves the exchange at 48 volts and is limited to 6-80 ma by a series resistor. Often, the resistor's value is selected depending on the resistance of the loop itself. A little known fact is that a standard plain AT&T telephone incorporates a varistor which, by sending loop current, automatically adjusts voice level to compensate for various loop lengths. The dc resistance of loops varies from a few to 1,300 ohms depending on length.

The incoming audio level varies from approximately -30 to -15 dBm. Send audio is required

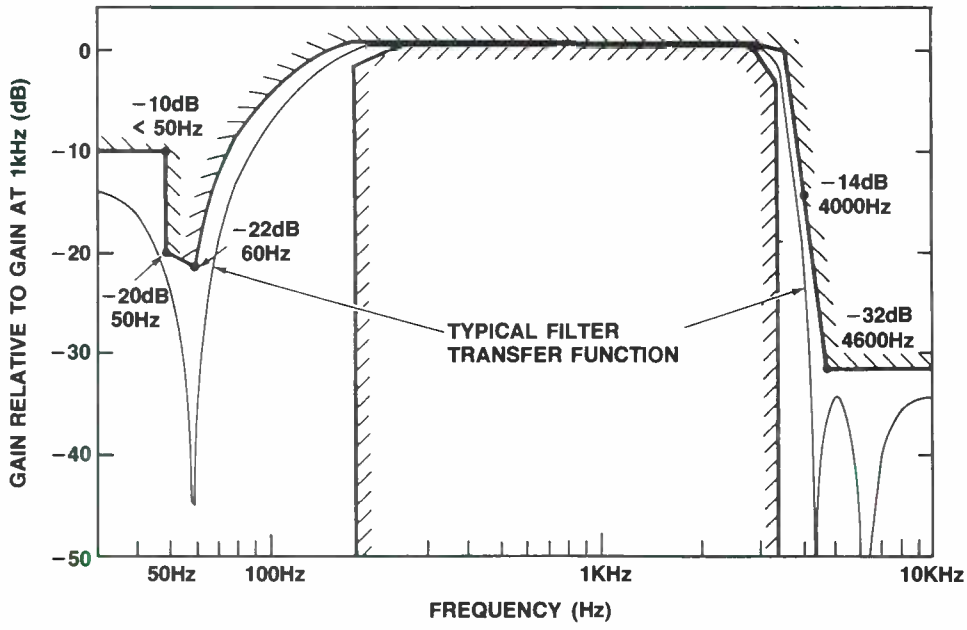


Fig. 1 Anti-alias filters limit phone line response.

to be limited to -9 dBm. Loop audio loss from the exchange to the subscriber location is supposed to be kept to 8 dB or less. Ring voltage is around 90 volts and varies from 10 to 60 Hz.

The telephone company uses a special weighting curve called "C-message weight" to determine the signal-to-noise ratio on a phone line.

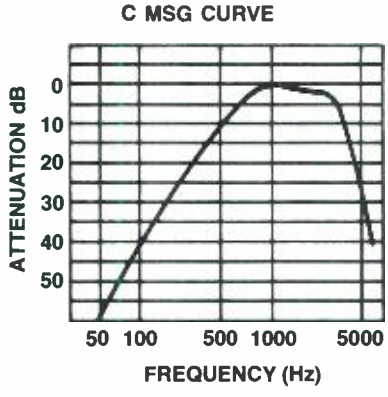


Fig. 2. C-message weight curve.

As you can see, this weighting curve has considerable low-frequency roll-off. This, of course, allows a line to have a lot of hum and other low-frequency noise and still meet the officially mandated noise specs. While this makes life easier for the phone company, it can be troublesome when you are using phone audio on the air. If you are having noise problems, you might try to get the telephone company to switch their noise meter to the "flat" position, since their gear usually does have this option available. Incidentally, the C-message curve was developed years ago to simulate the frequency response of an old-style telephone earpiece!

The FCC rules for connection of equipment to the phone company lines can be found in The Rules and Regulations of the Federal Communications Commission, Part 68: Connection of Terminal Equipment to the Telephone Network. The rules can be ordered from the government printing office, or can be found reprinted in the Code of Federal Regulations in the reference section of most larger libraries.

Terminal Equipment

Now that we know a bit about the nature of the phone network, we can explore what happens after the lines become "ours." "Terminal Equipment" is the equipment we connect to the lines after the official "Customer Demarcation Point," and includes PBX and Key systems as well as simple single-line phones. Of course, we'll also explore specialized broadcast interfacing systems.

PBX, or Private Branch Exchange systems are used where there is a need for a large number of extension phones. PBX's are sort of miniature central office exchanges, allowing local phones to call each other as well as being able to access "trunk" lines for incoming and outgoing calls. PBX systems often have a number of specialized features for call routing and control.

"Key Systems" are used where the number of extensions is smaller. Key systems are generally

distinguished from PBX systems by the presence of incoming CO (Central Office) lines on individual buttons on each extension phone. The common standard 5-line and 10-line phones connected to a central Key Service Unit are of this type.

With the newer phone systems, the distinction between PBX's and Key Systems has begun to blur. Some PBX system phones now can button-access individual lines, and some of the newer "Key" systems have PBX-like features. When selecting a system, however, it is very important to determine whether it is classified officially as PBX or Key, since, as of this writing, business line charges in some states are considerably different depending on which type system will be connected. Lines destined for PBX connection can cost twice that of those wired to key systems.

Key System Nuts and Bolts

While newer, sophisticated electronic phone systems are quickly replacing the old-style key systems in radio station "front offices," the old reliable "1A2" key systems are still used in the on-air studios by the vast majority of stations. These offer the advantage of providing a solid contact-closure connection between studio equipment and incoming lines for least quality degradation, as well as high reliability and relatively simple interfacing.

Understanding how a Key System works, if you have one, will be useful if you intend to make use of commercial telephone-to-broadcast equipment which connects to this kind of system or if you desire to build your own interfacing devices.

Leading from the Key Service Unit to each phone is a thick cable with a number of wires, usually "25 pair" or 50 individual wires. Understanding the function of each wire is the key to understanding how key systems work. See Box, this page.

Tip/Ring—The name originated with the tips and rings of the patch cords telephone operators first used to connect callers. The tip/ring pair is the actual telephone line connected through from the incoming lines. They may be located with headphones or a telephone.

"A" leads—These tell the key system which lines are off-hook. Any time a line is selected on a phone and taken off-hook, a connection is made from that line's "A" lead to another wire called "A common." The "A" lead is at -24 volts, and "A common" is at ground potential, so when a line is selected, the "A" lead goes from -24 V to ground.

If the "A" lead connection is broken before the tip/ring is disconnected, the system puts the line on HOLD.

These wires may be located by using a volt meter while selecting lines on a nearby phone.

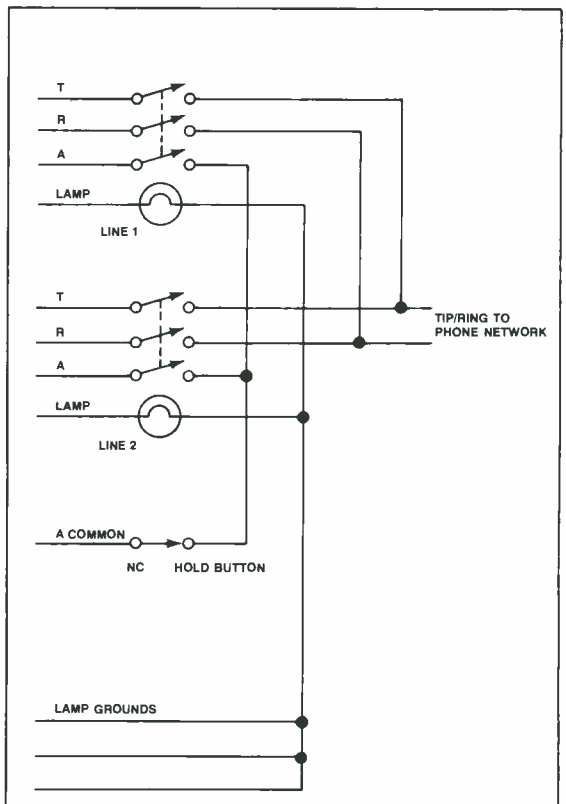
There is usually only a single "A common" wire for all lines in a system.

Lamp leads—These light the lamps on the phone's line buttons. The lamps use 10 volts ac. The lamp circuit is completed through the "LG" lamp ground wires.

All of the LG wires are connected together at the KSU. Multiple wires are used to distribute the current to reduce the voltage drop when a number of lamps are lit.

In the great majority of systems, the lamp grounds and the "A" common are connected to ground, and are effectively the same.

In standard old-type "six-wire fan-out systems," the A common is renamed "A1" and bussed to each line so that there are a full six leads devoted to each line—Tip/Ring, A/A1, and L/LG.



TELEPHONE SWITCHING CIRCUIT

6-wire fanout	5-wire fanout	Color
Line 1 Tip	Line 1 Tip	white/blue
Line 1 Ring	Line 1 Ring	blue/white
Line 1 'A'	Line 1 'A'	white/orange
'A' circuit common (gnd)	'A' circuit common (gnd)	orange/white
Line 1 lamp ground	Line 1 lamp ground	white/green
Line 1 lamp	Line 1 lamp	green/white
Line 2 Tip	Line 2 Tip	white/brown
Line 2 Ring	Line 2 Ring	brown/white
Line 2 'A'	Line 2 'A'	white/slate
'A' circuit common (gnd)	Usually line 9 'A'	slate/white
Line 2 lamp ground	Line 2 lamp ground	red/blue
Line 2 lamp	Line 2 lamp	blue/red
Line 3 Tip	Line 3 Tip	red/orange
Line 3 Ring	Line 3 Ring	orange/red
Line 3 'A'	Line 3 'A'	red/green
'A' circuit common (gnd)	Usually line 8 'A'	green/red
Line 3 lamp ground	Line 3 lamp ground	red/brown
Line 3 lamp	Line 3 lamp	brown/red
Line 4 Tip	Line 4 Tip	red/slate
Line 4 Ring	Line 4 Ring	slate/red
Line 4 'A'	Line 4 'A'	black/blue
'A' circuit common (gnd)	Usually line 7 'A'	blue/black
Line 4 lamp ground	Line 4 lamp ground	black/orange
Line 4 lamp	Line 4 lamp	orange/black
Line 5 Tip	Line 5 Tip	black/green
Line 5 Ring	Line 5 Ring	green/black
Line 5 'A'	Line 5 'A'	black/brown
'A' circuit common (gnd)	Usually line 6 'A'	brown/black
Line 5 lamp ground	Line 5 lamp ground	black/slate
Line 5 lamp	Line 5 lamp	slate/black
Line 6 Tip	Line 6 Tip	yellow/blue
Line 6 Ring	Line 6 Ring	blue/yellow
BL, AG, or spare	BL, AG, or spare	yellow/orange
SG, LK, or spare	SG, LK, or spare	orange/yellow
Line 6 lamp ground	Line 6 lamp ground	yellow/green
Line 6 lamp	Line 6 lamp	green/yellow
Line 7 Tip	Line 7 Tip	yellow/brown
Line 7 Ring	Line 7 Ring	brown/yellow
B or B1	B or B1	yellow/slate
R or R1	R or R1	slate/yellow
Line 7 lamp ground	Line 7 lamp ground	violet/blue
Line 7 lamp	Line 7 lamp	blue/violet
Line 8 Tip	Line 8 Tip	violet/orange
Line 8 Ring	Line 8 Ring	orange/violet
Line 9 lamp ground or T1	Line 9 lamp ground or T1	violet/green
Line 9 lamp or R1	Line 9 lamp or R1	green/violet
Line 8 lamp ground	Line 8 lamp ground	violet/brown
Line 8 lamp	Line 8 lamp	brown/violet
Line 9 Tip	Line 9 Tip	violet/slate
Line 9 Ring	Line 9 Ring	slate/violet

Fig. 3. Standard 25 pair color-code.

If you ever need to deal with a key system, the standard 25 pair color-code and function chart should help you. Notice that in addition to these basic connections, there will also be some special wires devoted to intercom audio and control. These vary widely from system to system.

Audio Interfacing

One-way Audio Interfacing

Often, there is a need to take audio in only one direction at a time from a phone for broadcast. Newsroom phoners are a common application. Since there is no requirement that a two-way conversation be recorded, a simple interface will do. One approach is to obtain the common Voice Coupler, or "QKT" arrangement from the phone company. This small box is permanently wired into a phone instrument or line, and provides a quarter-inch phone jack output for feeding a line-level signal to a console or recorder input. When using a coupler, it is most convenient to have the telephone instrument on-line with it equipped with a push-to-talk switch on its receiver. This is because the phone's receiver has

to be off-hook while a feed is coming in, and the switch turns off the receiver's mouthpiece microphone when it is not depressed, thus insuring that noise from the studio side will not be included in the recording. Since a QKT works in both directions, you can use it to send audio down the phone as well, very useful in the production studio for letting clients hear commercial masterpieces before they go on the air.

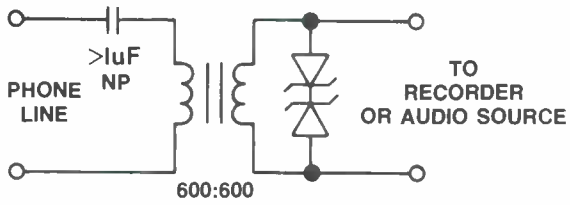


Fig. 4. Homebrew "QKT".

Since a QKT is nothing more than a transformer, a capacitor and a zener diode limiter, you can build your own.

The capacitor provides dc blocking so that the transformer does not become saturated with the phone line's dc potential. If you are sending audio into the phone line, remember you'll have to limit audio level to -9 dBm. The QKT has back-to-back zeners for this purpose; you may want to add them to your home brew interface if you expect audio levels to get out of hand.

If you are hooking up to a multi-line phone, you'll have to connect to a point where the selected tip/ring is present after line selection. The most convenient place is usually right at the phone network. Using headphones you should be able to find the spot.

Two-Way Interfacing Schemes

For on-air use when it's necessary for the caller to hear the announcer and the audience to hear the caller, you'll have to implement a more complex scheme. You will need some way to separate the "send" and "receive" audio paths. There are two basic methods for accomplishing this: the Switching method and the Hybrid approach.

The Switching Approach

This technique uses simple switching to keep the send audio from appearing at the receive output. Two electronic switches are used in such a way as to ensure that either the send or the receive path is closed at any given time, but never both simultaneously.

A decision circuit compares the send and receive levels, with the direction of transmission being determined by the relative signal strength.

Often, Voltage Controlled Amplifiers (VCA's) are used in place of the switches to provide soft-

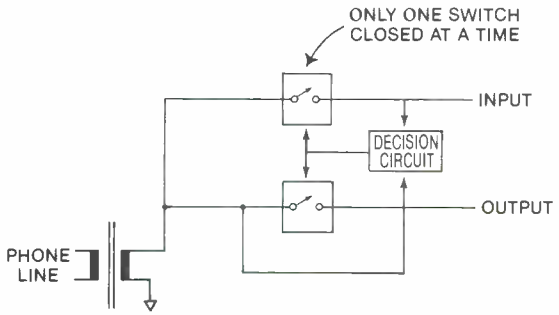


Fig. 5. Switching-type circuit.

switching rather than the absolute on-off of simple switches. The common telephone company-supplied speakerphones work this way.

The disadvantages of the switching technique result from the uni-directional nature of these systems. The primary problem is that the caller cannot be heard while the announcer is speaking —or laughing! Also, noises in the studio can sometimes cause a caller to "disappear" momentarily, especially on weak calls.

The Hybrid Approach

Hybrids were invented by the phone company many years ago in order to separate the send and receive signals from a standard two-way phone pair. Long distance calls went by microwave, and, of course, microwave links only go one way. Thus, the need for some way to split the two signal directions.

The first hybrids were made from transformers with multiple windings. Nowadays, most hybrids are made with active components-operational amplifiers (op-amps) or transistors-and are known as "active hybrids." Both circuit types use the same principle, and achieve the same effect. An op-amp version is shown in Fig.7.

The first op-amp is simply a buffer. The second is used as a differential amplifier, the two inputs are added out-of-phase (or subtracted, if you prefer). If the phone line and the box labeled "balancing network" have identical characteristics, then the send signals at A and B will be identical, and no send audio will appear at the output of the second op-amp.

The balancing network is a circuit consisting of capacitance and resistance, and sometimes inductance, forming an impedance network. Depending on the hybrid's application, this circuit can be very simple, or be made of a large number of components, with a very complex impedance characteristic. For more information on op-amps, see Chapter 7 of this Handbook.

Notice that R1 and the phone line form a voltage divider, as does R2 and the balancing network. If you think of the phone line and balancing network as pure resistances, then it is apparent

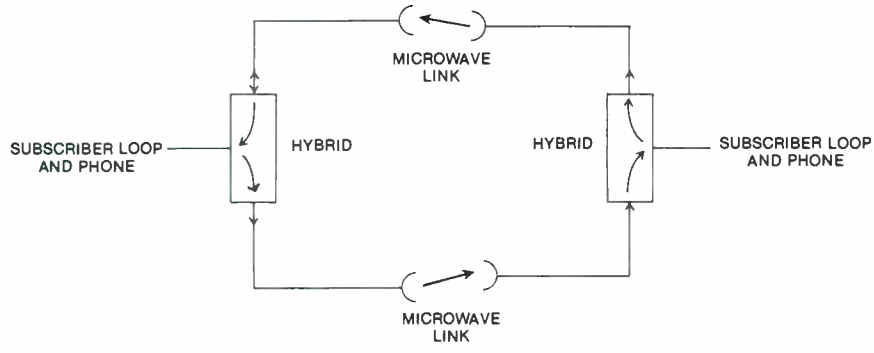


Fig. 6. Hybrid/microwave signal path.

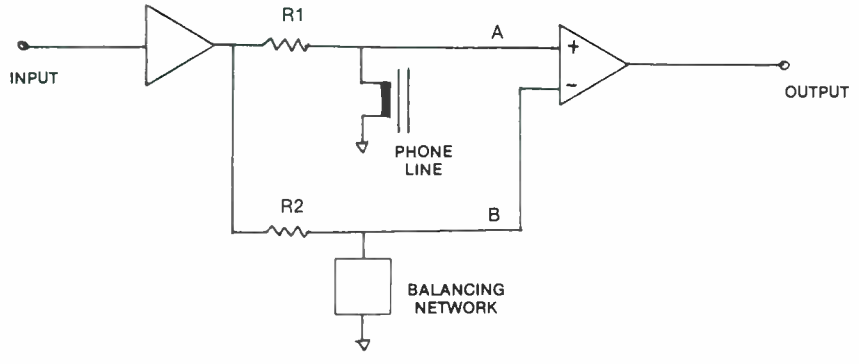


Fig. 7. Op-amp hybrid.

that the phone line and the balancing network must have the same value in order for signals at A and B to have the same amplitude, and full cancellation to occur.

In the real world, the phone line is not purely resistive, but rather a complex impedance, causing both the amplitude and phase to vary at A as the send signal frequency varies.

Only when the impedance of the balancing network is the same as the phone line, and the signal at B is matched to that at A in both amplitude and phase, will full cancellation of the send signal be achieved. Otherwise, leakage results, the scourge of hybrid circuits.

Since the phone company's requirements were not generally too stringent, they usually used (and still do) a simple network with compromise values of resistance and capacitance. The phone company's design goal is to get an average of about 12 dB rejection, with 6 dB acceptable on difficult lines. When better performance is required, modules with a number of R and C elements which can be switched in or out are employed, the switches being set to match the network to a particular line.

The amount of hybrid rejection is sometimes called "trans-hybrid loss". Trans-hybrid loss is *not* the loss from the phone line audio to the output.

Incidentally, while we're talking terminology, a standard phone pair is called a "two-wire" circuit in telephone engineering jargon, and the hybrid has two ports, send and receive (in addition to the telephone line and balance network connections), requiring four wires to connect, thus, a hybrid is sometimes called a "two-to-four wire converter."

Hybrid Application

In broadcast application, the telephone audio, including hybrid leakage, consisting of the local announcer audio phase-shifted because of the phone line reactance, is mixed with the original announcer audio.

If the amount of the leakage is too great, and the phase shift too extreme, the announcer audio will suffer degradation. When this occurs, the announcer most often sounds "hollow" or "tinny" as the phase cancellation affects some frequencies more than others. Also, feedback can be a problem when it is desired to have the caller on a speaker in the studio. Clearly, a hybrid will be useful only when leakage can be kept acceptably low.

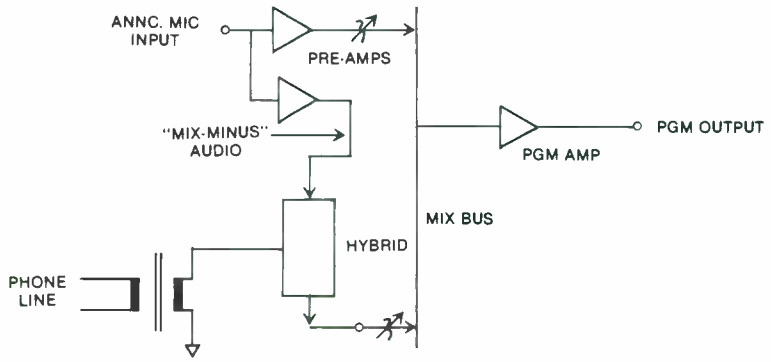


Fig. 8. Console/hybrid mix path.

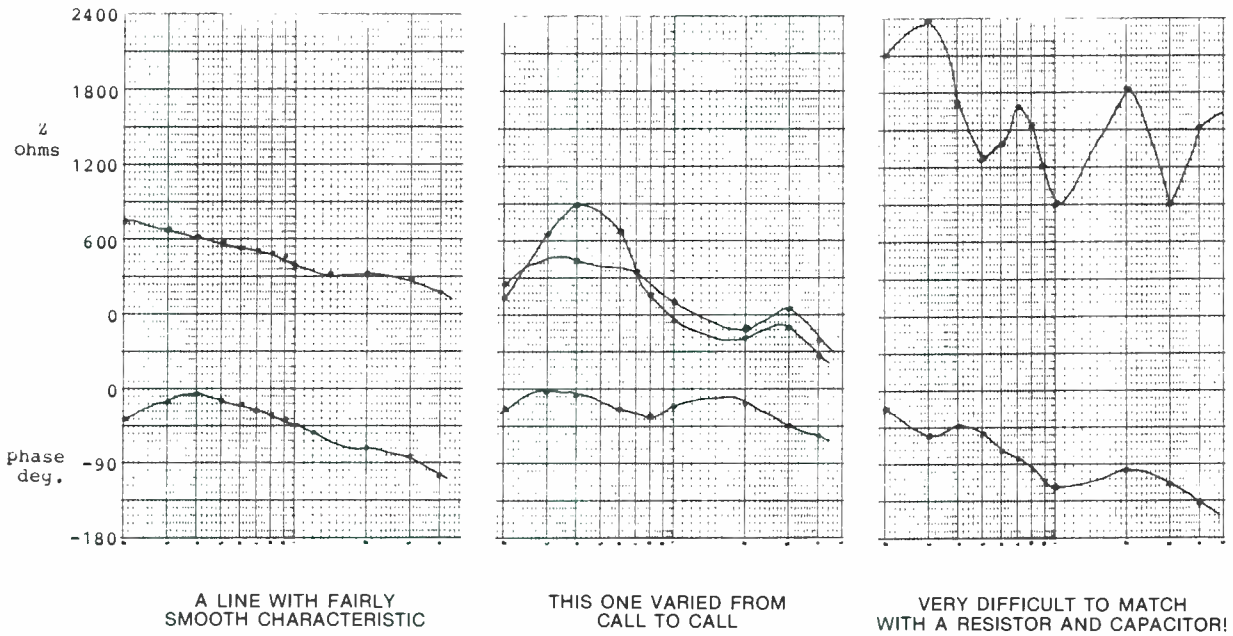


Fig. 9. Phone line graphs.

Fig. 9 shows some graphs of impedance vs. frequency and phase shift measured for some phone lines.

The lines with the smooth curves have impedance characteristics which can be simulated with a simple resistor-capacitor combination. These lines would work very well with a hybrid type interface device, since a practical RC balance network would make the cancellation of send audio at the receive output port high enough to prevent announcer audio coloration. Of course, if the hybrid is to be switched among a number of lines, they would all have to have nearly the same curve. Another consideration: the line characteristic would have to be consistent from call to call.

While it would theoretically be possible to make a balance network to match the more difficult lines, practical considerations usually keep this approach from being used, the line impedances are often inconsistent from call to call, or the impedance characteristic required is too difficult to produce.

Interfaces with an automatically-adjusted resistor-capacitor balance network work well when the phone lines to be used have a smooth impedance curve, but poor performance will still result when the line impedance characteristic is not a simple first-order RC curve and cannot be adequately matched by a simple RC network.

Another way to improve hybrid performance on widely varying or difficult lines is to trade

single-frequency rejection for wide-band loss by making the phone line look less reactive to the hybrid with some series resistance.

Before leaving the subject of hybrids, another point should be made:

The true test of hybrid performance is determined by measuring the amount of rejection across the entire audio frequency range, preferably with pink noise as a test signal at the send input.

Any hybrid with an adjustable R and C balance network can claim high rejection at any given frequency, since both phase and amplitude at a single frequency can be tweaked for good cancellation. Voice is rarely a single-frequency source.

Combination Systems

The best systems for broadcast use combine the hybrid and VCA-type switching techniques. Here is one such configuration: The hybrid is used to produce as much send-to-receive isolation as can be achieved. The "override" or "caller-control" VCA causes the "dynamic" rejection to be greater than the hybrid alone can produce. When send audio is present, the VCA reduces the gain of the receive signal. Thus, leakage is reduced on a dynamic basis. However, it should be apparent that the level from the phone is also reduced when the announcer is speaking. A control pot in the VCA control signal path is often used to adjust the amount of receive ducking, allowing full duplex operation (when the hybrid alone produced sufficient rejection), or a speaker-phone-like effect whereby the caller is turned-off when the announcer speaks. As a practical matter, this control is usually set to provide the minimum amount of ducking which provides adequate send-to-receive leakage.

Digital Signal Processing Hybrid

One interface device (developed by the author) uses Digital Signal Processing to reduce hybrid leakage so that simultaneous conversation is possible without distortion of the announcer mike send audio. Phone audio is digitized and processed in a high-speed signal processor chip. The signal processor software produces good cancellation of send audio due to its adapting the balance network to an optimum value for each phone line to which it is connected. The hybrid is automatically adjusted to account for even very complex phone line impedances. Fig. 11 shows a block diagram of this device.

Improving Phone Audio Quality

As studio and distribution quality improve modern broadcast audio, it has become more important that we do what we can to make telephone audio less of an "earsore." Filtering and equalization are the primary tools.

On a standard phone line, there is little or no audio above three to four kHz, but there is noise. Thus, a filter device with a very steep roll-off above 3 kHz can be employed to reduce phone line noise significantly without affecting conversation audio.

The low-end can be improved as well. On dial-up lines, low-frequency hum is often a problem. The hum is usually 60 Hz mixed with the second harmonic, 120 Hz. Thus, it is important to have a sharp roll-off starting at 200 Hz, or so. Again, there is very little phone audio present at these frequencies.

An inexpensive filter may be constructed using an IC filter intended for digital telephone exchanges and PBX's. The telephone filter IC used in the example in Fig. 12 has both a 5th order

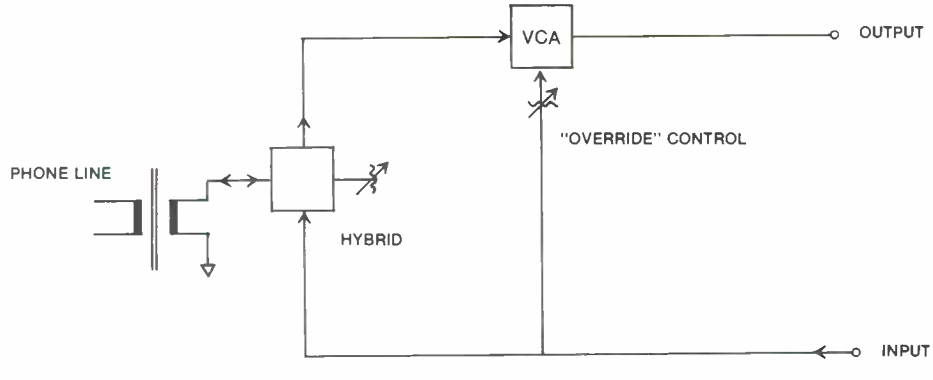


Fig. 10. Combination-type interface circuit.

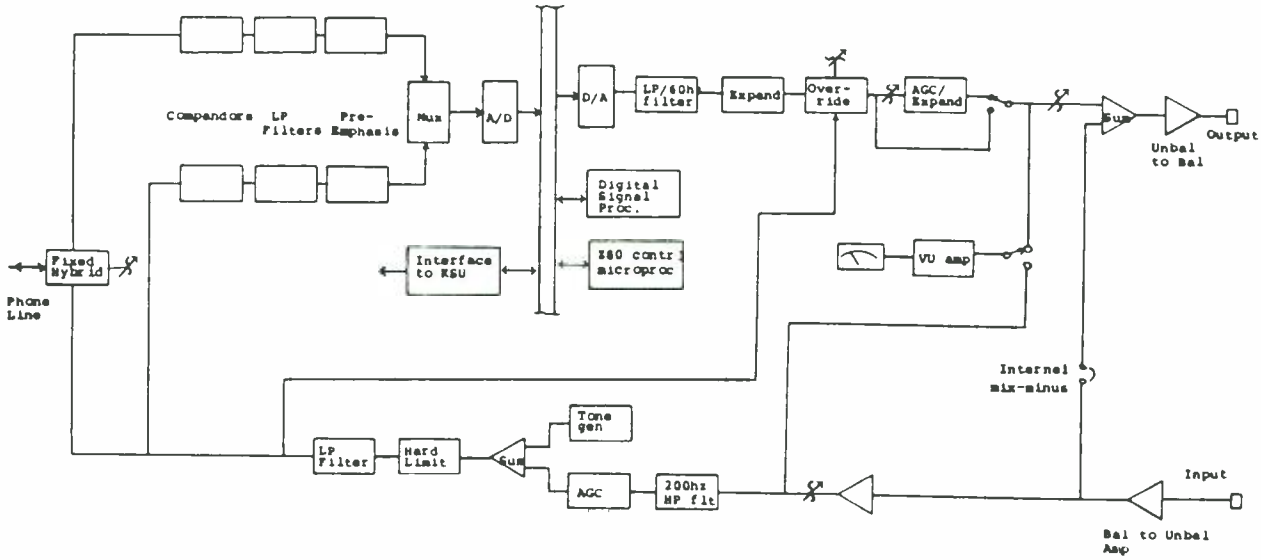


Fig. 11. Telos 10 digital interface block diagram.

elliptical low-pass section and an effective 60 Hz hum filter.

Since it is a switched-capacitor type filter, the 2912A needs an oscillator to operate. Also, note that the supply voltages are plus and minus *five* volts rather than the usual ±15.

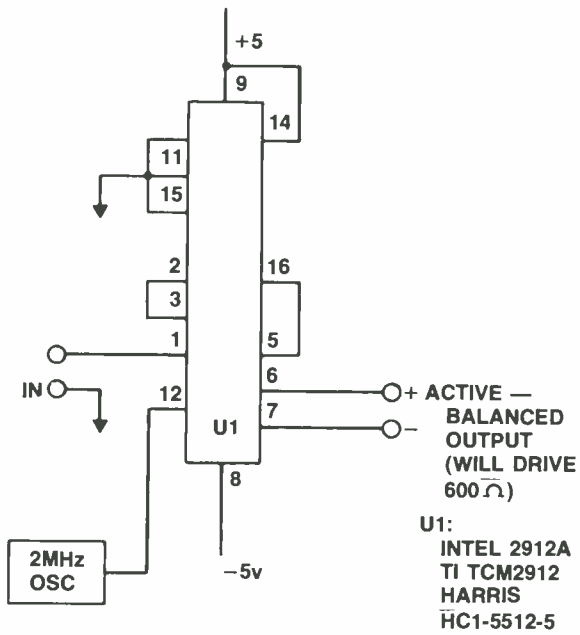


Fig. 12. Telephone audio filter using 2912A IC.

Additional Processing

The next step is equalizing the phone line to improve quality and increase intelligibility. Using an equalizer to shape the frequency response of the phone line within its audio bandwidth can result in marked improvements in perceived quality. A typical phone line has an excess of energy at around 400 Hz and considerable roll-off at both the top and bottom ends of its passband, so the idea is to compensate by adding gain at both. Try boosts at 2.5 kHz and 250 Hz, a cut at 400-500 Hz, or some combination. Parametric equalizers are the preferred device for achieving the proper sound. Since every phone line is different, the ear is usually the best instrument to evaluate the results.

Another effective processing device is the expander, or noise gate. These devices may be used to reduce gain "between the words" of a conversation, thus making phone line noise less objectionable. On extremely noisy lines, though, the gating action may make the noise *more* distracting by its coming and going with the word than if it were there at a constant level all the time. A unit with adjustable threshold and duck ratio can be set so that the optimum compromise may be achieved between the benefit of reduced noise and audibility of the effect.

Bandwidth and Signal-to-Noise Extension

So far, this chapter has covered processing at the studio-end only. We will now consider the situation where we have a planned remote origination using dial-up phone lines. Until recently, broadcasters could count on the phone company to provide high-quality equalized loops at moderate cost. In addition to the increased cost of equalized loops, there have always been problems when short-notice remotes were required, or when remotes were to be originated from an area

where equalized service was unavailable. One solution is to make use of the dial telephone system for remote broadcasts. The problem here is the 300 to 3 kHz and 35 dB or so S/N that the dial network provides is not adequate for modern broadcast needs. Frequency shifting and amplitude companding can be used to make the dial-up network acceptable for some kinds of remotes.

Frequency Shifting

Frequency Shifting Using One Line

Frequency shifting offers a way to squeeze more *frequencies* into a line than it will normally pass. Or, more accurately, the process allows *different* frequencies than the usual 300-3,000 Hz to be passed through a standard phone line.

The popular Comrex unit shifts all audio frequencies up by 250 Hz in the encode mode (going into the phone line) and down by 250 Hz in the decode mode. The result is a 250 Hz improvement at the low end at the expense of a 250 Hz loss on the high end. This means a typical phone line's response will be changed by the shifting process to be 50-2750 Hz. The 250 Hz loss at the top is not very significant due to the logarithmic nature of audio frequency response.

The Comrex and similar units perform the shifting function by heterodyning the input audio with a low-frequency carrier. The "phasing" SBB (Single SideBand) generation method is employed to allow only one sideband to emerge at the output; the carrier and other sideband having been cancelled in the SSB process. Encoding and decoding can easily be accomplished in the same unit, since only a simple signal path change is required to cause an encoder to decode, and vice-versa.

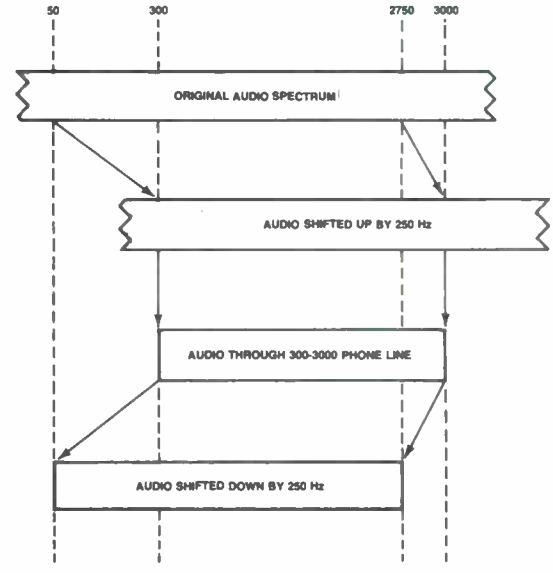


Fig. 13. An audio frequency shifter allows transmitting an improved low end response with only a small loss at the upper end.

Subjectively, frequency-shifter feeds sound less "telephone-like". However, the result of improvement at the low end without high-end enhancement is often a somewhat muddy or "flat" sound.

One approach to improving subjective quality is to boost the high end that you *do* have with a sharp EQ rise above 2 kHz. A parametric EQ

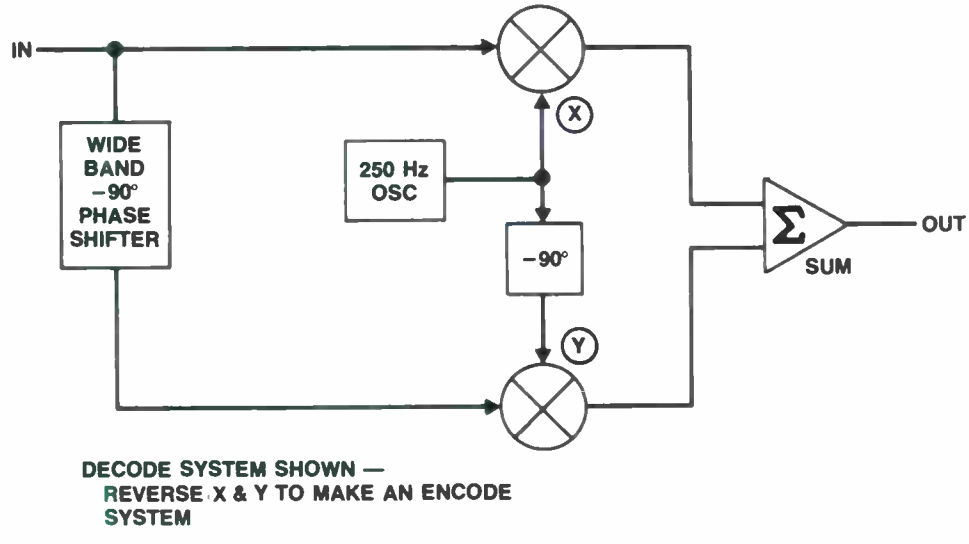


Fig. 14. Frequency shifter block diagram.

or custom filter would be preferred so that the desired high-Q curve can be obtained.

Another way to improve the subjective high-end quality is with the application of Aphex or EXR "exciter" equipment. These units generate harmonics of the input audio, which are then combined with the input to produce a "harmonically-enhanced" output. This output will have new high-frequency information above the 3 kHz phone line bandpass, so, the generator unit should be placed after any HF roll-off filters.

Yet another, more elaborate, approach to high-end improvement is the half-speed transmission technique. With this approach, another encode process is used in addition to the frequency shifting already described; this time operating to improve high-end response rather than low-end. A phone line with fixed bandwidth can be made to have more if we are willing to trade-off transmission time for better fidelity.

The technique is very simple: the recorded material is played back at half-speed; after reception, the received material, having also been recorded, is played back at twice the record speed. What goes through the phone line is nearly unintelligible, since it is half-speed audio. Of course, this method cannot be used when real-time transmission is desired, and toll calls cost twice as much—another example of the futility of expecting something for nothing!

The combined shifting and half-speed techniques result in an effective bandpass of 100 to 5,500 Hz.

One note regarding frequency shifting: decoding must be done from a direct input. That is, frequency-shifted audio should be decoded as it comes out of the phone line, before it goes to tape. If the shifted audio is recorded un-decoded, with the intention of later playing the tape back through the decoder, interesting but unairable results may occur. These are due to the additional slight frequency shifts introduced by the recorder. The decoder is not expecting to see these, and is quite intolerant of them.

Frequency Shifting Using Two Lines

Despite the benefits derived from extending the frequency of a phone line to 50 Hz, the frequency response obtained from a single phone line is still limited to a very "low-fi" 3 kHz. Response to 5 kHz is, however, possible with the use of two phone lines (the half-speed transmission technique described above extends response, but, cannot be used when "real time" transmission is required).

In a two-line extension system, highly selective crossover networks split the program audio into two bands each of about 3 kHz or so in width. These bands are then heterodyned to occupy the available phone bandwidth using the same kind of process as in the single-line shifters. In the Comrex unit, input audio is separated into bands of 50 Hz and 2400 Hz and 2500 to 5000 Hz. The first band is then shifted up 250 Hz, while the second band is down-shifted 2 kHz. A five-band

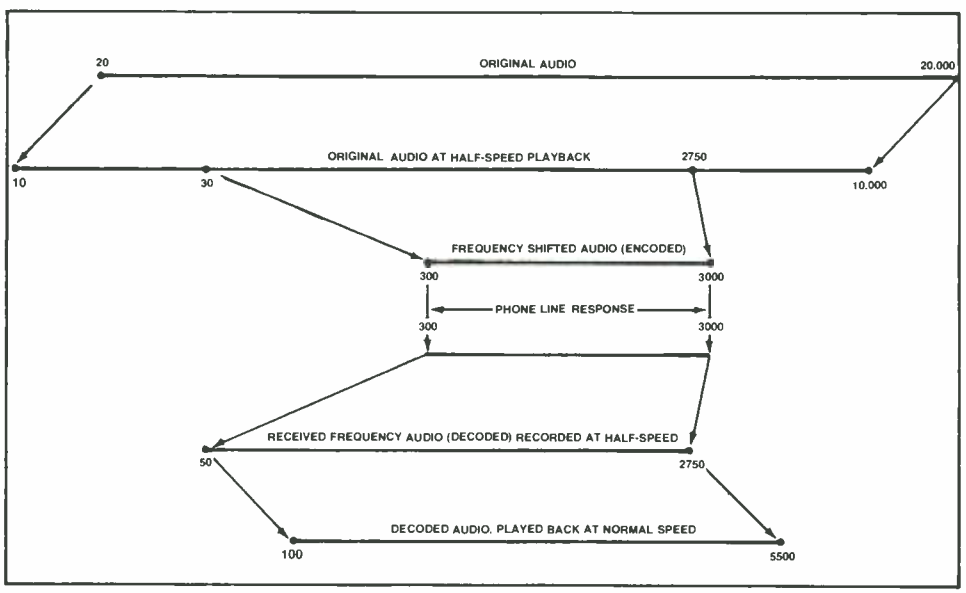


Fig. 15. Combined half-speed, frequency-shifted transmission offers a playback response of 100 Hz to 5.5 kHz.

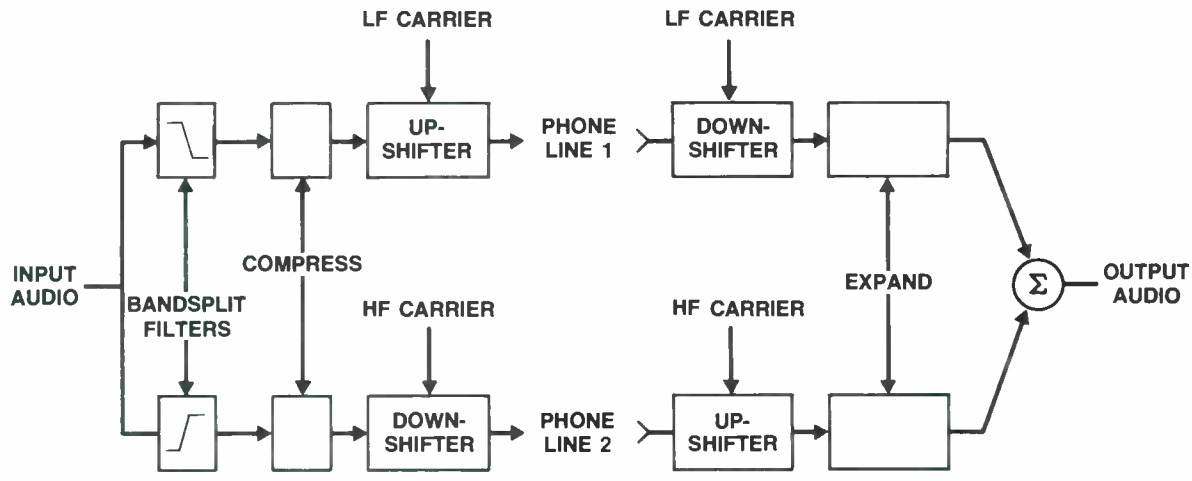


Fig. 16. Two-line shifting scheme.

companding system is employed to improve signal-to-noise performance.

New Technology

Cellular Telephone

Many cities now have access to the new cellular telephone service. Cellular telephones are perfect for use as communication/cueing channels during full-fidelity remote broadcasts, and can be used for originating low-fi telephone-grade location broadcasts, such as might be appropriate for news reports.

The audio quality of cellular phones is generally comparable to that of the standard wired network. Of course, all of the phone quality enhancement techniques described above may be applied to feeds originating from cellular phones. It would even be possible to combine a two-line frequency extender with two cellular phones for higher-fidelity remotes.

Digital Phone Services and ISDN

With the current explosion in the area of computing technology and the resulting demand for computer-to-computer communication, phone companies are gearing-up to provide end-to-end digital transmission service. Someday these new services may be useful to broadcasters as replacements for equalized loops.

AT&T has experimented with a digital switched network system called "Accu-Net." This system operates at 56K bps (bits per second). Unfortunately, 56K bps is not fast enough for high fidelity audio transmission. At 12 bits and a 32 kHz sampling rate, hi-fi audio needs at least a 384K bps data rate. New technologies for data compression, though, may eventually allow this kind of service to be used for transmission of program audio.

Then there's the Integrated Services Digital Network, or ISDN. The ISDN was devised by The United Nation's telephone committee, and has been endorsed by AT&T and a number of IC manufacturers. It comprises a set of specifications that define standards to permit interconnection of a wide range of digital voice and data equipment to the telephone network. Since the ISDN specifies a bit rate of 192K bps, remote-quality audio is a possibility. As this is written, the potential for broadcast use of ISDN services is unclear. What is certain, however, is that the technology of telephony and the technology of radio will continue to grow and evolve—together.

6.4

Telephone Systems and Interfacing

Part II: Telco Audio Program Service

Skip Pizzi
Technical Director
National Public Radio
Washington, DC

Telco lines are used in most remote broadcasts and as STL's (studio-transmitter links) for many radio and television stations, and for the interconnection of many radio and television networks, so it is clear why they are such an indispensable part of broadcasting as we know it. This heavy reliance by broadcasters on telephone company services can cause catastrophic results when something goes amiss at Telco, and every broadcast engineer has his or her share of horror stories to tell on that topic. Nevertheless, if the truth be told, the majority of the time, service is rendered promptly, and the Telco installation staff are often quite helpful and reasonable in most broadcast service divisions.

Dealing with the Phone Company

The best way to minimize problems with your telephone company is to establish a good working relationship with the appropriate personnel, and to understand as much as possible about their operation. If your people come across as friendly and knowledgeable, but also professionally firm and businesslike, things should go well.

Obtaining and Testing Your Lines

For a local, stereo pair, order two type 6008 or 6009 lines, specifying "stereo conditioning." This incurs a one-time additional charge on each stereo pair, which can be hefty, (around $300 or more in most places, currently), but without this, there is no guarantee that the two lines will travel similar routes, and if they are sufficiently different in path length, significant phase errors can occur, wreaking havoc on your stereo image and mono compatibility. Some broadcasters always order *three* lines and have them all stereo-conditioned, so there is always one backup. Others forego the extra charge and try conditioning themselves with a very high resolution DDL or similar device at the receive end. (Approximately five microseconds time difference occurs for every mile of path length difference.) Although linear distances between ends of the circuits might be short, actual circuit routing may be much longer, and these miles of path length difference may mount up quickly in an unconditioned pair. Nevertheless, even with conditioned pairs, it seems that about half the time, the polarity between lines is inverted as installed. This is of course a simple matter for the broadcaster to fix, but it is one of the first things to be checked after stereo lines are installed. Other items to be checked, for *all* lines, are frequency response (should be well within ±3 dB of ordered response), phase response, S/N ratio, distortion, and headroom. (When spare lines are ordered, all should be measured, and the poorest delegated for "back-up.") Regarding flat response, check well outside the cutoff frequencies, because it is not always safe to assume that response *rolls off*

beyond them. Occasionally in order to get a line to pass specs, Telco equalizers are used to boost the extreme frequencies and if this is not done properly, the response may indeed be flat up to the specified frequency, and then *rise* for another octave or two before finally rolling off. Obviously, this reduces headroom and alters frequency response, and is also a particular problem when lines are being fed with noise-reduction-encoded (i.e. HF pre-emphasized) audio.

Fig. 1. DON'T meter the signal across the input to the repeat coil (transformer at rt.) and DON'T feed the repeat coil directly from another transformer, if possible.

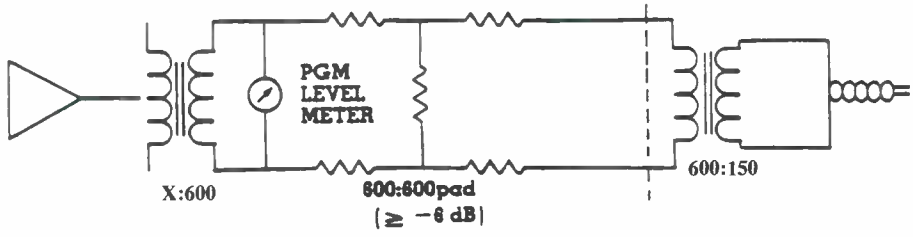


Fig. 2. DO place a pad between the output device's transformer and the repeat coil; and DO place a level meter before the pad, calibrated for the voltage across the pad's output when terminated with a 600 ohm resistor.

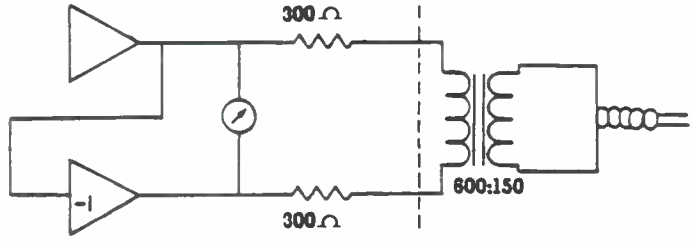


Fig. 3. DO feed low-impedance sources (e.g. op-amps) through a 600 ohm differential balanced pad; and DO place the level meter before the pad, calibrated as above.

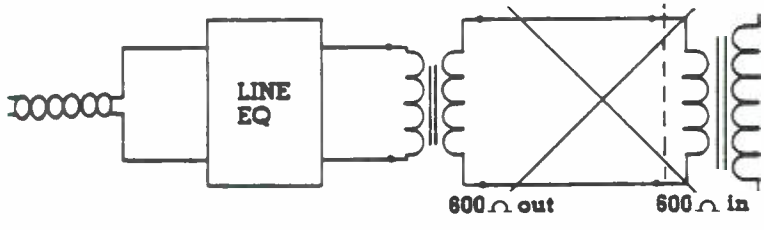


Fig. 4. DON'T terminate the receive-end repeat coil (transformer at right) with another transformer, if possible; its loading may vary with frequency from the true 600 ohm resistive termination used in line-up causing level and frequency response variations.

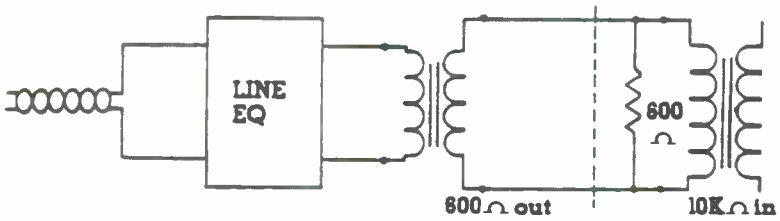


Fig. 5. DO terminate the receive-end of a program circuit with a 600 ohm resistive load and bridge the load with a high-impedance transformer or active balanced input. Note: Common mode rejection of the transformer or active input must be considered if the distance from the repeat coil is great or is near other lines which induce cross-talk. Ideally, the secondary of the repeat coil should be resistively terminated. An active, balanced input circuit does this nicely, provided any RF is bypassed before the first stage of amplification. An alternative is the use of an input transformer with a high-impedance, bridging input. This allows the 600 ohm resistor, as shown in Fig. 5 to match the repeat coil. Another version, often seen on the input of broadcast line amps and modulation limiters is a 600 ohm H-pad; effectively the reverse of Fig. 2. Following the above steps at both ends usually insures that transmission loss and frequency response closely match those of the phone company set up.

Proper Interfacing

For testing circuits, sinewave frequencies of 400 Hz and lower may be fed at Telco "P.O.L." (program operating level) of +8 dBm, but frequencies above 400 Hz must be fed at "Telco test" level of 0 dBm. Recording type consoles whose reference levels (0 VU) are +4 dBm can operate well into these circuits, and gain an additional 4 dB of headroom while losing 4 dB of S/N. However, it is essential that any mixer used to feed a Telco line directly is capable of driving a 600 ohm balanced load, the standard impedance of all Telco lines (150 ohm lines are available upon request in most areas). Many consoles—even expensive ones—cannot do this, in which case a distribution amplifier is the best solution. Often, a variety of tape recorders, IFB, mults, etc. are also being fed by the mixer at the remote site, so an audio distribution amplifier (DA) is essential in providing isolation between all these (usually Hi-Z) inputs, as well as proper drive for the 600 ohm phone line. When this is the case, always try to have the phone line driven by its own DA output, with no other (even bridging) inputs attached.

Remember that dc voltages may appear across the phone line, and the isolation that the DA provides is useful in protecting the inputs to all the other devices as well. For this reason it is also wise to *not* use transformerless DA's in this application. A *good* transformer can be your friend on remotes, especially when interfacing with Telco. Nowadays, a good installation will commonly be provided by Telco with repeat coils, however, which serve this purpose well, so an active-balanced output capable of driving at least +18 dBm (preferably higher) into 600 ohms would work well in that sort of application. See Fig. 3.

Note well that Telco equalizes its lines for flat response with a 600 ohm source impedance and 600 ohm termination. If any other impedances are used by the customer, flat response is *NOT* guaranteed. In today's equipment it is common to see bridging conditions, so most consoles' output impedances are lower than 600 ohms. This will usually cause a high-end rise on the receive end, if such a console is used to feed telco lines directly.

The "H"-pad in Fig. 2 above does NOT provide a 600 ohm source to the line by itself. Note in this diagram that the secondary of the output transformer on the left is 600 ohms. If it is not, the pad will not set things right; it is there to provide isolation of the meter or an oscillator from the repeat coil. Optimally, in such a case, the output of the feeding device should be modified to provide a 600 ohm source impedance. The situation in Fig. 3 *does* provide both isolation and proper source impedance.

To determine the source impedance of a device's output, place a bridging input meter across the output while feeding 1 kHz. (No other inputs should be attached.) Terminate the output with various resistances; the source impedance is the value of the resistor which drops the level by 6.02 dB. Check at other frequencies—level shouldn't change.

Finally, the meter on the xmit end should be used only for initial absolute level calibration (as shown in Figs. 2 & 3). Relative levels for frequency response tests are not valid from such a meter connection, and oscillator level at different frequencies should NOT be re-zeroed based on this meter's readings. To correct for any oscillator drift, use a more isolated meter such as the meter on the oscillator itself, which feeds a console or D.A. which in turn feeds the phone line as shown in Fig. 2 or 3.

The Specs

In terms of S/N ratios, the telephone company uses a peculiar sort of measurement. They declare a noise level of −90 dBm as "absolute quiet" and measure a noise *up* from there, using the unit dBrn. Therefore a circuit with a Telco noise spec of 40 dBrn would have a noise level of −50 dBm which, if the Telco reference level of +8 dBm is used as P.O.L., gives the user a 58 dB S/N ratio on the line. The longer a line travels, the noisier it gets, of course. Telco specs for local circuits (varies with location and local operating company) usually call for a S/N ratio of 65 dB or better (33 dBrn) for 15 kHz lines. "Interexchange service" (IXC), to use predivestiture terminology, which entails the inclusion of AT&T Long Lines (generally microwave) service, had a S/N spec of 57 dB or better (41 dBrn) for 15 kHz lines. The local 5 kHz spec was 52 dB S/N, long distance 5 kHz was 42 dB.

Another option offered by many telephone companies is the so-called "loss-less" or "zero-loss" line, where the Telco line acts as a unity gain device. Normally, signal provided to the customer on the receive end may fall to as low as -30 dBm when 0 dBm is being fed from the transmit site. (Audio signals in copper cable lose about 1 dB/mile). A line amp on the receive end can bring the signal up to house P.O.L. If the customer so desires, however, Telco will provide (at an additional cost) a loss-less line, so that +8 in gives +8 out. This is achieved by the insertion of additional Telco amplifiers along the route, and is not always desirable, since these amps are of unknown quality and reliability, and your line amp is a single, known, and easily accessible unit. Nevertheless, if the line is long, and the Telco amps are OK, a loss-less line may give you a few dB quieter performance, although with perhaps a slightly higher distortion spec. This may be advisable in places like New York City where crosstalk and impulse noise from old, waterlogged and densely trafficked lines is quite common. In most cases, however, fewer amplifiers used in regular lines (there may indeed be none at all in short hops within one exchange or service area) provide better overall sound. In cases where both regular and loss-less lines were ordered from the same site, in my experience, the regular lines were almost always chosen.

Gaussian or random noise is of course far less objectionable than the coherent noises sometimes found on Telco lines, such as the above mentioned crosstalk, impulse noise (clicking from dial pulses and other switching), and the so-called "sings" or tones caused by carrier beating and other nefarious sources. For this reason, lines should be monitored on the receive end for a good while after they are installed without any audio being fed from the remote site. They should also be turned up and auditioned as early as possible before their on-air use. Call Telco at the earliest sign of trouble.

Although there are no published Telco specs to be met for distortion or phase response, distortion should be 0.25% THD or better for 15 kHz local lines. For stereo pairs, relative phase response should be within 30 degrees across the passband. Widely divergent frequency response across the stereo pair is a tip-off to check phase response carefully. When spare lines are ordered, the two closest to each other in frequency and phase response should be made the main pair, assuming all other specs are equivalent.

The published headroom spec is only 10 dB on most lines (+18 dBm maximum). Using a P.O.L. of +4 dBm instead of Telco's +8 will give you 14 dB of headroom, at the expense of S/N, which is a more prudent approach in most cases.

Communication Lines

Whenever ordering program circuits for live remotes, always order an "MB" or "PL" to the site as well. This is a standard dial-up telephone line for use in voice communication between the studio and the site. Stations equipped with RF communication systems may want to use these instead if they are within range, but these may leak into the program audio, prohibiting communication while the site is on the air. This "MB" service is relatively inexpensive, and usually well worth the cost. A way to save, however, is to provide your own telephone instruments (with visual ring/bell cut-off if desired), and just order the line from Telco. Normally this will be a regular seven digit telephone number, but other variations such as dedicated "PL" (private line, also known as "ringdown") or OPX (off-premises extension) services are possible. PL is a non-eq line with dialless instruments at each end; one end rings whenever the other is picked up (also called "PLAR"—private line with automatic ringdown—in some areas). OPX is an extension of a customer's PBX system placed at a permanent remote site. The terms "MB" and "PL" are often used in the broadcast industry to indiscriminately refer to any sort of regular telephone at the remote site for communications purposes. This is all well and good until actual Telco orders are being placed; then exact terminology becomes important. Telco lives by abbreviations, and a single misplaced letter could cost you a lot of time, hassle and money. Additionally, these sorts of services are ordered from a different office and are installed by a different crew than the broadcast program lines, so careful coordination on your part is required. This is the area

where most problems occur, in my experience, since these folks are not working only with broadcasters but are usually the regular telephone service office and installation staff, so they are dealing with you as just another regular customer. It may be advisable to order this service earlier, and request it to be in place sooner than your program lines. Since it is generally a much cheaper service than the program lines, the extra cost isn't very much, and no matter how well the program circuits are functioning, lack of communications can seriously compromise a remote broadcast's quality.

The Final Frontier

For longer-haul circuits or networking, satellite hook-ups have become commonplace in recent years. For network distribution, it is a particularly cost-effective method (especially in the long term), but it is also a useful and high quality method for remote feeds ("back-hauls") to a station or network hub as well. Various broadcast organizations now have satellite networks in place, and most offer their excess space on these to outside customers. These networks have leased their satellite space from the satellite owners, the "common carriers" such as Comsat, AT&T, Western Union, RCA and others. Individuals can also lease satellite space from the common carriers, but for one-time, point-to-point needs, it is usually better to go to one of the networks, since the common carriers generally prefer dealing with the big, full-time, mass users, and their sales offices will often freely admit to prospective customers that price and service might be better from one of the smaller, more broadcast-oriented companies as the excess-capacity selling networks. Among these, an example is National Public Radio. NPR leases a full video "transponder" (satellite channel) on Western Union's Westar IV satellite, and uses the rather wide spectrum provided therein for dozens of frequency-modulated analog audio channels of various bandwidths. This so-called "multicasting" approach allows a network to offer several choices of programming to its stations simultaneously (in mono or in stereo pairs of channels, without the need for "stereo conditioning" since all satellite path-lengths among the audio channels are identical), and have excess space left over which it may sell to other customers. Regional "uplinks" (satellite earth stations with receive and transmit capability—also called "RT's") can feed to these several channels, while "downlinks" (receive-only earth stations—"RO's") at each of the network's stations can be tuned to the channels desired at the time. Since noise is a big problem in satellite transmission (40 dB is considered good in many cases), most analog satellite systems use some sort of companding to achieve reasonable S/N (65 dB or higher) for wideband audio. Some systems use the video transponder for a smaller number of digital audio channels. Even with all this variation, there are some reasonably priced, off-the-shelf "fully-agile downconverters" which can handle most of the analog frequencies and companding systems in use, when hooked up to a dish pointed at the right bird, equipped with sufficient LNA's (low-noise amplifiers). The digital systems are still a bit more proprietary, but probably not for too much longer.

A third more recent option is to obtain the services of a satellite communications contractor. These companies have as their sole function the selling of satellite hook-ups for point-to-point or network use, one-shot or permanent. They utilize both existing earth stations and "portable uplinks" (mobile satellite transmitters), and provide customized service to the individual customer's request, using their own or subcontracted facilities.

For live remote transmissions on satellite circuits, terrestrial Telco lines, microwave or VHF-band RPU's (remote pick-ups) are usually employed to get audio to the nearest uplink (except when a portable uplink is used), and again, if necessary, from the nearest downlink to the end-user (so-called "handoff" service). These "first-mile" and "last-mile" hookups are often on Telco program lines, so although satellite technology is well in place in the broadcast audio world, until the portable uplink becomes as commonplace as the telephone, Telco lines will be a part of the typical live remote.

One other thing to remember about satellite service that differs from the terrestrial, is the element of time delay. Because geostationary satellites are used, the distance from earth to satellite is over 23,000 miles. Signals travelling up and back from that satellite take about 1/4 second. (Terrestrial line delays rarely exceed 100 ms., except on long network lines). If satellite back-haul *and* satellite network feeding is used, there is about ½ second delay. In any case, this provides for more difficulty in monitoring. The remote site cannot simply monitor off-air on the network affiliate in that town. More lines—terrestrial ones—must be used for "backfeeding" the remote site with a "mix-minus" program feed and any IFB (interruptable foldback) or other cueing. Again, these are usually Telco lines of a lesser quality (5 kHz or non-eq).

What Next?

Aside from the price increases, the future holds great promise for this technology. Copper wire is being replaced by fiber optic in many areas,

LEGEND

CM - Channel Mileage (per air-mile basis)
CT - Channel Termination (flat rate)
IOC - AT&T's Interoffice connection (mileage rate)
LATA - Local Access and Transport area (service area)
LEC - Local Exchange Company (local Telco)
POC - Program Operating Center (old name for Telco "Toll")
SO - AT&T's Serving Office
SWC - Serving Wire Center (new name for Telco "Toll")

Fig. 6A. Typical intraLATA service.

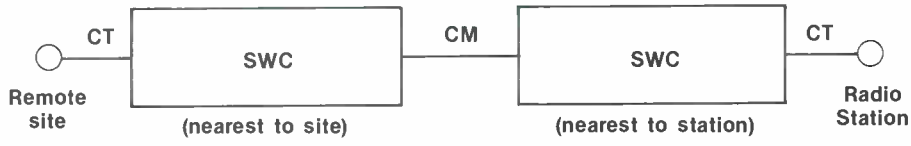


Fig. 6B. IntraLATA service where site and radio station are in different "rate centers" of the same local exchange company.

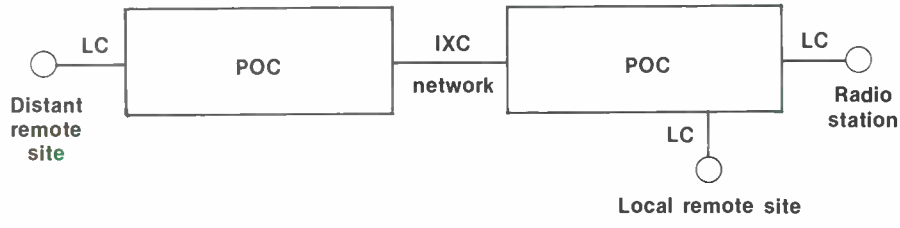


Fig. 7A. Typical pre-divestiture arrangement for distant & local remotes.

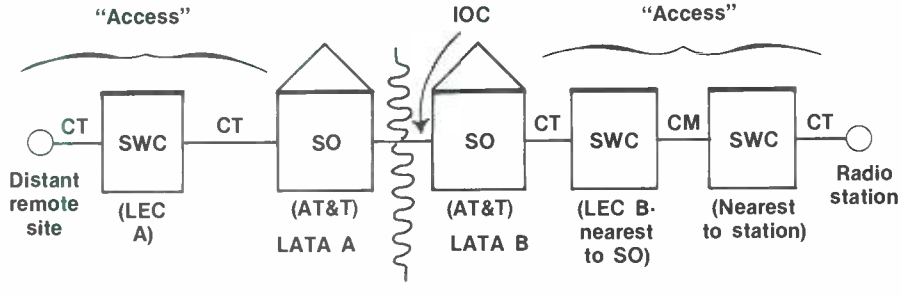


Fig. 7B. Typical (post-divestiture) intraLATA service. In this example, access charges in LATA B will be higher than in LATA A, since radio station is in a different rate center of LEC-B than AT&T's SO.

improving fidelity and reliability, and providing much greater capacity to areas of high traffic. (The most obvious improvement is in terms of freedom from hum, buzz, impulse noise and crosstalk in downtown areas, due to the system's operation in the digital and optical domains, rather than the analog and electrical). Cellular phones are beginning to be used for com-links and back-feeding, along with more sophisticated RF equipment, replacing the traditional dial-up phone at the remote site. Noise reduction on Telco lines has been in use by some broadcasters for years (with varying results), but more recently, stereo radio remotes using PCM or CPDM digital encoding on a single NTSC video circuit have provided excellent results, albeit at a higher cost for the line and the hardware. The work gets harder, the costs go up, but the results improve.

Postscript: Local Access and Transport Areas

To understand the basics of post-divestiture private line operation, it is important to understand the concept of LATA's, Local Access and Transport Areas. These LATA's are the boundaries of operation for each of the local operating companies. These companies were formed when the Bell System was broken up and AT&T divested itself of its local telephone operations. (AT&T kept its Long Lines, Western Electric (manufacturing), and Bell Labs (R&D) divisions.) Along with the former Bell System, there are several areas that have always been served by independent, non-Bell companies (such as GTE, Continental and the like), and these also have been assigned LATA's corresponding to their former operating areas.

Broadcast circuits within a LATA (the old "LC," now called "intra-LATA service") will operate technically as before, but with different billing mechanisms. Instead of a single, fixed rate LC charge, the line will be billed as shown in Figure 6A. The part of the circuit from the remote site to the nearest Telco "Toll" office (now known as a "Serving Wire Center"—SWC) is called a "Channel Termination" (CT). The line from this SWC to the radio station's studio is also billed as a CT. CT rates range up to almost 300 percent higher than the corresponding old LC rates, but as you can see, each intraLATA circuit is billed as *two* CT's, so actual costs for these lines will be twice that. There may also be a "Channel Mileage" (CM) charge for local circuits in which the SWC for the remote site is different from the studio's SWC, over and above the two (fixed rate) CT charges, see Fig. 6A. The air-mile distance between the two SWC's (also called "rate centers") is tacked on at "X" dollars/mile.

Circuits which extend across a LATA boundary (the old "IXC," now "interLATA service") get even more involved. Your local company will charge you a CT for your connection to their nearest SWC and then another CT for a connection from SWC to the AT&T service office (SO) in that LATA. Those two circuits are called "access" to the AT&T network. AT&T then provides the inter-office circuit (IOC) between that SO and their SO in the LATA where the remote site is. The local exchange company (LEC) for that LATA provides "access" from the AT&T SO to the remote site. "Access" charges may vary depending on the distance between SO and SWC in each LATA. See Fig. 7.

Multi-point networking set-ups follow this same basic building block and "access" billing approach, with additional "secondary service functions" by AT&T for switching, direction-reversal monitoring, etc.

Chapter 1: Color Television: NTSC Basics, PAL and SECAM
Chapter 2: Using Operational Amplifiers in Broadcasting
Chapter 3: AC Power Systems
Chapter 4: Translators and Low Power Television Systems
Chapter 5: Instructional Television Fixed Service and Multipoint Distribution Service
Chapter 6: Broadcast Newsroom Computer Systems
Chapter 7: Weather Radar Systems
Chapter 8: The Emergency Broadcast System
Chapter 9: Broadcast Audio Measurement

7.1

Color Television

Part I: The Basic NTSC System

FUNDAMENTALS

Color is a dimension that has been added skillfully to black-and-white television. To the engineering fraternity as a whole it signifies one of the most dramatic technological achievements of this age.

Nearly every branch of science including chemistry and psychology contributes in some way to the reality of color television. Through chemistry, improved phosphors are continually being found for use in color-picture tubes. Psychology enters into the selection of lighting arrangements and picture composition to obtain desirable interpretations by the viewer. But physics plays the leading role with intense application in optics and illumination as well as in the design of electronic circuitry and components for the complete television system.

Two specialized branches of physics, namely radio and television engineering, are responsible for the electronic techniques which make color television "compatible" with black-and-white, or monochrome, television, marking what is probably the greatest technical advance in television in the past decade.

This section of the handbook has been reproduced through the courtesy of RCA Corporation who kindly permitted us to use portions of their "Color Television, Manual for Technical Training."

NOTE: Superscript numbers refer to footnotes at the end of this chapter.

Compatibility

The compatible color system offers tremendous economic advantages to the home viewer as well as to the television broadcaster. Because of compatibility, color telecasts can be seen (in monochrome) on black and white television receivers without any changes or added devices. Also, color receivers can receive monochrome as well as color telecasts. Since compatible color is transmitted over the same channels as monochrome and within the same framework of standards, the television broadcaster can utilize his monochrome system as the transmitting nucleus when installing equipment to broadcast color. Moreover, he can utilize his color equipment to produce monochrome telecasts.

Another important advantage of the compatible color system is the part it plays in the conservation of the radio-frequency spectrum. Compatible color requires no additional space in the spectrum. However, it employs techniques which make much more efficient use of the standards originally set up for monochrome television.

A brief review of the fundamentals of monochrome television, particularly the areas wherein specialized color methods are employed, is presented in the next few paragraphs as an aid in describing the basic color concepts.

Television: A System of Communications

Basically, television is a system of communications consisting of the television station at one

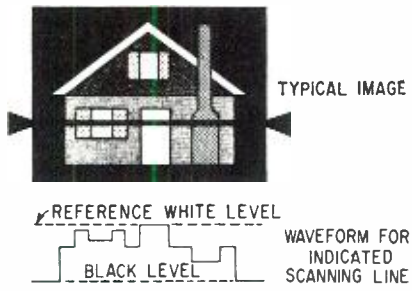


Fig. 1. Typical image and camera output waveform produced by light and dark areas during one scan along line indicated by arrows.

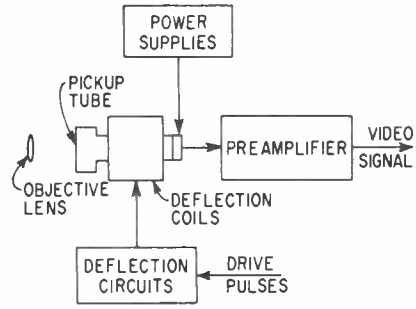


Fig. 2. Block diagram of monochrome-camera circuits.

end of the system and the television receiver at the other. As such, it is actually one of the highest capacity systems in use today, being able to transmit from station to receiver more than five million "bits" of picture information every second.

Very simply, the function of the television station is to divide and subdivide the optical image into over 200,000 picture elements, each of different light intensity; convert these light elements to electrical equivalents; and transmit them in orderly sequence over a radio-frequency carrier to the television receiver.

Reversing the process at the receiver, these electrical signals are each converted to light of corresponding brightness and reassembled to produce the transmitted image on the face of the picture tube.

Scanning

Picture elements to be transmitted in sequence are selected by a process of image scanning which takes place in the television camera focused on the studio scene at the station. Within the camera, an electron beam in a pickup tube scans a sensitive surface containing an "electrical image" of the scene of action. The electron beam successively scans the image at great velocity, beginning at the upper left corner and continuing left to right in a series of parallel lines to scan the image completely. Movement of the electron beam, which can be controlled magnetically by vertical-and horizontal-deflection coils surrounding the tube, is analogous to that of the eye in reading a printed page. The speed of movement is such, however, that 30 complete image frames of approximately 500 lines each are scanned every second. Of course, at the receiver, an electron beam in the kinescope, or picture tube, moves with the same speed and in synchronism with the camera-tube beam so that the corresponding picture elements appear in the proper relative position on the television screen.

Owing to "persistence of vision" and the speed of scanning, these elements appear to be seen all at once as a complete image rather than individually. Thus, the impression is one of continuous illumination of the screen and direct vision.

Scanning standards have been established in this country to assure that all television receivers are capable of receiving programs broadcast by any television station within range. The scanning pattern adhered to by manufacturers in the design of television receivers and broadcast equipment

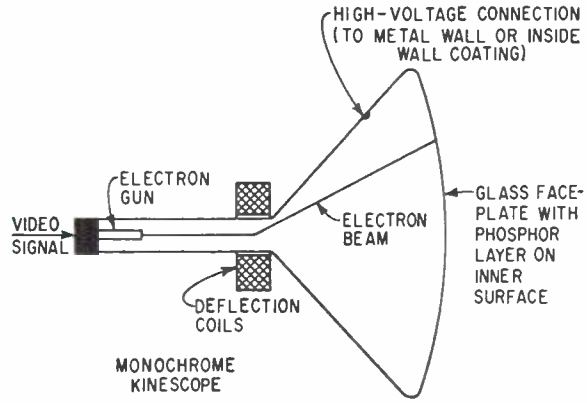


Fig. 3. Diagram showing principal elements of the monochrome kinescope picture tube.

consists of 525 lines with odd-line interlaced scanning. Interlaced scanning, effective in eliminating perceptible flicker, is a method whereby the electron beam scans alternate rather than successive lines. For example, the beam begins by scanning odd-numbered lines (1, 3, 5, 7, etc.) until it reaches the bottom of the image, whereupon it returns to the top of the image to scan the even-numbered lines (2, 4, 6, 8, etc.). Thus, each scan, or field, comprises only half of the total number of scanning lines, and two fields are required to produce the 525-line frame. Each field is completed in one-half the frame time. The vertical scanning frequency is 2 X 30 or 60 Hz, and horizontal scanning frequency is 30 X 525 or 15,750 Hz.

Resolution and Bandwidth

The degree of resolution, or fine detail, that can be seen in a televised image depends upon the number of scanning lines used and the bandwidth of the transmitting and receiving system.

The relationship between resolution and bandwidth can be seen by considering the number of picture elements that can be transmitted each second.

The standard 6 MHz broadcast channel provides a video bandwidth of approximately 4.1 MHz (the remaining bandwidth being required for a vestigial sideband plus the sound signal). Since each cycle of a sine wave is capable of conveying two picture elements (one black and one white), the maximum rate at which picture elements can be transmitted is 4,100,000 X 2, or 8,200,000 per second. Since 30 complete frames are transmitted per second, the number of picture elements per frame would be 8,200,000/30, or 273,333, if it were not for the retrace blanking problem, which requires interruption of the picture signal periodically by blanking pulses. Since the combination of horizontal and vertical blanking pulses requires nominally 25 percent of the total time, the maximum number of picture elements per frame is reduced in practice to 0.75 X 273,333, or approximately 205,000.

Synchronizing

In addition to the picture information, or video signals, blanking and synchronizing signals are transmitted by the television station to control the intensity and movement of the scanning beam in the kinescope of the television receiver. Both these signals are in the form of rectangular pulses. Moreover, their polarity and amplitude are such that they are received as "black" signals and therefore do not appear on the receiver screen.

Blanking pulses eliminate the "retrace" lines which would otherwise appear between scanning lines and at the end of each field from the bottom of the picture to the top. Horizontal blanking pulses, transmitted at the end of each line, or at intervals of 1/15,750 sec, blank the beam during retrace periods between lines. Vertical blanking pulses, transmitted at the end of each field, or at intervals of 1/60 sec, blank the beam during the time required for its return to the top of the picture. Because the vertical retrace is much slower than the horizontal, the vertical blanking periods are longer than the horizontal blanking periods. Vertical blanking pulses are about 20 lines duration, while horizontal blanking pulses have a duration of only a small fraction of a line.

Synchronizing signals keep the scanning beam of the kinescope in step with that of the camera tube. These signals consist of horizontal and vertical pulses which are transmitted within the respective blanking periods. Although the sync pulses are of the same polarity as the blanking pulses, they are of greater amplitude ("blacker than black") and thus easily separated in the receiver and fed to the deflection circuits of the kinescope.

Since the vertical sync pulses are quite long compared with the horizontal sync pulses and the two are of the same amplitude, separation at the receiver is accomplished through frequency discrimination. Serrations, or slots in the vertical pulses, prevent loss of horizontal sync during the vertical blanking period.

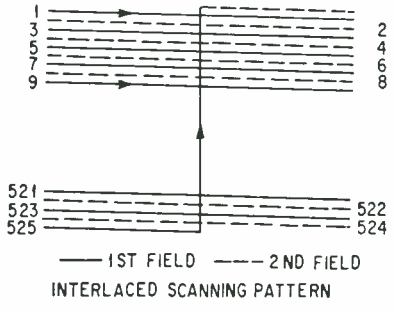


Fig. 4. Diagram showing paths of the electron beam in both the pickup tube and kinescope to produce the interlaced scanning pattern.

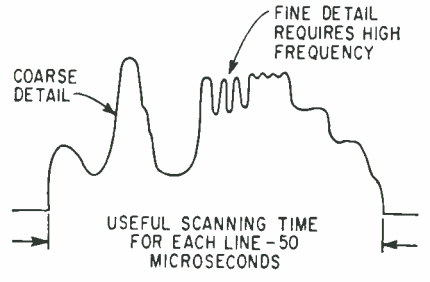


Fig. 5. Diagram illustrating the relationship between picture detail and signal bandwidth.

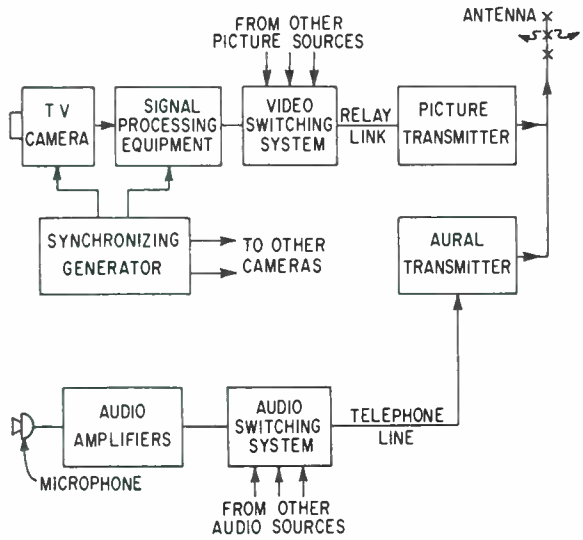


Fig. 6. Simplified block diagram of the monochrome-television station.

The Monochrome Television System

The major equipment in a typical television station consists of the aural and visual units illustrated in the block diagram of Fig. 6. In the visual channel, the video signal leaving the camera is passed through processing equipment which inserts the blanking and synchronizing signals and performs other functions such as aperture compensation and gamma correction. From the processing chain, the video signal is fed to a switching system which provides for selection from a number of video sources. The selected signal is then sent to the visual transmitter through coaxial cable or over a microwave relay link, depending upon the distance between the television studio and transmitter. In the transmitter, the composite video signal amplitude-modulates a carrier in the VHF or UHF range, which is radiated by the television antenna.

In the aural channel, the audio signal is fed from the microphone or other sound source through the switching system and to the aural transmitter. Frequency-modulated output from the aural transmitter is combined with the visual output and radiated from the same antenna.

The Radiated Picture Signal

Amplitude relationships between the synchronizing pulses and the tonal gradations from white to black in the picture are represented in the waveform of the radiated picture signal. From the illustration, it can be seen that modulation takes place in such a way that an increase in the brightness of the picture causes a decrease in carrier output power. Note that the reference-white line indicated on the sketch is relatively close to zero carrier level. Also, the synchronizing pulses are in the "blacker than black" region, representing maximum carrier power. Use of a widely different range of amplitude for the sync pulses makes it possible for home receivers to separate them by a simple clipping technique.

Receiver

The basic elements of the television receiving system are illustrated in the block diagram of the television receiver. The radiated television signal is picked up by an antenna and fed to a tuner which selects the desired channel for viewing. Output from the tuner is passed through an intermediate-frequency amplifier which provides the major selectivity and voltage gain for the receiver. A second detector then recovers a video signal which is essentially the same as that fed to the visual transmitter.

The sound signal is usually taken off at the picture second detector in the form of a frequency-modulated beat between the picture and sound carriers. The sound signal is further amplified in a special IF stage, detected by a discriminator or ratio detector, and applied to the speaker through an audio amplifier.

Picture output from the second detector is fed to two independent channels. One of these is the video amplifier which drives the electron beam in the kinescope, and the other is the sync separator, or clipper, which separates the sync pulses from the picture information. The separated pulses are then used to control the timing of the horizontal and vertical deflection circuits. The high-voltage supply, which is closely associated with the horizontal deflection circuit, provides accelerating potential for the electron beam.

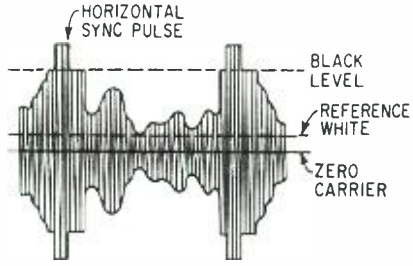


Fig. 7. Waveform and radiated picture signal.

The Three Variables of Color

Color is the combination of those properties of light which control the visual sensations known as brightness, hue, and saturation. Brightness is that characteristic of a color which enables it to be placed in a scale ranging from black to white or from dark to light. Hue, the second variable of a color, is the characteristic which enables a color to be described as red, yellow, blue, or green. Saturation refers to the extent to which a color departs from white, or the "neutral" condition. Pale colors, or pastels, are low in saturation, while strong or vivid colors are high in saturation.

The monochrome system is limited to the transmission of images that vary with respect to brightness alone. Thus, brightness is the only attribute of a color which is transmitted over a monochrome-television system. To produce a color image, therefore, provision must be made for the transmission of additional information pertaining to all three of the variables of color. However, since the primary-color process can be employed, it is not necessary to transmit information in exactly the form expressed by the three variables.

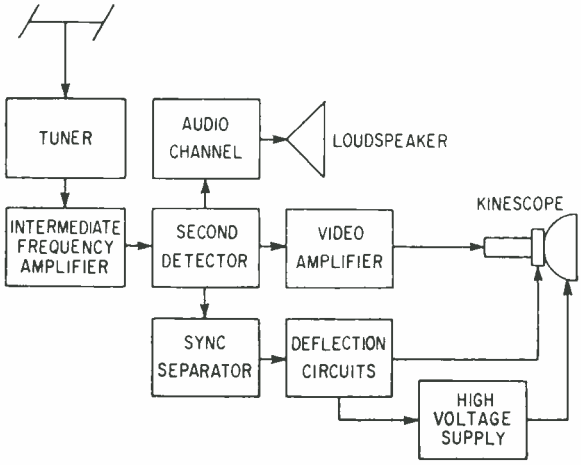


Fig. 8. Block diagram of monochrome-television receiver.

Primary Colors in Television

Experiments have proved conclusively that virtually any color can be matched by the proper combination of no more than three primary colors. While other colors could be used as primaries, red, green and blue have been selected as the most practical for color-television use. A few of the many colors that can be made by mixing lights of red, green, and blue are illustrated in Fig. 9 (see page 7.1-9). Red and green combined produce yellow, red plus blue give purple, and green plus blue give cyan or blue-green. The proper combination of all three of the primary colors produces white, or neutral, as shown at the center of the illustration. By relatively simple optical means, it is possible to separate any color image into red, green, and blue, or RGB components, as shown by Fig. 10.

Generating RGB Signals

Major components of a color-television camera may have the block-diagram form shown in Fig. 11. Whereas the monochrome camera contains only one pickup tube, or solid-state sensor, the color camera usually contains three separate pickup devices. An objective lens at the front of the camera forms a real image within a condensor lens which is located where the pickup device is usually mounted in a monochrome camera. A relay lens transfers this real image to a system of dichroic (color separating) mirrors or prisms which shunt the red and blue light to the red and blue pickup devices and permit the green to pass straight through to the green tube or sensor. In this manner, the three pickup devices produce three separate images corresponding to the RGB components of the original scene. These images are scanned in the conventional manner by common deflection circuits.

A single scanning line through the typical color image at the point shown (Fig. 18) produces three separate waveforms. It is important to note the correlation between these waveforms and the image at the top. The yellow shutters in the image, for example, must be produced by a mixture of red and green, and the blue signal is not required. Thus, at this interval of scanning the red and green signals are both at full value and the blue signal is at zero. The white door utilizes all three color signals. Of course, similar correlations can be seen for other parts of the image along the scanning line.

Displaying RGB Signals

RGB signals are displayed in color by the tricolor kinescope, the basic components of which are shown in the diagram of Fig. 12. Three electron guns produce three beams which are independently controlled in intensity by the red,

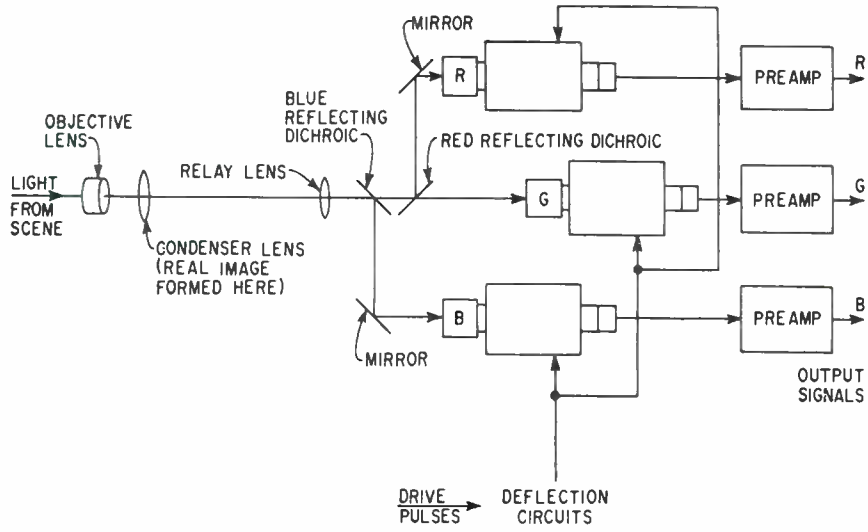


Fig. 11. Simplified block diagram of the optical and electrical components of the color camera.

green, and blue signals. These three beams are all made to scan in unison by deflection coils around the neck of the tube. The three beams converge at the screen owing to the magnetic field produced by a convergence yoke.

The phosphor screen of the color kinescope consists of an array of very small primary-color dots. Approximtely ½ in. behind the phosphor screen is an aperture mask which has one very small opening for each group of red, green, and blue phosphors. Alignment of this aperture mask and screen is such that each beam is permitted to strike phosphor dots of only one color. For example, all the electrons emitted by the red gun must strike red phosphor dots on the aperture mask; they cannot strike either the green or blue dots because of the "shadow" effect of the mask. Likewise, the beams emanating from the other two guns strike only green or blue dots.

In this way, three separate primary-color images are produced on the screen of the tricolor tube. But since these images are formed by closely intermingled dots too small to be resolved at the normal viewing distance, the observer sees a full-color image of the scene being televised.

ELECTRONIC ASPECTS OF COMPATIBLE COLOR TELEVISION

To achieve compatibility with monochrome television, color-television signals must be processed in such a way that they can be transmitted through the same channels used for monochrome signals, and they must also be capable of producing good monochrome pictures on monochrome receivers. Since color television involves three variables instead of the single variable (i.e., brightness) of monochrome television, an encoding process is required to permit all three to be transmitted over the one available channel. Likewise, a decoding process is required in the

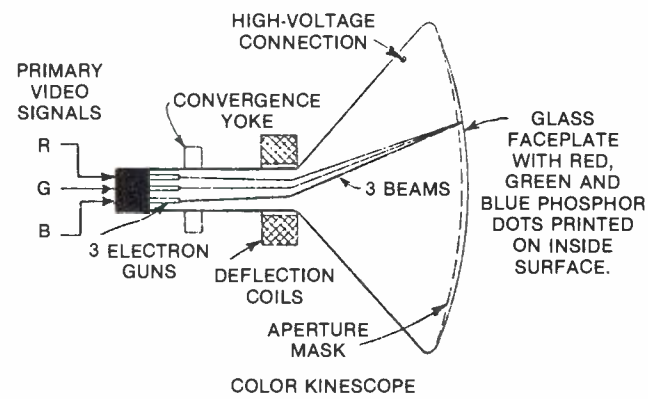


Fig. 12. Diagram showing components of the three-gun kinescope picture tube.

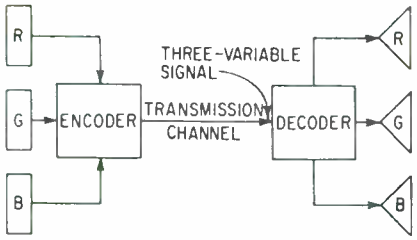


Fig. 13. Encoding of the RGB signals provides a three-variable signal which can be transmitted over existing monochrome channels.

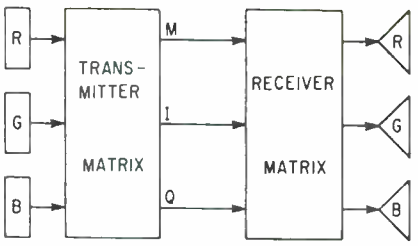


Fig. 14. A part of the encoding process is the matrixing of R, G, and B signals to provide M, I, Q signals.

color receiver to recover the independent RGB signals for control of the electron guns in the color kinescope. Moreover, the process used must enable existing monochrome receivers to produce a monochrome picture from the color information.

Encoding and decoding processes used in compatible color television are based on four electronic techniques known as matrixing, band shaping, two-phase modulation, and frequency interlace. It is these processes which make the color system compatible with monochrome and enable the color system to occupy the existing 6 MHz channel.

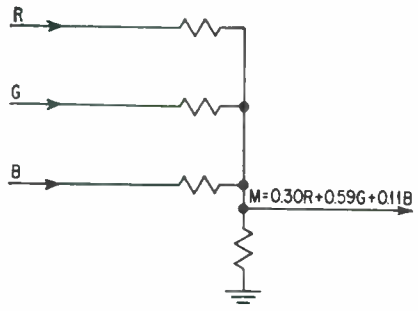


Fig. 15. Diagram of resistance matrix circuit used to produce the M luminance signal.

Matrixing

Matrixing is a process for "repackaging" the information contained in the red, green, and blue output signals from a color camera to permit more efficient use of the transmission channel. The matrix circuits which perform this function consist of simple linear cross-mixing circuits. They produce these signals, commonly designated M, I, and Q, each of which is a different linear combination of the original red, green, and blue signals. Specific values for these signals have been established by FCC standards.

The M-signal component, or *luminance* signal, corresponds very closely to the signal produced by a monochrome camera, and therefore is capable of rendering excellent service to monochrome receivers. The M component is obtained by combining red, green, and blue signals in a simple resistor network (Fig. 15) designed to produce a signal consisting of 30 percent red, 59 percent green, and 11 percent blue.

The I and Q signals are *chrominance* signals which convey information as to how the colors in the scene differ from the monochrome, or "neutral" condition. The component I is defined as a signal consisting of 60 percent red, -28 percent green, and -32 percent blue. Minus values are easily achieved in the matrix circuits by use of phase inverters to reverse the signal polarity (see Figs. 16 and 17). The Q signal is defined as

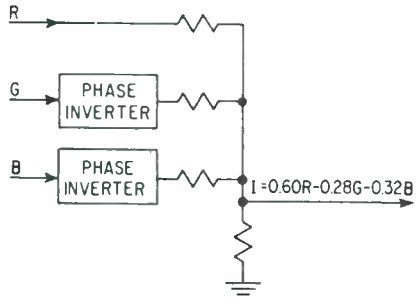


Fig. 16. Diagram of I matrix showing phase inverters to produce minus green and blue quantities.

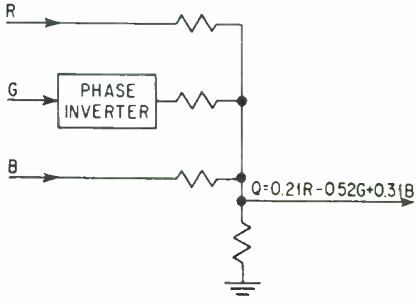


Fig. 17. Diagram of the Q matrix showing phase inverter to produce required minus green signal.

21 percent red, -52 percent green, and 31 percent blue.

It can be seen that the quantities are related so that when red, green, and blue are equal, corresponding to the neutral condition, both I and Q go to zero. Thus, when the color camera is focused on an object having no color information, such as a monochrome test chart, the I-signal and Q-signal components are absent, leaving only the M component, or monochrome signal.

The matrix circuits, therefore, produce a new set of waveforms corresponding to the M, I, and Q components of the image. A comparison of the MIQ and RGB waveforms (Figs. 18 and 19, see page of color illustrations on page 7.1-9) obtained from the image illustrates the correlation among the types of signals. It will be seen that the M signal remains in the region between black level and reference white. The I and Q signals, on the other hand, swing positive and negative around a zero axis.

Band Shaping

The eye has substantially less acuity in detecting variations in chrominance than it has for resolving differences in brightness. This important characteristic of human vision was considered in setting up the I and Q equations because it permitted a significant reduction in the bandwidth of these signals through use of low-pass filters. A bandwidth of approximately 1.5 MHz was found to be satisfactory for the I signal, which corresponds to color transitions in the range extending from orange to blue-green. For color transitions in the range from green to purple, as represented by the Q signal, the eye has even less acuity and the bandwidth was restricted to only 0.5 MHz. The M-signal component, which conveys the fine details, must be transmitted with the standard 4 MHz bandwidth.

Two-Phase Modulation: Generation of Color Subcarrier

Two-phase modulation is a technique by which the I and Q signals can be combined into a two-variable signal for transmission over a single channel. This is accomplished by adding the sidebands obtained through modulation of two 3.6 MHz carriers separated in phase by 90°. The resultant waveform is the vector sum of the components. Elements of the transmitting and receiving system are shown in Fig. 20. The two carriers, which are derived from the same oscillator, are suppressed by the balanced modulators. Thus, only the two amplitude-modulated sidebands, 90° out of phase, are transmitted. At the receiving end of the system, the I and Q signals are recovered by heterodyning the two-phase wave against two locally generated carriers of the same frequency but with a 90° phase separation and applying the resultant signals through low-pass filters to the matrix circuits. Typical signal waveforms are illustrated in Fig. 21.

The 3.6 MHz oscillator at the receiver must be accurately synchronized in frequency and in phase with the master oscillator at the transmitter. The synchronizing information consists of 3.6 MHz, "bursts" of at least 8 Hz duration transmitted during the "back-porch" interval following each horizontal sync pulse. The bursts are generated at the transmitter by a gating circuit which is

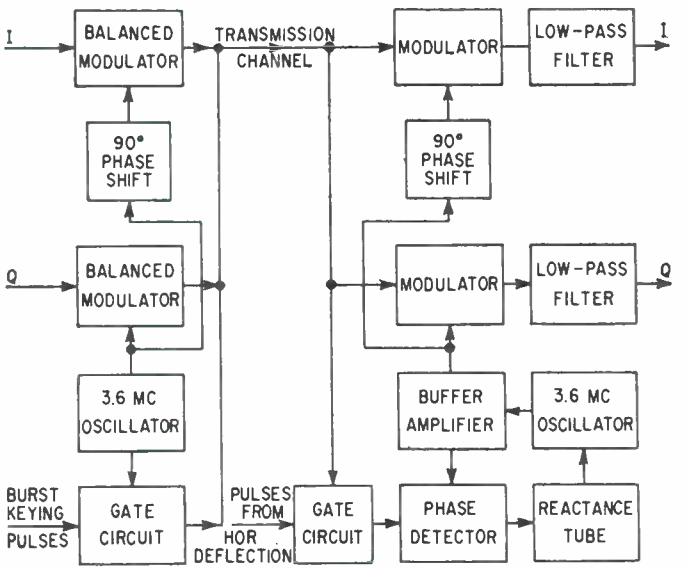


Fig. 20. Simplified block diagram showing elements for transmitting and receiving the I, Q, and burst signals.

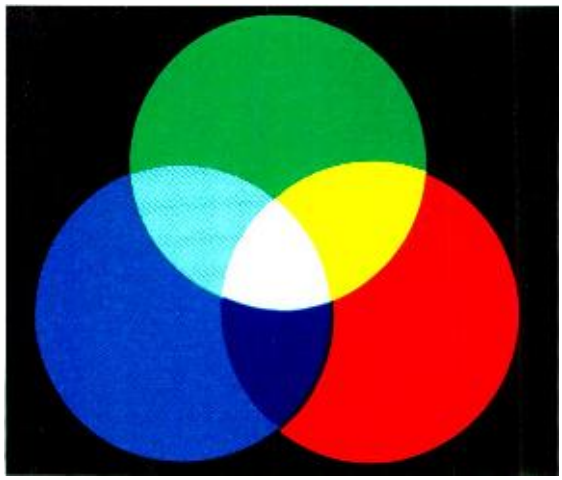


Fig. 9. The primary colors of television are red, green, and blue. Virtually any color can be matched by combining proper amounts of these primaries. White is produced by a combination of all three.

Fig. 10. Illustrating how a typical color image (upper left corner) can be separated by optical means into red, green, and blue counterparts.

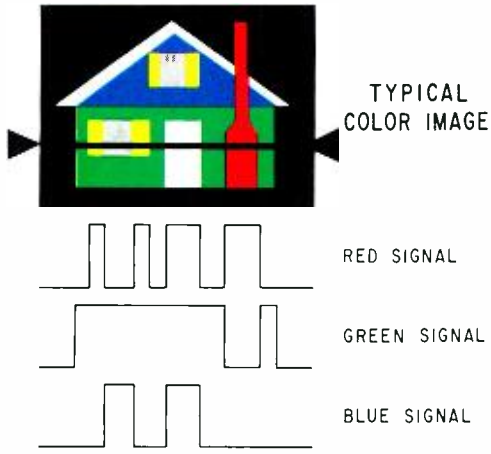


Fig. 18. Typical color image and RGB waveforms.

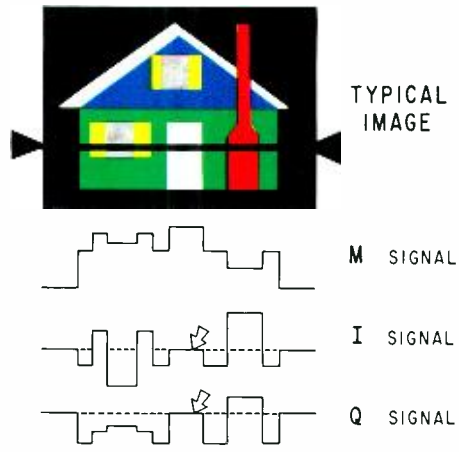


Fig. 19. Typical color image and MIQ waveforms.

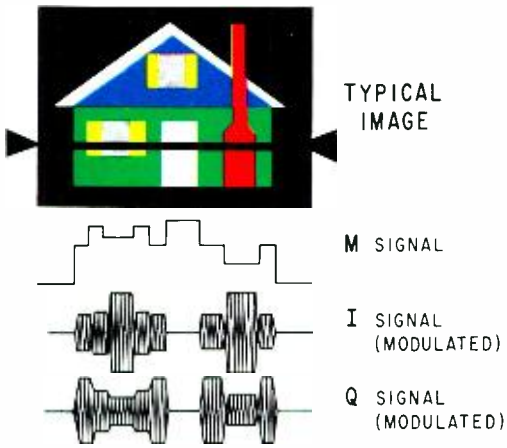


Fig. 27. Typical color image and waveforms of the M signal and modulated I and Q signals.

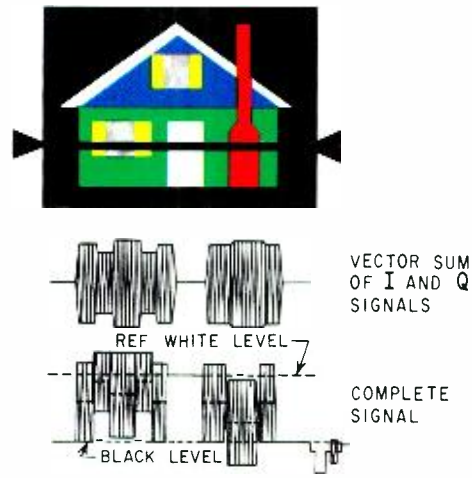


Fig. 28. Typical color image.

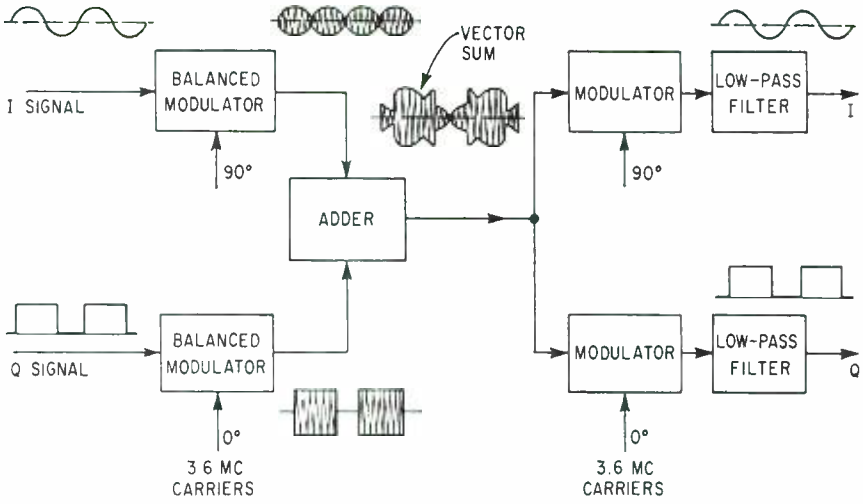


Fig. 21. Representative waveforms of the separate I, Q signals and the vector sum of the suppressed carrier sidebands at the modulator output. Original I and Q signals are recovered by heterodyning in balanced modulators at receiver.

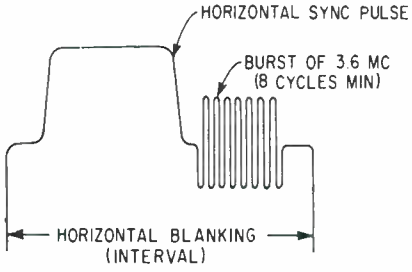


Fig. 22. Diagram showing position of subcarrier burst during horizontal blanking interval.

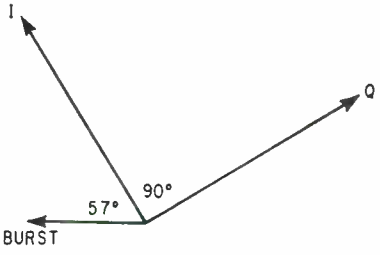


Fig. 23. Diagram showing phase relationship of I, Q, and burst signals.

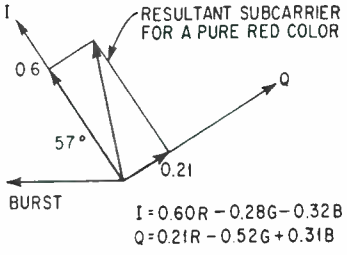


Fig. 24. Vector diagram showing phase and amplitude of subcarrier for a pure red signal.

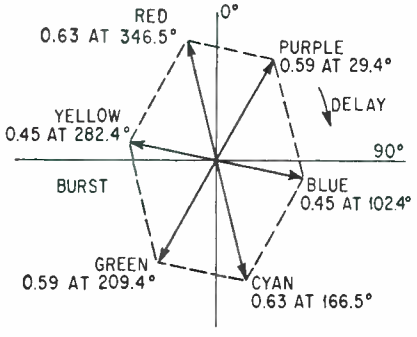


Fig. 25. Composite vector diagram showing subcarrier phase and amplitude for each of six colors.

turned "on" by burst keying pulses derived from the synchronizing generator. At the receiver, the two-phase modulated signal is applied to another gating circuit, known as a burst separator, which is keyed "on" by pulses derived from the horizontal deflection circuit. The separated bursts are compared in a phase detector with the output of the local 3.6 MHz oscillator. Any error voltage developed is applied through a smoothing filter to a conventional reactance tube or varactor which corrects the phase of the local oscillator.

FCC Standard phase relationships between the I and Q signals and the color synchronizing burst are shown in the vector diagram of Fig. 23. The

I and Q signals are transmitted in phase quadrature, and the color burst is transmitted with an arbitrary 57° phase lead over the I signal.

Several interesting properties of the two-phase modulated signal are illustrated by the vector diagrams which represent the resultant signal under known transmission conditions. For example, when a pure red color of maximum amplitude is being transmitted, the green and blue components are at zero and the I and Q signals have levels of 60 and 21 percent, respectively. When modulated upon their respective carrier, these signals produce the resultant shown in Fig. 24. The phase and amplitude shown are characteristic of pure red of maximum relative luminance. Fig. 25 is a composite vector diagram showing the phase and amplitude characteristics of the three primaries and their complementary colors. This composite diagram indicates that there is a direct relationship between the *phase* of the resultant two-phase modulated signal and the *hue* of the color being transmitted. There is also a relationship (although indirect) between the *amplitude* of the resultant signal and the saturation of the color being transmitted. If the phase of the resultant subcarrier and the level of the monochrome signal both remain constant, then a reduction in the amplitude of the subcarrier indicates a decrease in color saturation. The composite vector diagram also shows an interesting symmetry between complementary colors (colors are complementary if they produce a neutral when added together); the resultants for any two complementary colors are equal in amplitude but opposite in phase.

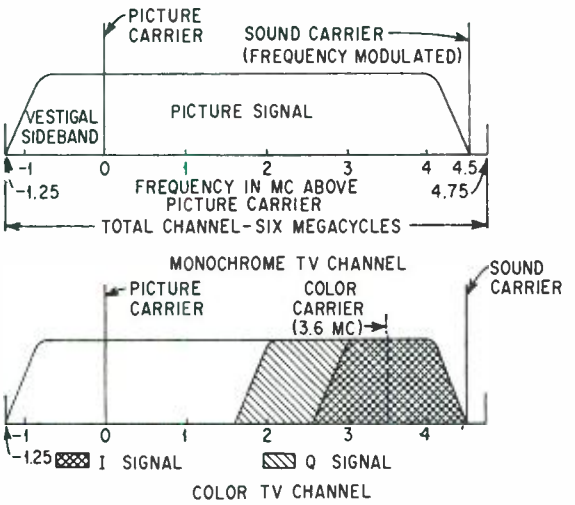


Fig. 26. Diagram of television channel showing portions occupied by color and monochrome signal components.

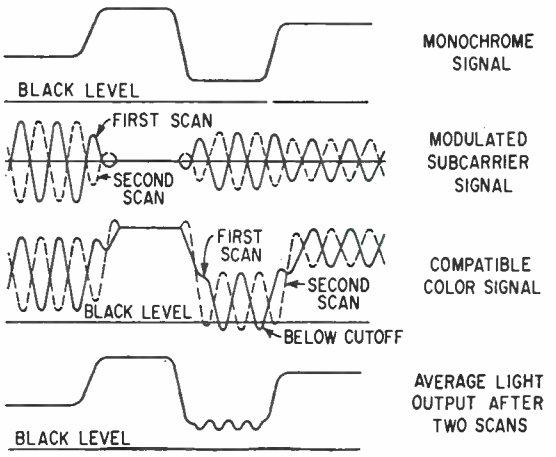


Fig. 29. Waveforms showing superposition of modulated subcarrier on scanning signals, compatible color signal, and effect of subcarrier on average light output.

Frequency Interlace

Since the 3.6 MHz carriers, consisting of the I and Q sidebands, fall within the video passband as shown in the diagram of the television channel (Fig. 26), they become subcarriers and can be handled in many respects like unmodulated video signals. By use of *frequency interlace* it is possible to add the several components of the chrominance and monochrome signals together without causing objectionable mutual interference.

The significance of the straightforward addition of signal components made possible by frequency interlace may be brought out by a study of waveforms derived from a simple color image. Fig. 27 shows M, I, and Q signals after the latter two have been modulated upon 3.6 MHz subcarriers. Note that both the I-and Q-signal components are at zero during the scanning of the white door, a neutral area. Fig. 28 (see page of color illustrations on (page 7.1-9) shows the vector sum of the I and Q signals and also the complete compatible color signal formed by adding together all the components, including synchronizing pulses and color-synchronizing bursts. The most significant fact about this signal is that it is still capable of providing good service to monochrome receivers, even though a modulated wave has been added to the monochrome-signal component. Although the modulated wave is clearly a spurious signal with respect to the operation of the kinescope in a monochrome receiver, its interference effects are not objectionable because of the application of the frequency-interlace principle.

The frequency-interlace technique is based on two factors: a precise choice of the color subcar-

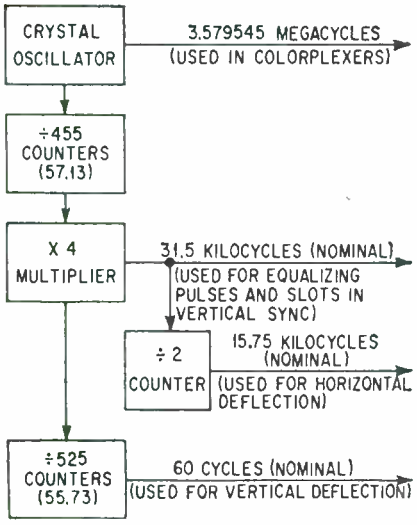


Fig. 30. Block diagram showing relationship between various frequencies used in color-television station.

rier frequency and the familiar "persistence-of-vision" effect. If the color subcarrier is made an *odd multiple of one-half the line frequency*, its apparent polarity can be made to reverse between successive scans of the same area in the picture. Since the eye responds to the average stimulation after two or more scans, the interference effect of the color subcarrier tends to be self-canceling, owing to the periodic polarity reversals. (see Fig. 29).

Color-Frequency Standards

The relationships among the various frequencies used in a compatible color system are illustrated in the block diagram of Fig. 29. The actual frequency of the color subcarrier, which has been referred to as 3.6 MHz is specified by FCC Standards as 3.579545 MHz or exactly 455 multiplied by ½ the line frequency.

In broadcast practice, the frequency of the color subcarrier provides a frequency standard for operation of the entire system. A crystal oscillator at the specified frequency provides the basic control information for all other frequencies. County stages and multipliers derive the basic frequencies needed in the color studio. A frequency of nominally 31.5 kHz required for the equalizing pulses which precede and follow each vertical sync pulse and for the serrations in the vertical sync pulse. A divide-by-2 counter controlled by the 31.5 kHz signal provides the line-frequency pulses at nominally 15.75 kHz needed to control the horizontal blanking and synchronizing waveforms. Another counter chain provides the 60 Hz pulses needed for control of the vertical blanking and synchronizing circuits.

The Overall Color System

The major functions performed in transmitting and receiving color are shown in the overall block diagrams of the transmitting and receiving systems (Figs. 31 and 32).

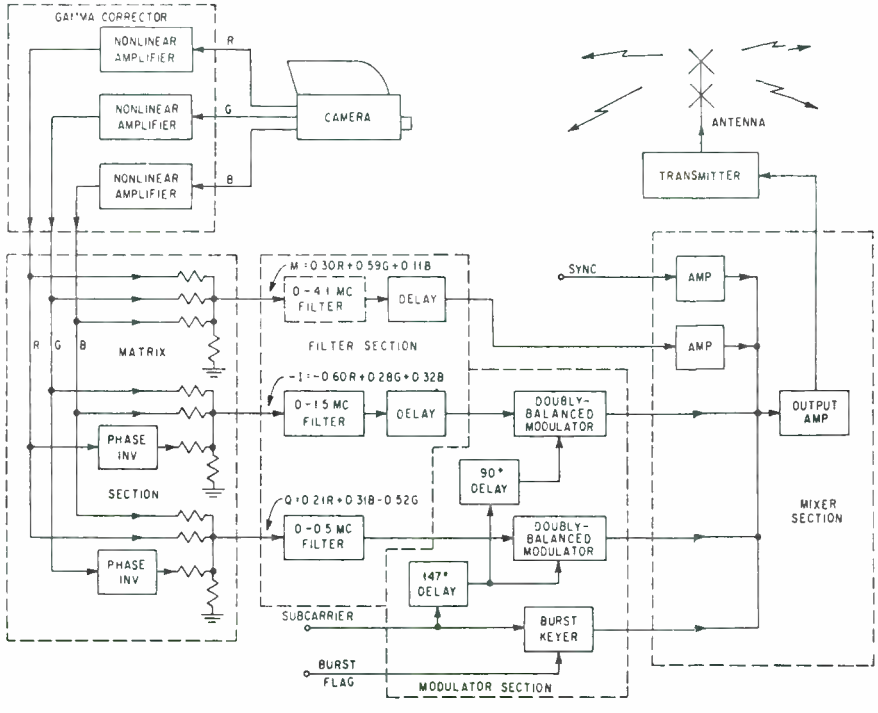


Fig. 31. Block diagram showing major functions of color-transmitting system.

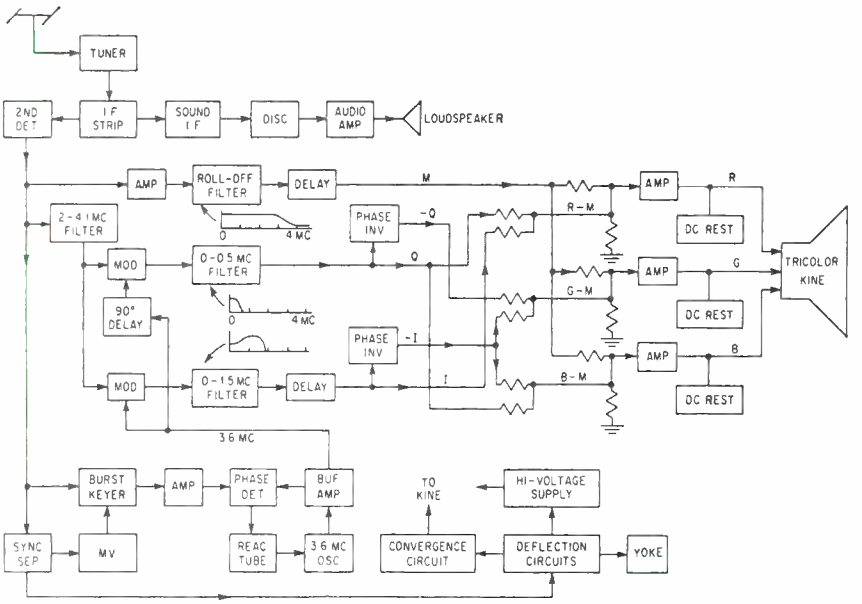


Fig. 32. Block diagram showing major functions of color-receiving systems.

At the transmitting end, camera output signals corresponding to the red, green, and blue components of the scene being televised are passed through nonlinear amplifiers (the gamma correctors) which compensate for the nonlinearity of the kinescope elements at the receiving end. Gamma-corrected signals are then matrixed to produce the luminance signal M and two chrominance signals I and Q. The filter section establishes the bandwidth of these signals. The 4.1 MHz filter for the luminance channel is shown in dotted lines because in practice this band shaping is usually achieved by the attenuation characteristics of the transmitter, and the filter is not required.

The bandwidths of 1.5 and 0.5 MHz known for the I and Q channels, respectively, are nominal only; the required frequency-response characteristics are described in more detail in the complete FCC signal specifications. Delay compensation is needed in the filter section in order to permit all signal components to be transmitted in time coincidence. In general, the delay time for relatively simple filter circuits varies inversely with the bandwidth. The narrower the bandwidth, the greater the delay. Consequently, a delay network or a length of delay cable must be inserted in the I channel to provide the same delay introduced by the narrower band filter in the Q channel, and still more delay must be inserted in the M channel.

In the modulator section, the I and Q signals are modulated upon two subcarriers of the same frequency but 90° apart in phase. The modulators employed should be of double balanced type, so that both the carriers and the original I and Q signals are suppressed, leaving only the sidebands. Some sort of keying circuit must be provided to produce the color-synchronizing bursts during the horizontal blanking intervals. To comply with the FCC signal specifications, the phase of the burst should be 57° ahead of the I component (which leads the Q component by 90). This phase position was chosen mainly because it permits certain simplifications in receiver designs. Timing information for "keying in" the burst can be obtained from a "burst flag generator," which is a simple arrangement of multivibrators controlled by horizontal and vertical drive pulses.

In the mixer section, the M signal, the two subcarriers modulated by I and Q chrominance signals, and the color synchronizing bursts are all added together. Provision is also made for the addition of standard synchronizing pulses, so that the output of mixer section is a complete color-television signal containing both picture and synchronizing information. This signal can then be put "on the air" by means of a standard television transmitter, which must be modified only to the extent necessary to assure performance within the reduced tolerance limits required by the color signal. (Since the color signal places more information in the channel than a black-and-white signal, the requirements for frequency response, amplitude linearity, and uniformity of delay time are more strict).

The Color-Receiving System

In a compatible color receiver, the antenna, RF tuner, IF strip, and second detector serve the same functions as the corresponding components of a

black-and-white receiver except that the tolerance limits on performance are somewhat tighter.

The signal from the second detector is utilized in four circuit branches. One circuit branch directs the complete signal toward the color kinescope, where it is used to control luminance by being applied to all kinescope guns in equal proportions. In the second circuit branch, a band-pass filter separates the high-frequency components of the signal (roughly 2.0 to 4.1 MHz) consisting mainly of the two-phase modulated subcarrier signal. This signal is applied to a pair of modulators which operate as synchronous detectors to recover the original I and Q signals. It should be noted that those frequency components of the luminance signal falling between about 2 and 4.1 MHz are also applied to the modulators and are heterodyned down to lower frequencies. These frequency components do not cause objectionable interference, however, because they are frequency-interlaced and tend to cancel out through persistence of vision.

The remaining two circuit branches at the output of the second detector make use of the timing or synchronizing information in the signal. A conventional sync separator is used to produce the pulses needed to control the horizontal-and vertical-deflection circuits which are also conventional. The high-voltage supply for the kinescope can be obtained either from a "flyback" supply associated with the horizontal deflection circuit or from an independent RF power supply. Many color kinescopes require convergence signals to enable the scanning beams to coincide at the screen in all parts of the picture area; the waveforms required for this purpose are readily derived from the deflection circuits.

The final branch at the output of the second detector is the burst gate, which is turned "on" only for a brief interval following each horizontal sync pulse by means of a keying pulse. This pulse may be derived from a multivibrator controlled by sync pulses, as illustrated , or it may be derived from the "flyback" pulse produced by the horizontal output stage. The separated bursts are amplified and compared with the output of a local oscillator in a phase detector. If there is a phase difference between the local signal and the bursts, and error voltage is developed by the phase detector. This error voltage restores the oscillator to the correct phase by means of a reactance tube or varactor connected in parallel with the tuned circuit of the oscillator. This automatic-frequency-control circuit keeps the receiver oscillator in synchronism with the master subcarrier oscillator at the transmitter. The output of the oscillator provides the reference carriers for the two synchronous detectors; a 90° phase shifter is necessary to delay the phase of the Q modulator by 90° relative to the I modulator.

There is a "filter section" in a color receiver that is rather similar to the filter section of the transmitting equipment. The M, I, and Q signals must all be passed through filters in order to separate the desired signals from other frequency components which, if unimpeded, might cause spurious effects. The I and Q signals are passed through filters of nominally 1.5 and 0.5 MHz bandwidth, respectively, just as at the transmitting end. A step-type characteristic is theoretically required for the I filter, as indicated in Fig. 26, to compensate for the loss of one sideband for all frequency components above about 0.5 MHz. Actually, this requirement is ignored in many practical receiver designs, resulting in only a slight loss in sharpness in the I channel. A roll-off filter is desirable in the M channel to attenuate the subcarrier signal before it reaches the kinescope. The subcarrier would tend to dilute the colors on the screen if it were permitted to appear on the kinescope grids at full amplitude. Delay networks are needed to compensate for the different inherent delays of the three filters, as explained previously.

Following the filter section in the receiver there is a matrix section in which the M, I, and Q signals are cross-mixed to recreate the original R, G, and B signals. The R, G, and B signals at the receiver are not identical with those at the transmitter because the higher frequency components are mixed and are common to all three channels. This mixing is justifiable because the eye cannot perceive the fine detail (conveyed by the high-frequency components) in color. There are many possible types of matrixing circuits. The resistance mixers shown provide one simple and reliable approach. For ease of analysis, the matrix operations at the receiver can be considered in two stages. The I and Q signals are first cross-mixed to produce R-M, G-M, and B-M signals (note that *negative* I and Q signals are required in some cases), which are, in turn, added to M to produce R, G, and B.

In the output section of the receiver, the signals are amplified to the level necessary to drive the kinescope and the dc component is restored. The image which appears on the color kinescope screen is a high-quality full-color image of the scene before the color camera.

It should be made clear that the block diagram of Fig. 32 is intended only to illustrate the principles used in color receivers and does not represent any specific model now on the market. Design engineers of color receivers have shown great ingenuity in simplifying circuits, in combining functions, and in devising subtle variations in the basic process which have made possible significant cost reductions while maintaining excellent picture fidelity. The principles of compatible color television are firmly established, and it

is to be expected that steady progress will be made in the practical application of those principles.

COLOR FIDELITY

"Color fidelity" as used herein, is the property of a color-television system to reproduce colors which are realistic and pleasing to the average viewer.

Although perhaps not apparent at first, color fidelity is analogous to "high fidelity" as applied to sound reproduction. Just as a high-fidelity audio system faithfully reproduces sounds reaching the microphone, the color-television system is capable of faithfully reproducing colors as seen by the television cameraman. In fact, the color television system is capable of reproducing colors more accurately than techniques presently used in color printing and color photography.

Tests have shown, however, that color-television pictures are generally more pleasing to the viewer when deliberate modifications are made in the reproduced colors to compensate for the surroundings in which they are reproduced. The situation is similar to that experienced in the art of sound reproduction in the case of a symphony orchestra recorded at high sound levels in a large hall and reproduced at lower sound levels in a small room. In this case, a more pleasing effect is obtained if the ear's new environment is taken into consideration and the reproduction is modified accordingly. Similarly, in color television, the changed environment of the eye must be con-

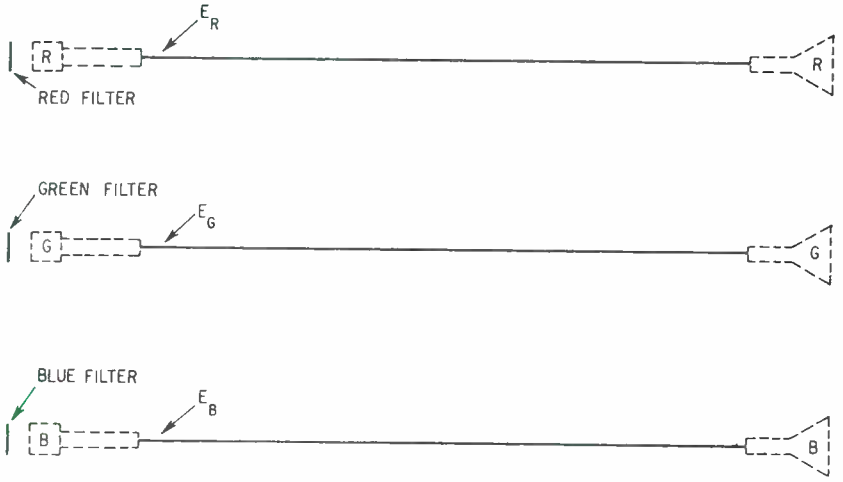


Fig. 33. Diagram of a theoretical color system showing linear RGB pickup tubes and kinescopes interconnected by wire.

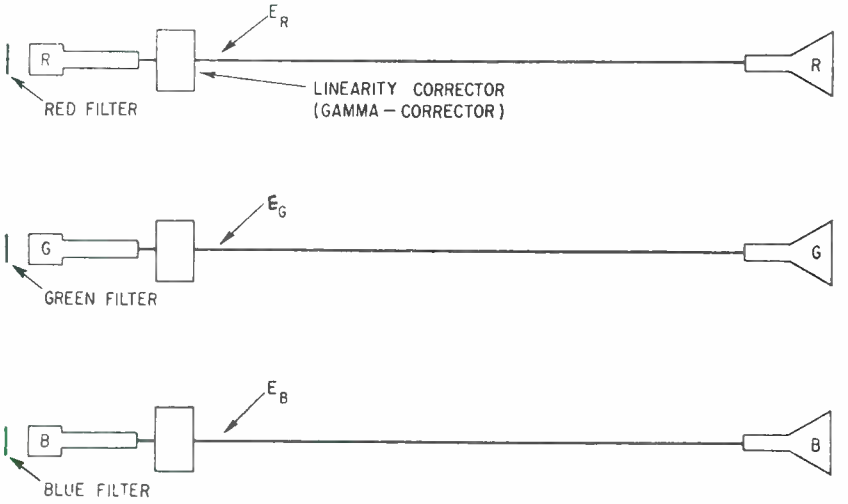


Fig. 34. The basic color system shown with necessary linearity correctors to compensate for color errors introduced by the nonlinear transducers.

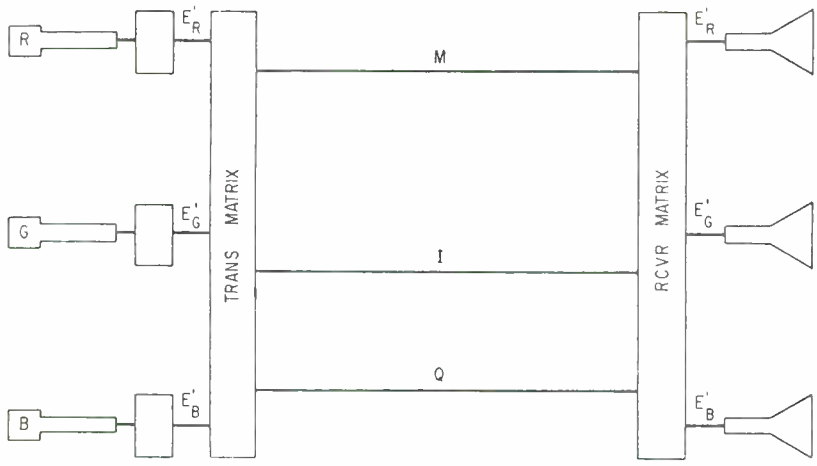


Fig. 35. Diagram showing transmitter and receiver matrix functions in the color system.

sidered and the reproduced colors modified accordingly.

Color fidelity, therefore, is a term used to indicate a color reproduction which pleases the viewer aesthetically and persuades him that he is viewing a faithful reproduction of the original colors in the scene being televised.[1]

The following describes possible distortions in the color system and their effect on the picture and prescribes amounts or degrees of distortion that can be tolerated without adverse effects on picture quality.

Color-System Analysis

Individual elements or areas of the complete color system are discussed in the following paragraphs with the aid of the diagrams shown in Fig. 33 through 37.

Fig. 33 is a theoretical color system in that it assumes linear camera tubes and a linear kinescope interconnected by a distortionless wire system. The only distortion that can result from this system is a flaw in colorimetry.

Fig. 34 introduces linearity correctors to compensate for color errors produced by nonlinearities in the transducers.

Figs. 35, 36, and 37 successively introduce the complexities of matrixing, band limiting, delay compensation, and the transmission system (shown dotted in Fig. 37). These diagrams, each representing a possible color system, introduce techniques used in compatible color television and permit the study of color distortions peculiar to each technique.

The systems diagrammed in Figs. 33 and 34 are described under Possible Distortions in Transducers, and those in Figs. 35, 36, and 37 under Possible Distortions in Encoding and Decoding Processes. The system shown in Fig. 37 is discussed under Distortions in the Transmission System.

Characteristics of the Eye

To appreciate fully the significance of color fidelity, it is helpful to consider some of the characteristics of the eye associated with color perception and to analyze such terms as color adaptation, reference white, and primary colors and determine their relationship to a color-television system.

Color Adaptation

One amazing characteristic of the eye is the phenomenon knows as color adaptation. It is this adaptation which enables one to describe accurately the color of an object under "white" light while viewing in nonwhite light. That is to say, recognition of color is surprisingly independent of the illumination under which an object is viewed. For example, if sunlight at high noon on a cloudless day is taken as "white" light, then, by comparison, the illumination from a typical 100-watt incandescent bulb is very yellow light. Yet it is known that an object viewed under sunlight looks very little if any different when viewed under incandescent light. Moreover, it is obvious to the observer, after a very few minutes in a room illuminated with incandescent lights, that the light is not yellow at all; it is really "white."

It is apparent, then, that the color seen by an observer is dependent upon the illumination to which that observer has been exposed for the past several minutes. This ambient illumination will have a marked effect on his choice of what color he is going to call "white."

This phenomenon can cause a loss of color fidelity under certain conditions. Consider, for example, a theoretically perfect color system with

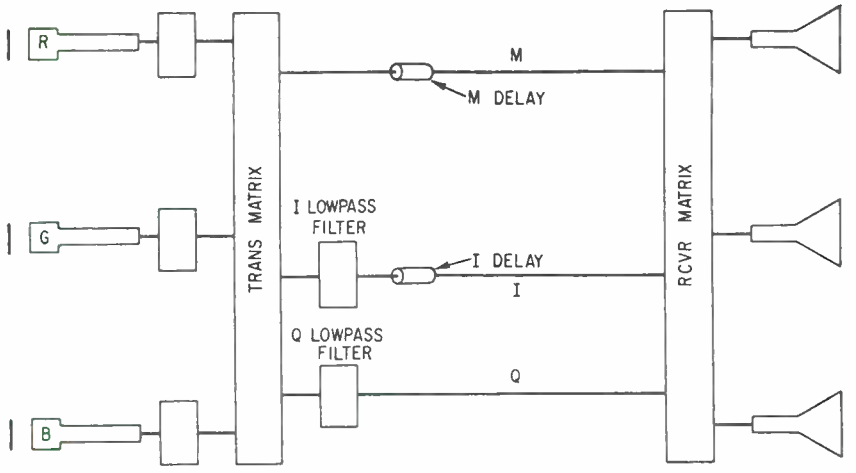


Fig. 36. Basic color system with band limiting and delay compensation.

camera viewing an outdoor scene under a midday sun while the reproduced picture is being viewed in a semidarkened room, with what little light is in the room also being derived from the midday sun. Under these conditions, the ambient illuminations at both camera and receiver are identical, so a man standing alongside the camera and a man viewing the receiver would both see the same colors. Now, if a change in the weather at the camera location should cause a cloud to cover the sun, the ambient illumination at the camera location would shift toward a bluer color. This shift would not disturb the viewer standing alongside the camera, because his eyes, bathed in the new ambient light, would rapidly adapt to the new viewing conditions and he would perceive the scene as being unchanged.

The man viewing the receiver would not be so fortunate. Assuming that he is far enough away that this same cloud would not affect his ambient, he would observe that everything on his screen had suddenly and inexplicably taken on a bluish cast, which he would certainly find most disturbing.

Such errors in color fidelity can be corrected by making the camera imitate the human eye in adaptation. The eye adapts to changes in ambient illumination by changing its sensitivity to a certain color. For example, if a light source changes from white to blue-white (as in the above example), the eye reduces its blue sensitivity until the light again appears to be white to the observer. Likewise, a camera operator can correct for the same situation by decreasing the gain of the blue

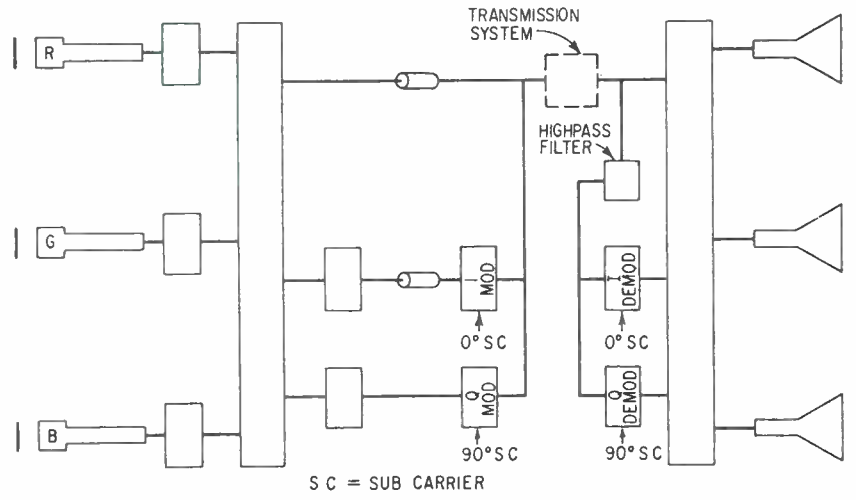


Fig. 37. Basic color system showing all major elements, including the transmission system.

channel of the camera or by attenuating the light reaching the blue camera tube. In this way, the camera is made to "color adapt," and the reproduced picture on a receiver loses its bluish cast.

Reference White

Although color adaptation can generate a problem such as the one just described, it also simplifies certain requirements. Specifically, it eases the requirement that white be transmitted as a definite, absolute color, for there clearly can be no absolute white when almost any color can be made to appear subjectively white by making it the color of the ambient illumination to which an observer's eye has adapted.

In color television, we take advantage of this characteristic in the following manner: A surface in the studio which is known by common experience to white, for example, the EIA Gray-Scale Chart of a piece of Neutracor white paper, is selected to be reproduced as white on a home receiver. The relative sensitivities of the three-color channels of the camera are then adjusted so that the camera "adapts" to this white regardless of the studio illumination. The home receiver can then be adjusted to reproduce the surface as any "white" which the home viewer prefers, depending upon his surroundings.

It has already been mentioned that the eye adapts readily to the illumination that surround conditions of an overcast day. This representative standard illumination has been adopted internationally as a base for the specification of the color of objects when they are viewed outdoors. This standard (Illuminant C) has been chosen to be the "standard-viewing-white" of the receiver. A slightly different illuminant has been proposed as (Illuminant D) more accurately representative of outdoor illumination and may replace Illuminant C in the near future.

The change in reference white between studio and home will inevitably produce errors in all reproduced colors, but the errors are small and, more important, then to be subjectively self-correcting, so that any given object will tend to produce the same color sensation whether viewed in relation to the studio reference white or the home reference white.

Consequently, a viewer may become familiar with an object such as a sponsor's packaged product and will recognize it on his television screen, under the fluorescent lighting of his supermarket, or under the incandescent lighting of his home and, furthermore, will note little difference in the colorimetric values of the package under the three conditions, even though the absolute colorimetric values would be appreciably different in the three situations.

Primary Colors

Of all the characteristics of the eye, there is perhaps none more fundamental to practical color television than that characteristic which allows us to choose certain colors called primary colors, and from these synthesize almost any other desired color by adding together the proper proportions of the primary colors. If it were note for this characteristic, each hue in a color system would have to be transmitted over a separate channel; such a system would be too awkward to be practical. Because of the eye's acceptance of synthesized colors, it is possible to provide excellent color rendition by transmitting only the three primary colors in their proper proportions.

Possible Errors in Transducers

The block diagram of Fig. 33 shows a fundamental color-television system using red, green, and blue primaries and three independent transmission channels. The camera tubes and kinescopes are shown dotted to indicate that any inherent nonlinearities in these devices are to be disregarded, for the moment, in order to simplify the discussion of the colorimetry of the system.

The general plan is a system such as that of Fig. 33 is to provide the three kinescopes with red, green, and blue phosphors, respectively, and to allow the corresponding camera tubes to view the scene through an appropriate set of red, green, and blue filters. If a phosphor and a filter have the same dominant wavelength, that is, if they appear to the eye to be the same color, it might be mistakenly supposed that they would be colorimetrically suited to be used as a filter and phosphor set for the channel handling that color. Actually, the basis for choosing filters and phosphors is much more complex and is based on the shape of the response curve of the filter, plotted against wavelength, and the shape of the light-output curve of the phosphor, also plotted against wavelength. The following paragraphs will discuss briefly a technique which might be used to determine the required relationship between the phosphor curves and the filter curves.

The color characteristics of the phosphor are generally less easily changed than are filter characteristics; for this reason characteristics of phosphors are taken as the starting point, and characteristics of the filters are determined from them. A laboratory setup which could be used to determine these characteristics is shown in Fig. 38. In this figure, an observer (who must have "normal" vision) is viewing simultaneously two adjacent areas, one of which is illuminated by a source of single-wavelength light which can select any wavelength in the visible spectrum, the other of which is illuminated by a red kinescope, a green kinescope, and a blue kinescope. The

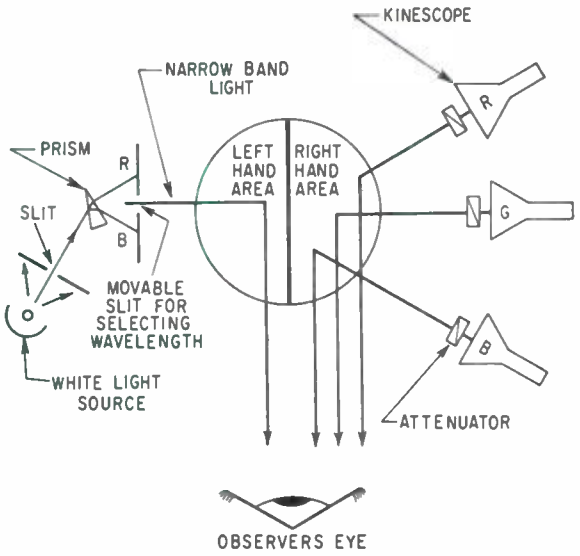


Fig. 38. Diagram showing laboratory setup arranged to compare narrow-band light source and R, G, and B light produced by kinescopes to determine proper camera-filter color characteristics.

phosphors of these kinescopes are the phosphors which are to be used in the color system. Starting at, say, the red end of the spectrum, a single-wavelength red is selected to illuminate the left-hand area, and the light from each of the three phosphors is varied until a color match is obtained between the left-hand and right-hand areas. The respective amounts of red, green, and blue lights needed to accomplish this match are recorded. Then another wavelength is chosen, the kinescope outputs varied to produce a match, and the new amounts of red, green and blue needed for a match are recorded. Similarly, points are obtained throughout the entire spectrum, and a graph is plotted showing the various required outputs versus wavelength. The shapes of these three curves—one for red, one for green, and one for blue—are the required shapes for the three camera-filter response curves. The resulting curves would in general resemble Fig. 38.

(To simplify the above discussion it was assumed that the camera tubes responded equally well to all wavelengths. In practice, camera tubes show higher output at certain wavelengths than at others. The filter-response curves derived by the above technique would have to be modified so that the combined response of filter and camera would be correct.)

Certain practical difficulties could result in errors in the above procedure. For example, if the observer had any deviations from normality in his color-vision characteristics (as most people do), these deviations would result in "nonstandard" matches and, hence, improper camera-filter characteristics. Also, if the phosphors were contaminated in any way during their manufacturing process (as most phosphors are, at least to some small degree), the resulting phosphor characteristics would not be the proper ones and hence would give rise to improper camera-filter characteristics. the observer errors can be normalized out by standard colorimetric procedures, but phosphor errors represent a basic error which may possibly be present not only in the above experiment but also in varying degrees in a large number of receivers. Quality control of phosphor manufacture is sufficiently good, however, to make the net effect unnoticeable in home receivers.

A striking practical difficulty would also arise regardless of observer or phosphor errors. For most wavelengths, no combination of red, green, and blue kinescope outputs could be found which would produce a match. In order to obtain a match at these wavelengths, it would be necessary to move one or two of the kinescopes over to the other side so that they could add their light to the single-wavelength light being matched. This procedure can be described mathematically, for graphing purposes, by saying that adding light to the left-hand area is the same as subtracting light from the right-hand area. Therefore, the amount of light added on the left would be considered as a negative quantity and would result in a point below the axis on the graph. Since this condition would be found to exist for several successive wavelengths, the resulting graph would show one or more minor lobes below the axis. These are called negative lobes.

These negative lobes represent a need for filters with negative light-transmission characteristics at certain wavelengths. Simple attenuating filters cannot yield such a characteristic, much more elaborate means would be required.

It is theoretically possible to achieve these negative lobes with added camera complexity but it has been shown that excellent color fidelity can be obtained by ignoring the negative lobes and

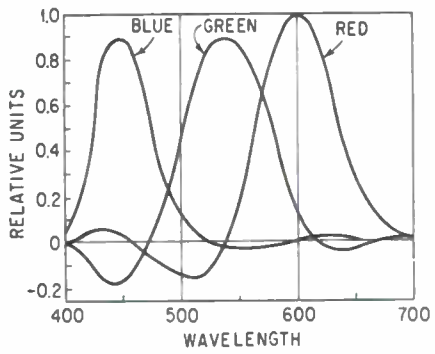


Fig. 39. Curves showing relative quantities in camera output required to produce correct kinescope colors over the visible spectrum.

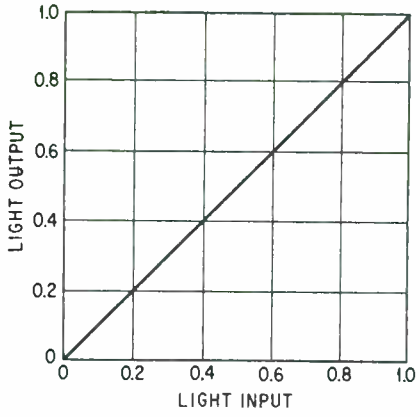


Fig. 40. Curve showing light-transfer characteristics of a perfectly transparent piece of window glass.

using filters which yield the positive lobes only. Positive-lobe processes such as color photography have gained wide acceptance for years. Masking techniques which employ electrical matrixing have been introduced which can modify the spectrum characteristics of a color camera. These techniques can be used to help compensate for deficiencies in the color fidelity such as the lack of negative lobes.

Transfer Characteristics

A piece of window glass is perhaps the nearest approach to a perfect video system. For a piece of glass, the light output (to the viewer) is essentially identical with the light output (from the scene). This fact is shown graphically in Fig. 40. This plot could be called the "transfer characteristic" of a piece of glass, since it describes the way that light is transferred through the system.

If the window glass is replaced by a neutral-density filter which attenuates light 3 to 1, the transfer characteristic will then be given by Fig. 40. The difference between Fig. 40 and 41 can be described by these simple relationships:

For the glass:

$$\text{Light output} = \text{light input}$$

For the neutral-density filter:

$$\text{Light output} = k \times \text{light input}$$

Where:

$k = \frac{1}{3}$ in this case.

Both systems are linear; that is, doubling the light input of either will double its light output; tripling input will triple output; etc. A nonlinear system does not exhibit this simple proportionality. For example, consider a system described by

$$\text{Light output} = k \times (\text{light input})^2$$

Doubling the input to this system will quadruple its output; a threefold increase in input will

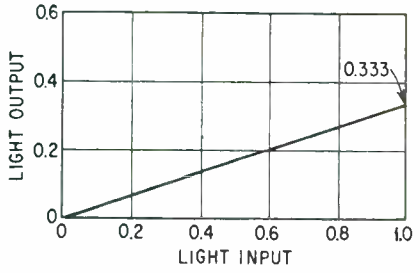


Fig. 41. Curve showing transfer characteristic of a neutral density filter with 3-to-1 light attenuation.

result in a ninefold increase in output; etc. The transfer characteristic for this type of system is shown in Fig. 42. Note that the characteristic is definitely nonlinear; that is, it is not a straight line as were Fig. 30 and 40.

In television and photography, nonlinearity is more common than linearity. For example, an ordinary kinescope is a nonlinear device, having a transfer characteristic which can be approximated by the expression

$$\text{Light output} = k\ (\text{voltage input})^{2.2}$$

Camera tubes can be linear or nonlinear devices. For example, the characteristic of a vidicon is approximately

$$\text{Current input} = k\ (\text{light input})^{0.65}$$

The general expression for nonlinear transfer characteristic can be given approximately as

$$\text{Output} = k(\text{input})^{\gamma}$$

where the exponent is the Greek letter gamma.

Graphical Displays of Transfer Characteristics

Linear Plots

The first reaction of any person asked to display two variables (like light input and light output) on a set of XY coordinates is to divide

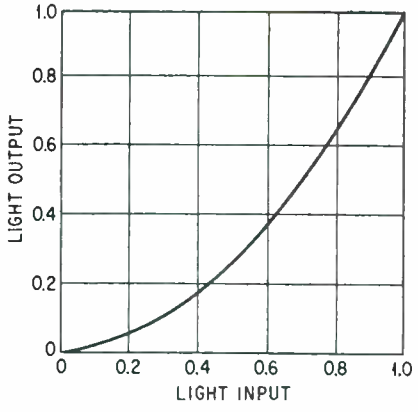


Fig. 42. Curve showing a nonlinear transfer characteristic.

X and Y coordinates into equal increments and plot the variables in this manner. A typical result of such a plot has already been described (Figs. 40 and 41). Such a plot has the advantage of showing at a glance the linearity of the device described by the variables. If the plot is a straight line, we say the device is linear; if curved, we say the device is nonlinear. Moreover, the slope of the line describes the attenuation (or gain) of the device. If the slope is unity (which occurs when the plot makes a 45° angle with the X axis), there is no attenuation; we are dealing with a very good piece of glass. For the neutral-density filter described above, which has the equation (light output) = ⅓ (light input), the line has a slope of one-third (see Fig. 41).

Such are the advantages of plotting transfer characteristics with equal-increment divisions of the X and Y axis. However, other advantages—very important ones—can be obtained by dividing up the X and Y coordinates logarithmically. Such a plot is called a log-log plot.

Log-Log Plots

Consider a system which has a transfer characteristic given by $L_0 = (L_{in})^{2.2}$ If this equation is plotted on axes which are divided logarithmically, the resulting plot is the same as though the logarithm of both sides of the equation were plotted on equal-increment axes. Taking the logarithm of both sides, we obtain

$$\log L_0 = \log (L_{in})^{2.2}$$

Since $\log (L_{in})^{2.2}$ is the same as $2.2 \log (L_{in})$, then

$$\log L_0 = 2.2 \log L_{in}$$

Comparing the form of this equation with an earlier equation, light output = ⅓ light input, we can see that just as the attenuation, 1/3, was the slope of the earlier equation, so 2.2, the exponent, is the slope of the latter equation. We see, then that the use of logarithmically divided coordinates yields a plot in which the exponent is given by the slope of the line. Therefore, this plot will show at a glance the magnitude of the exponent and will also show whether or not the exponent of the system is constant for all light levels. It also is advantageous in showing the effects of stray light.

Figs. 43a and 43b compare the two types of plotting for three types of transfer characteristics.

The Effect of a Nonlinear Transfer Characteristic on Color Signals

Effect of Identical Nonlinearities in Each Channel

In monochrome television, some degree of nonlinearity can be tolerated, but such is not the case for a color-television system. It can be shown that a system exponent different from unity must inevitably cause a loss of fidelity. For an example, consider a situation in which signals are being applied through linear amplifiers to the red and green guns of a perfectly linear (theoretical) kinescope. The green amplifier is receiving 1.0 volt; the red amplifier, 0.5 volt. If everything is perfectly linear, the proportions of the light output should be 1.0G + 0.5R = greenish yellow. However, if the kinescope has an exponent of 2.0, the light output will be $(1.0)^2G + (0.5)^2R$ = 1.0G + 0.25R = greenish yellow with an excess of green.

From the above specific case, it may be correctly inferred that in general, a system exponent greater than 1 will cause all hues made of the combination of two or more primaries to shift toward the larger or largest primary of the combination. Conversely, a system exponent less than 1 will shift all hues away from the largest primary of the combination.

In the above example, an exponent of 0.5 would yield $(1.0)^{0.5}G + (0.5)^{0.5}R$ = 1.0G + 0.707R = a greenish yellow which is a shade off a pure yellow.

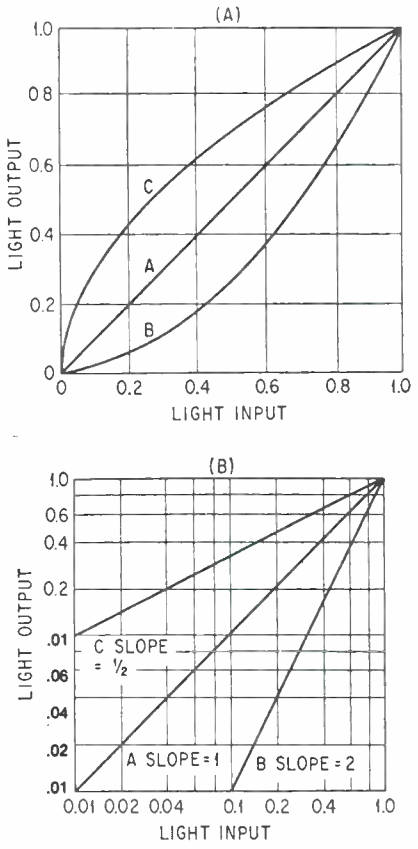


Fig. 43. Graphs showing the curves obtained by plotting A, B, and C types of transfer characteristics on linear coordinated (A) and on log-log coordinates (B).

In addition, the reader can correctly conclude that white or gray areas, in which all the primaries are equal, will not be shifted in hue by a nonunity exponent.

Effect of Differing Exponents in Each Channel

The preceding discussion assumed that all three channels (in Fig. 33) have the same exponent, whether unity or not. In practical systems, however, there is always the possibility that the exponents of the channels may differ from one another. This situation will produce intolerable color errors if the differences become even moderately large. In general, the requirements for "tracking" among the light-transfer characteristics of the individual channels are even more stringent than the requirement for unity exponent.

Figs. 44a, 44b, 44c, and 44d show graphically the effects of unequal exponents in the three channels. In all four figures, the red and blue exponents are taken as unity; in Figs. 44a and 44b the green exponent is taken as less than 1, and in Figs. 44c and 44d, as greater than 1. In Fig. 44a, the transfer characteristics are shown for the system adjusted to produce peak white properly. It can be seen that the bowed characteristic of the green channel will cause all whites of less than peak value to have too much green. A gray-scale step tablet before the camera would be reproduced properly only at peak white; the gray steps would all have a greenish tinge. Relative channel gains could be readjusted to reproduce one of the gray steps properly (Fig. 43b), but then all highlight steps would be purplish while lowlight steps would still be greenish.

A green-channel exponent greater than unity would reverse the above results (Figs. 44c and 44d). With gains adjusted to reproduce peak white properly (Fig. 44c), lowlights would be purplish; with gains readjusted to provide proper reproduction for one of the lower steps (Fig. 44d), highlights would be green and lowlights purple.

The Effect of Stray Light

If a kinescope is viewed in a lighted room, there will always be some illumination on the faceplate. Therefore, the eye will always receive some "light output" from the kinescope, regardless of the magnitude of the signal input voltage. Under this condition, a true black is impossible to obtain.

This condition is reflected in the transfer characteristic of the system. If, for example, the stray light were 5 percent of the peak highlight brightness of the picture, a linear plot of light output versus light input would have the entire transfer characteristic shifted upward by 5 percent. However, the most interesting change is found in the log-log plot, where, as seen in Fig. 45, the stray light causes a change in the slope in the lowlight regions. Since the slope is equal to the exponent, this change shows that stray light causes an effective exponent error in the lowlight regions of the picture and hence will cause color-fidelity errors which will be most marked in lowlight regions.

These errors will be noted by an observer as improper hues and saturations, with the saturation errors—a "washing out" of the more saturated lowlight areas—being the more objectionable to a viewer.

Stray light is not the only cause of errors of this type. Similar effects will be noted whenever the kinescope bias ("brightness") is set too high, if camera pedestal is set too high, or if stray light enters the camera (whether through lens flare or any other source). In general, any condition which prevents the light output of the system from becoming zero when the light input is zero will cause errors similar to those caused by stray light.

Linearizing a System

It can be shown that a system using a vidicon with an exponent of 0.675 to drive a kinescope with an exponent of 2.2 will have an overall exponent given by the product 0.65 x 2.2 = 1.43, assuming that all devices in the system are linear.

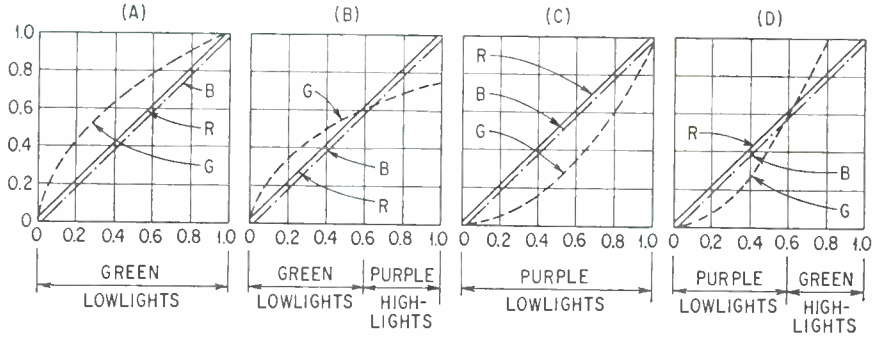


Fig. 44. Linear plots showing graphically the effect of unequal exponents in the R, G, and B channels. In all four graphs the R and B exponents are taken as unity. In (A) and (B) the green exponent is taken as less than 1, and in (C) and (D), as greater than 1.

In general, the overall exponent of a system is the product of the exponents of the cascaded elements.

This knowledge provides an excellent tool for linearizing a system. For example, a system with an overall exponent of 1.43 could be linearized by inserting somewhere (in a video path) an amplifier having an exponent of 1/1.43 (=0.7) so that the product becomes unity:

$$1.43 \times 1/1/43 = 1$$

In Fig. 34, a nonlinear amplifier, or gamma corrector, is shown inserted in each of the three paths.

Possible Encoding and Decoding Distortions

The second of the two systems discussed in the preceding section bordered on being a practical system but still required three independent 4 MHz channels. A fortunate characteristic of the human eye—the inability to see colored fine detail—allows us to modify this requirement to one 4 MHz channel for monochrome fine detail and two much narrower channels for color information. Before this modification can be made, the red, green, and blue signals must be combined to form three other signals, usually called M, I, and Q, such that the M signal alone requires a 4 MHz channel, and the I and Q channels, which contain the color information, are confined to narrower channels. This rearrangement of red, green, and blue to form M, I, and Q is called matrixing and was described in the previous part. A system which uses a matrix is block-diagramed in Fig. 35. The illustration also shows that to recover the original red, green, and blue signals at the receiving end, a "rearranging" device is needed. This device is usually called the receiver matrix.

Matrixing alone offers no advantage unless steps are taken actually to limit the I-signal and Q-signal channels to the narrow bandwidths allowed. Fig. 36 shows a system employing such band shaping. The band-shaping filters themselves always introduce delay, which must be compensated for by placing delay lines in the wider band channels, as shown in the diagram.

To put both color and monochrome information in the spectrum space normally occupied by monochrome only requires that the color information overlap the monochrome. This overlap can be allowed for both I and Q signals, without incurring visible cross talk, if two techniques, known as frequency interlace and two-phase modulation are employed. A system using these techniques, which were described in the section on Electronic Aspects of Compatible Color Television, is block-diagramed in Fig. 37.

Possible Errors in the Matrixing Process

The entire matrixing process can be summed up in two sets of equations, the first set describing how the transmitter matrix takes in red, green, and blue and turns out M, I, and Q:

$$\begin{aligned} M &= 0.30R + 0.59G + 0.11B \\ I &= 0.60R - 0.28G - 0.32B \\ Q &= 0.21R - 0.52G + 0.31B \end{aligned}$$

and the second set describing how the receiver matrix takes in M, I, and Q and recreates red, green, and blue:

$$\begin{aligned} R &= 0.94I + 0.62Q + M \\ G &= 0.27I + 0.65Q + M \\ B &= 1.11I + 1.7Q + M \end{aligned}$$

Both matrices can therefore be considered as analog computers which continuously compute the desired output from the given input. The coefficients in the above six equations are usually determined in the "computers" by precision resistors or, in the case of negative numbers, by precision resistors and signal-inverting amplifiers. The basic error that can occur, therefore, is a change in a resistor value or an amplifier gain, resulting in a change in one or more coefficient. In general, the resulting picture error resembles cross talk among the primary colors.

More specifically, the transmitter matrix can have two distinct types of errors. The first type involves the coefficients of the equation for M; the second type, the coefficients for I and Q. An error in an M coefficient will brighten or darken certain areas. In a monochrome reproduction of a color signal, such an error, if small, would not be noticed; if large, it would still probably be tolerated by the average viewer. In a color reproduction, however, even a small error would be objectionable. For example, a reduction of the red coefficient from 0.3 to 0.2 would cause a

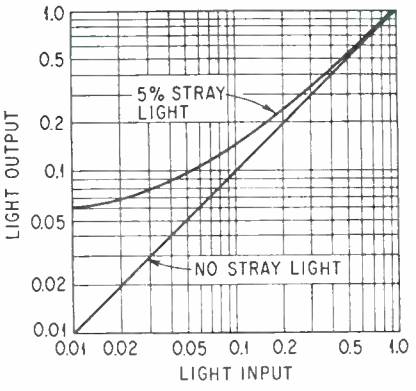


Fig. 45. Log-log plot of system with stray light, illustrating change of slope in the low-light regions.

human face to be reproduced with an unnatural ruddy complexion and dark red lips.

Note that the sum of the M coefficients is 1. An error in one coefficient would change this sum, so that peak white would no longer occur as 1 volt. An operator could mistake this condition for a gain error and adjust either M gain or overall gain in an effort to obtain the correct peak-white voltage. Changing M gain would cause errors to occur in all M coefficients; changing overall gain would put errors in all coefficients. Although such an error is rare in well-engineered equipment, it is a possible source of color error which can be compounded by misdirected attempts at correction.

Note that the sums of the Q and I coefficients are each zero, which means that when R = G = B (the condition for white or gray), Q and I both equal zero. An error in a Q or I coefficient would cause color to appear in white or gray areas and, in addition, would cause general errors in colored areas resembling cross talk among the primaries. Controls are usually provided in the Q and I matrices, called Q white balance and I white balance, respectively, which allow the operator to adjust the sum of the Q or I coefficients by changing the value of one of the coefficients. If the coefficient controlled is the one in error, then adjusting white balance restores the condition that the sum of the coefficients is zero, that is, it removes the color from white and gray objects, but it does so by giving the controlled coefficient an error which just counteracts the error of a nonadjustable coefficient, so that two coefficients are wrong instead of one. Again, such an error is rare in well-engineered equipment, for the adjustable coefficient is usually the one in error. However, the possibility of an error compounded by adjustment should be kept in mind.

A far more likely cause of white-balance error is an error in input level, that is, a discrepancy between the peak white levels of input red, green, or blue. In such a case, an operator can still achieve white balance (Q and I = 0 for white input) but the entire system will be in error. The starting point for all investigations of the cause of white balance errors should be the levels of the red, green, and blue colorplexer inputs.

In the receiver matrix, only one general type of error can occur instead of two as in the case of the transmitter matrix. This type of error, a general coefficient error, results in cross talk among the primary colors. For example, a change in the I coefficient for the red equation from 0.94 to 0.84 would yield about a 7 percent reduction in the peak red output available and would also result in unwanted red light output in green or blue areas at about 3½ percent of the green or blue level.

Gain Stability of M, I, and Q Transmission Path

In the system of Fig. 35, every gain device or attenuating device in the three transmission paths must maintain a constant ratio between its input and output in order to maintain the proper ratios among the levels of M, I, and Q at the input to the receiver matrix. A variation in the gain of one of these paths will result in a loss of color fidelity.

For example, a reduction in M gain must obviously cause a reduction in the viewer's sensation of brightness. Not quite so obvious are the effects of I and Q gain. Since these are color signals, their amplitude would be expected to influence the sensation of saturation, but the manner of this influence is not intuitively obvious until the factors which influenced the selection of I and Q compositions are recalled. It previously was pointed out that the eye has the greatest need for color detail in the color range from orange to blue-green (cyan) and the least in the range from green to purple. Hence I, the wider band signal, conveys mainly orange and cyan information, and Q, the narrower band signal, conveys principally the greens and purples. Therefore, a reduction in I gain could be expected to reduce the saturation sensation for colors in the orange and cyan gamut, leaving the greens and purples virtually unaffected. Conversely, Q gain will influence the greens and purples without causing much change in the appearance of orange and cyan objects.

Modulation and Demodulation

The system of Fig. 35, which introduced bandwidth limiting of the I and Q signals in accordance with the capabilities of the eye to see colored fine detail, is a fairly practical and economical system, except for the fact that three individual transmission channels are employed. If we are to have a compatible system, however, these three channels must be reduced to one through some multiplexing technique. The technique used has already been described, and a system employing this technique is block-diagrammed in Fig. 37.

Possible Errors in Modulation

Burst Phase Error

Perhaps the most fundamental error in the multiplexing process would be an error in the phase of the main timing reference, burst. Since the entire system is based on burst phase, an error in burst phase will appear as an opposite error in every phase except burst, because the circuits will insist that burst phase cannot be wrong. The general result will be an overall hue error in the reproduced picture. This effect can be better visualized by referring to Fig. 46.

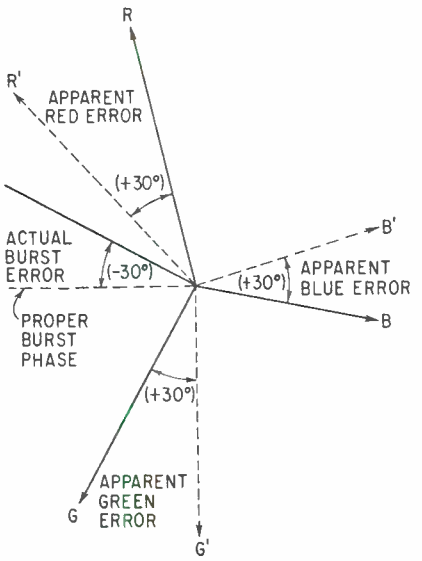


Fig. 46. Vector diagram showing how error in subcarrier phase becomes an opposite error in all other phases.

A phase error in burst produces the same result as holding burst phase stationary and allowing all other phases to slip around the circle an equal amount (but in a direction opposite to the burst-phase error). Each color "vector" then represents a hue other than the one intended.

Burst Amplitude Error

In theory, the receiver circuits which extract timing information from the burst are insensitive to variations in burst amplitude as long as the burst is large enough to maintain a respectable signal-to-noise ratio and not so large that some type of clipping or rectification upsets the burst circuitry. But practical receivers always exhibit some degree of sensitivity depending mainly upon the error in the subcarrier oscillator in the receiver. If the free-running frequency of the receiver oscillator is very different from burst frequency—particularly if the difference is so great that the burst is in danger of losing control of the oscillator—then a fairly appreciable amplitude sensitivity will be noted. This sensitivity will take the form of a phase error, and the net result will be indistinguishable from a burst phase error, as discussed above.

Some receivers have a circuit which automatically adjusts the gain of the color-information channels so that the viewer always sees the proper saturations, regardless of errors which might tend either to "wash out" or to oversaturate the picture. Such a circuit, called an automatic chroma control (ACC), derives its control information from the amplitude of burst, which is presumed to bear a constant ratio to the amplitude of chroma. Transmission distortions, for example, might decrease the amplitude of both burst and chroma, but since the ratios of their amplitudes would be preserved, an ACC receiver could automatically modify its chroma-channel gain to compensate for the decreased chroma amplitude. However, if a color encoder error should cause burst alone to decrease in amplitude, the ACC circuits would increase chroma gain just as in the above case, with the result that a viewer would receive an oversaturated picture.

Two-Phase Modulation Errors

The fidelity of color reproduction can be seriously affected if the phase separation of the Q and I subcarriers is not maintained at 90°. It can be shown that a "slip" in the angular position of the Q axis, for example, will result in cross talk of Q and I. The final result will be the same as cross talk among the primary colors.

Likewise, in a receiver, the phase relationship between the reference subcarriers must be maintained to avoid a similar error. Any deviation from the proper phase relationship will have a result similar to the above, that is, cross talk of I into Q or Q into I, with the net picture result resembling cross talk among all the primary colors.

Carrier Unbalance

In a properly operating doubly balanced modulator, the carrier component of the signal is suppressed in the modulator circuit. If some error in components or operation causes this suppression to be imperfect, the carrier will appear in the output. This condition is known as carrier unbalance.

The effect of carrier unbalance can be evaluated by considering the unwanted carrier as a vector of constant amplitude which adds itself vectorially to every vector present in the colorplexer output. In general, such a vector will shift all vectors and hence all hues seen in the picture toward one end of the other of the color axis represented by the unbalanced modulator. For example, a positive unbalance in the I modulator would shift all colors toward the color represented by the positive I axis, that is, toward orange. A negative I unbalance would shift all colors toward cyan.

To visualize this effect, refer to Fig. 47, in which has been added to each color vector a small positive vector which is parallel to the I axis. This small vector represents the amount of carrier unbalance. The resultant vectors will all be rotated toward the positive I axis and changed in amplitude as well. Such changes represent errors in both hue and saturation.

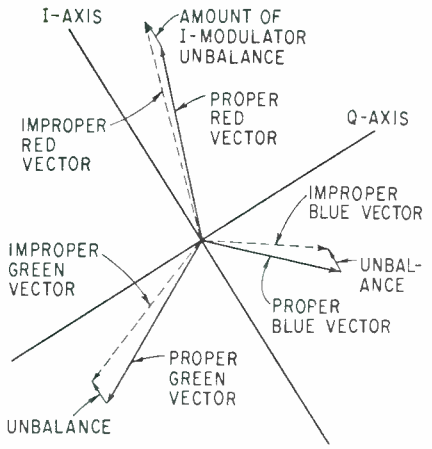


Fig. 47. Vector diagram of subcarrier phase and amplitude with positive vectors added to represent carrier unbalance in the I modulator.

Another error from carrier unbalance occurs in white and gray areas of the picture. In a normally operating colorplexer, a white (or gray) area in the scene causes the Q and I signals to become zero and thereby causes the modulator outputs to become zero. Hence, a white or gray area will normally appear in the signal as an interval of zero subcarrier amplitude. If one of the modulators begins to produce a carrier-unbalance vector, however, a white or gray area will become colored because of the subcarrier which will be added in this interval. Moreover, certain areas which are normally colored may have their subcarrier canceled by the carrier-unbalance vector and become white. Such white-to-color and color-to-white errors are very objectionable.

Video Unbalance

A doubly balanced modulator derives its name from the fact that it balances out or suppresses both the carrier (as described above) and the modulating video (Q or I). If, for any reason, the video suppression becomes less than perfect, the resulting condition is called video unbalance.

Video unbalance will cause unwanted Q or I video to appear in the modulator output, in addition to the desired sideband outputs. This unwanted video signal will be added to the luminance signal, thereby distorting the gray scale of the picture. For example, a slight positive unbalance in the Q modulator would slightly brighten reds and blues and slightly darken greens. A negative unbalance would have the opposite effect.

Subcarrier-Frequency Error

The color subcarrier frequency is specified by the Federal Communications Commission to be 3.579545 MHz $\pm$10 Hz. Deviations within this specified limit are of no consequence (provided they are slow deviations). Large deviations, however, can affect color fidelity. The effect does not usually become serious within the possible frequency range of a good crystal-controlled subcarrier source driving a properly designed receiver.

In receivers, the subcarrier timing information is extracted from the burst on the back porch and used to control the frequency of a subcarrier-frequency oscillator in the receiver. As long as the unlocked frequencies of the burst and the receiver oscillator remain the same, the locked phase relationship between the two will remain the same. But if either the burst frequency or the receiver-oscillator frequency becomes different (and the difference between them is not so large that lockup is impossible), then the locked error, which obviously cannot be a frequency error, manifests itself as a phase error. This error can become as large as $\pm 90°$ before the AFC circuit can no longer hold the receiver oscillator on frequency. The frequency range over which this phase shift occurs depends upon the receiver design.

Possible Distortions in the Transmission System

Preceding sections have described the processes involved in the generation and display of a color-television signal. Errors in these processes are not the only possible source of distortion; when the signal is transmitted over great distances, the transmission system itself may contribute errors. This section discusses parameters which specify the behavior of a transmission system and describes the effects that errors in these parameters can have on the reproduced picture.

This section is divided into two parts. The first relates to the parameters of a perfectly linear transmission system, while the second part discusses the additional parameters required to describe the nonlinearities that are inevitable in any practical system.

The Perfectly Linear Transmission System

A perfectly linear and noise-free transmission system can be described by its gain and phase characteristics plotted against frequency as the independent variable.[2] Typical plots are shown in Figs. 48 and 49, respectively. These two characteristics known, it is possible to predict accurately what effect the transmission system will have on a given signal.

Gain Characteristic

Fig. 48 is usually known as the frequency response or gain characteristic or the system.

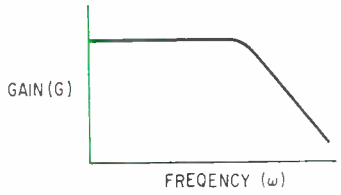


Fig. 48. Typical curve showing gain of a system plotted against frequency to determine its gain characteristic.

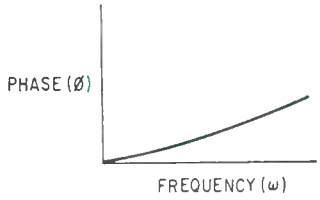


Fig. 49. Curve showing phase characteristic of a system plotted versus frequency.

Ideally, it should be perfectly flat from zero to infinite frequency, but this, of course, is impossible to attain. An amplifier has a definite gain-bandwidth product, depending upon the transconductance of its active elements (tubes or transistors), the distributed capacity shunting these elements, and the types of compensation (peaking) employed. The bandwidth of a given combination of tubes, transistors, stray capacitances, and peaking networks can be increased only by decreasing its gain, or conversely, its gain can be increased only by decreasing its bandwidth. There is a limitation, therefore, to the actual bandwidth that can be obtained. For a given scanning standard, the bandwidth required in a monochrome-television system is determined by the desired ratio between the horizontal resolution and the vertical resolution. Although nominally a 4.0 MHz bandwidth is required for the monochrome standards, the requirement can be relaxed to the detriment of only the horizontal resolution. The subjective result is a "softening" of the picture in proportion to the narrowing of the bandwidth (neglecting the influence of the phase characteristic in the vicinity of the cutoff frequency). As pointed out in preceding sections, the entire chrominance information of the color system is located in the upper 1.5 MHz of the prescribed 4.0 MHz channel; hence, any loss of response in this part of the spectrum can have a marked effect on the color fidelity of the reproduced picture.

One of the most serious forms of distortion inflicted on a color picture by bandwidth limiting is loss of *saturation*. Consider a case in which the bandwidth is so narrow as to result in no gain at the color subcarrier frequency. The output signal then contains no color subcarrier and hence reaches the color receiver as a monochrome signal, producing zero saturation. Nearly as poor results can be expected from an amplifier with response such that the gain at 3.58 MHz is one-half the low-frequency gain. Since the saturation depends chiefly on the amplitude of the subcarrier, the saturation will be correspondingly reduced. The resultant color picture will have a "washed out" look.

Loss of high-frequency response, which can be expected to contribute to loss of fidelity, is usually accompanied by phase disturbance, depending on the type of networks employed in the system. The intent in this section, however, is to treat each variable separately. Therefore, discussions are based on the effects of varying only one parameter of a system. It is suggested that the reader can determine the combined effect of two or more variables by comparing the results shown for the individual variables.

Phase Characteristic

An ideal system has a *linear* phase characteristic, as in Fig. 50a. Such a characteristic implies that all frequencies of a signal have exactly the same *time* delay in passing through this system, since the time delay is given by the phase angel divided by the (radian) frequency. It can be seen in Fig. 50 that if three frequencies are chosen arbitrarily, then the corresponding phase angles must have values proportional to their corresponding frequencies (because of the geometric properties of a right triangle). To state it another way, if $\phi_1/\omega_1 = 0.2$ μsec, then ϕ_2/ω_2 0.2 μsec and 2 also equals ϕ_3/ω_3, too, is 0.2 μsec. Plotting these three values and drawing a straight line through them as in Fig. 50a will show that the time delay for all frequencies is 0.2 μsec.

A signal is not distorted by delay as long as all parts of it are delayed by the same amount. However, when the phase characteristic is nonlinear (as in Fig. 51a), the time delays for all parts of the signal are no longer equal (see Fig. 51b). For example, if a complex waveform is made up of a 1 MHz sine wave and its third harmonic, these two components will suffer unequal delays in passing through a system having the characteristics of Fig. 50. The resultant distortion can be seen by comparing Fig. 52a, 52b, and 52c.

Such distortion is detrimental to both the luminance and chrominance of a composite signal. The luminance signal will have its edges and other important details *scattered*, or *dispersed*, in the final image. Such a transmission system is said to introduce *dispersion*. (Conversely, if a system does not scatter the edges and other

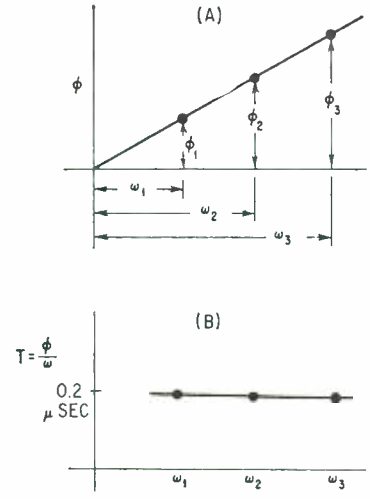


Fig. 50. Curves illustrating a system with linear phase characteristics, which will give the same time delay for signals of all frequencies.

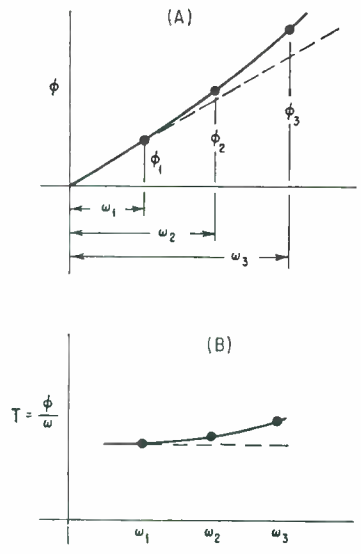


Fig. 51. Curves showing the effect of nonlinear phase characteristic on time-delay characteristic.

high-frequency information, it is said to be dispersionless.) The effect of phase distortion on the chrominance information is of a rather special nature and can best be explained by introducing the concept of *envelope delay*.

Envelope Delay

In the preceding discussion, the time delays ϕ_1/ω_1, ϕ_2/ω_2, and ϕ_3/ω_3 were always determined by measuring the frequencies and the phases from $\phi = 0$ and $\omega = 0$. It might be said that the delay at zero frequency is commonly taken as the reference point for all other delays. This method is usually adequate for determining the performance of systems that do not carry any signals which have been modulated onto a carrier. But a carrier, with its family of associated sidebands (Fig. 53b), can be thought of as a method of transmitting signals in which the zero-frequency reference is translated to a carrier-frequency reference. This translation can be understood by referring to Fig. 53a and 53b. To calculate the delay of the carrier-born signals *after* they have been demodulated, measurements of ϕ and ω must be referenced, not from zero frequency, but from *carrier* frequency.

In Fig. 54a, an impossible phase characteristic has been drawn to aid in further discussion of this subject. Such a characteristic, consisting of two perfectly straight lines, is never met in practice but makes a very simple system for developing the subject of envelope delay.

First, pass two frequencies ω_1 and ω_2 through this system. Let ω_1 be a carrier and ω_2 a sideband which might be, for example, 1,000 Hz higher. If ω_1 and ω_2 fall on the characteristic as

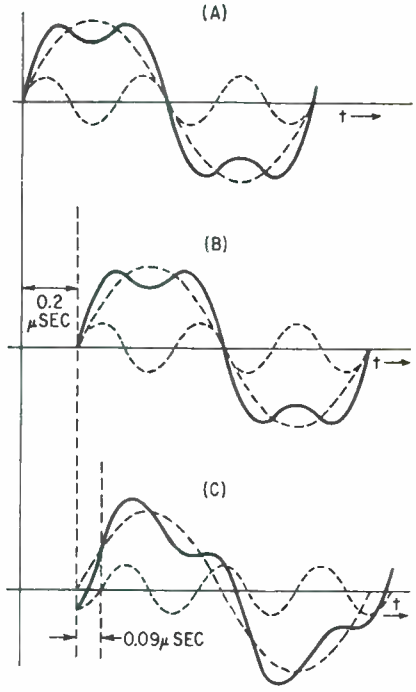


Fig. 52. Curves showing that a complex wave (A) is not distorted by time delay (B) when both components shown dotted) are delayed by the same amount. Unequal delays (C), however, cause distortion.

shown in Fig. 54a, the delay which the 1,000 Hz will show after demodulation can be found putting new reference axes (shown dotted) with ω_1, the carrier, at zero on these new axes. Now, when ω_s and ϕ_s are measured as shown, the time delay after demodulation is ϕ_s/ω_s. In this case, the

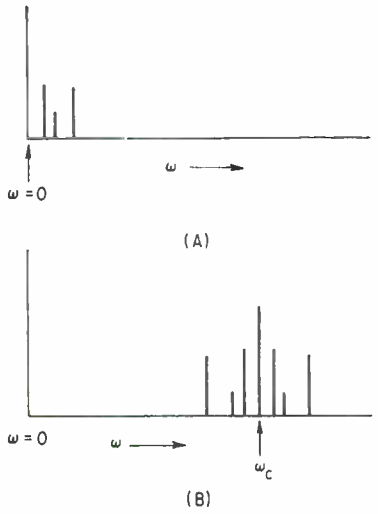


Fig. 53. Sketch showing how a group of frequencies near $\omega = 0$ [sec. (A)] can be translated by modulation onto a carrier to a group of sidebands near $\omega_c - \alpha$ carrier frequency (B).

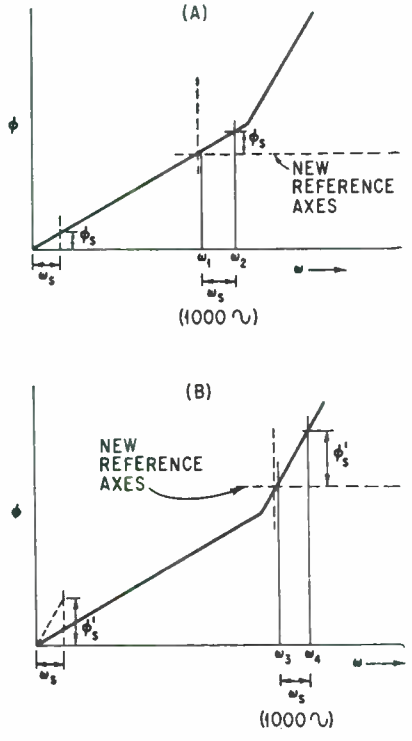


Fig. 54. Idealized straight-line phase characteristics showing how a carrierborne 1,000 Hz signal can be delayed excessively when the carrier and sideband fall on a steeper portion of the phase characteristic.

delay of the 1,000 Hz after demodulation is the same as it would have been had it been passed through the system directly.

Second, pass two other frequencies ω_3 and ω_4 through this system as redrawn in Fig. 54b. This time drawing in the new axes at ω_3, it can be seen that although ω_s is still 1,000 Hz, ϕ_s is larger than ϕ_s. Therefore, it can be concluded that the time delay ϕ_s/ω_s for this second case is greater than for the first case. The 1,000 Hz, when demodulated, will show a considerable error in timing.

Stressing the phrase "delay in a demodulated wave" should not be taken to mean that the demodulation process produces this delay or even make it apparent where it was previously not detectable. Any delay that a demodulated wave shows was also present when the wave existed as a carrier having an envelope. In short, the delay of the demodulated wave appears first as a delay of the envelope, hence the phrase "envelope delay."

Envelope delay does not constitute a distortion. If a system such as the one shown in Fig. 54a introduces a delay of 0.2 μsec to the 1,000 Hz wave (measured after demodulation), then the *envelope delay* of the system is 0.2 μsec. However, it was shown that a 1,000 Hz signal passed directly through the system (without first being modulated into a carrier) would also suffer a delay of 0.2 μsec. As long as the envelope delay ϕ_s/ω_s is the same as the time delay ϕ_1/ω_1, the envelope delay introduces no timing errors. But in the second system (Fig. 54b) the demodulated 1,000-Hz wave suffered a *larger* delay, say 0.29 μsec. A 1,000-Hz signal passed directly through this system, however, would still be delayed only 0.2 μsec. Therefore, the second system has an *envelope delay* of 0.29 μsec and an *envelope delay distortion* of 0.09 μsec.

It is probably wise to point out that the time delay ϕ_3/ω_3 in Fig. 54b is considerably less than the 0.29 μsec estimated for the value of envelope delay. Although ϕ_3/ω_3 would be greater than 0.2 μsec (say, for example, that ϕ_3/ω_3 is 0.22 μsec), the value would be optimistic about the amount of timing error that would be shown by the demodulated 1,000 Hz signal. The need for a knowledge of the envelope delay ϕ_s/ω_s of the system is therefore obvious.

Effect of Envelope-Delay Distortion on a Color Picture

A transmission system which exhibits envelope-delay distortion will destroy the time coincidence between the chrominance and luminance portions of the signal. This will result in misregistration between the color and luminance components of the reproduced picture. The following paragraph

explains briefly how envelope-delay distortion causes this error.

Any colored area in a reproduced picture is derived from two signals, a chrominance signal and a luminance signal. Since these two signals describe the same area in the scene, they begin and end at the same time. The chrominance signal arrives at the receiver as a modulated subcarrier; the luminance signal does not. Therefore, as shown above, the delay of the chrominance signal is determined principally by the envelope delay of the system and the delay of the luminance signal is determined principally by the ordinary time delay ϕ/ω. If the two delays are not identical (that is, if there is envelope-delay *distortion*), then the chrominance signal does not coincide with the luminance signal and the resultant picture suffers *color-luminance misregistration* in a horizontal direction.

For example, in a system having the characteristic of Fig. 54b, the luminance signal is delayed by 0.2 μsec but the chrominance signal is delayed by 0.29 μsec. The error in registration then amounts to 0.09 μsec, or about 0.2 percent of the horizontal dimension of the picture, which is about 0.3 in. on a 21-in.(diagonal) picture.

Although the subject of compatibility is outside the scope of this part, it is worth noting in passing that envelope-delay distortion adversely affects compatibility, since it causes wideband monochrome receivers to display a misregistered dot-crawl image in addition to the proper luminance image.

General Method for Envelope Delay

The specific cases described above (Figs. 54a and 54b) made use of simple, idealized straight-line approximations to develop the concept of envelope delay. Practical circuits are not so simple. For example, a simple *RC* network has a ϕ versus ω plot as in Fig. 55. Finding the envelope delay of this curved-line plot will clarify what is meant by envelope delay.

Referring back to the plots of Figs. 53a and 53b, it can be seen that the characteristic of the plot that determines the value of envelope delay is its *slope*. The larger envelope delay, which was suffered by the ω_3-ω_4 pair (Fig. 54b), was a result of their lying on the steeper slope. The envelope delay of *any* system is equal to the slope of the phase versus frequency characteristic. If this characteristic is a curved line (as for the *RC* network, Fig. 55), then the slope is different at every frequency.

The slope of a curved line can be found by the methods of the differential calculus or to a good approximation by breaking up the line into a number of straight-line segments, as in Fig. 56. If the slope of each of these straight lines is plotted against its corresponding frequency (that corresponding to the center of the line), the resulting curve will be approximately the envelope-delay characteristic.

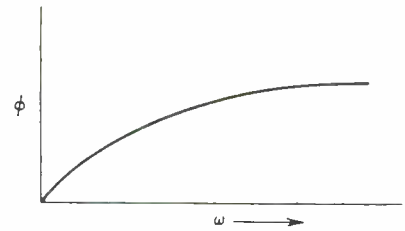


Fig. 55. Phase characteristic of an RC network.

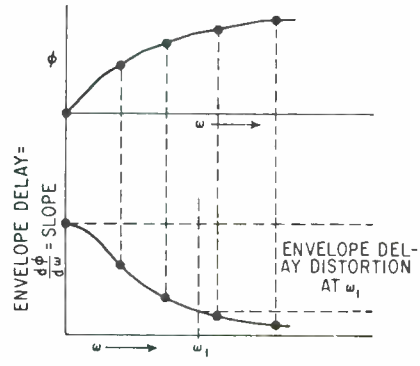


Fig. 56. Graphs showing how a series of straight-line segments can be used to approximate the smooth curve of Fig. 55 (top) and how the slopes of these segments may be plotted to approximate the envelope delay characteristics (bottom).

Nonlinearities of a Practical Transmission System

It is important to emphasize that the effect of nonlinearities in a color television system depends upon whether these nonlinearities precede or follow the matrixing and modulation sections of the system. Nonlinearities in transfer characteristics detract from color fidelity; the same degree of nonlinearity after matrixing and modulation also affects color fidelity although in a different way. The purpose of the following paragraphs is to discuss how a nonlinear transmission system affects a *composite* color signal. It is assumed that all other nonlinearities in the entire system either are negligible or have been canceled by use of nonlinear amplifiers such as gamma correctors.

The major sources of nonlinearity in a transmission system are its amplifying devices.[3] These devices—tubes and transistors—have a limited dynamic range. For example, if too much signal is supplied to them, an *overload* results.

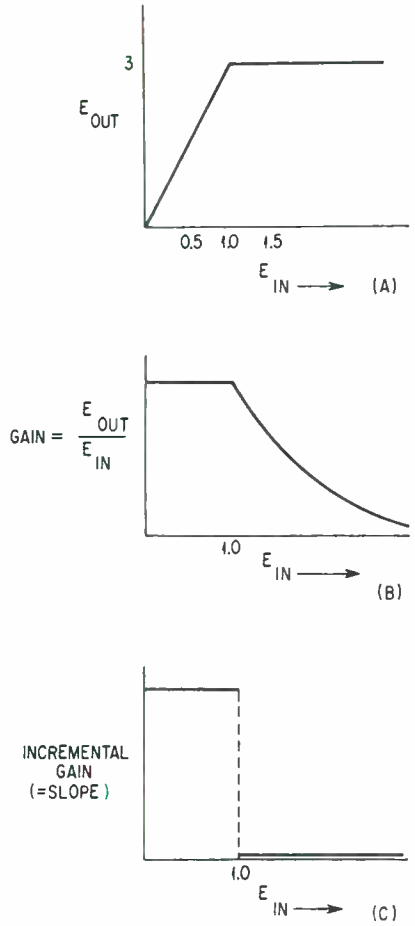


Fig. 57. Idealized straight-line plots showing (A) output voltage of an amplifier versus input voltage (B) gain of the amplifier versus input voltage and (C) incremental gain of the amplifier versus input voltage. Curve (C) is the slope of curve (A).

The transfer characteristic of such a system can be sketched as in Fig. 57a.

Such a nonlinearity is one of three types commonly encountered in video transmission systems. These three types are:

1. Incremental gain distortion
2. Differential gain
3. Differential phase

The paragraphs below will show that Type 2 is merely a special case of Type 1.

Incremental Gain

The concept of the slope of a plot, developed in the discussion of envelope delay, will be useful here as well. Consider a plot as in Fig. 57a which shows output voltage of an amplifier plotted against input voltage. Idealized straight-line plots are shown for simplicity. It can be seen that the amplifier has a maximum output of 3 volts for 1-volt input. Larger input voltages result in no more output; the amplifier *clips* or *compresses* when inputs larger than 1 volt are applied.

The gain of the amplifier is

$$\text{Gain} = \frac{E_0}{E_{in}} = \frac{3 \text{ volts}}{1 \text{ volt}} = 3$$

The gain is obviously constant below the clip point. For example, an input voltage of 0.5 volt gives

$$\text{Gain} = \frac{1.5 \text{ volts}}{0.5 \text{ volt}} = 3$$

But at an input of 1.5 volts, the output is still 3 volts, so the "gain" is only 2. (The word "gain" is of doubtful use here because of the clipping involved.) The gain, defined as E_0/E_{in}, is plotted against E_{in} in Fig. 57b. It can be seen in this figure that the gain is constant only as long as the *slope* of Fig. 57a is constant.

It is useful, then, to establish a new term, called *incremental gain*, which will be defined as the *slope* of a plot such as Fig. 57a. For the particular plot of Fig. 57a, the slope is constant up to $E_{in} = 1$ volt and then suddenly becomes zero. The corresponding plot of slope versus E_{in} is shown in Fig. 57c.

The importance of incremental gain in color television can be assessed by applying the input signal shown in Fig. 57 to the distorting system of Fig. 57a. Before being applied to the distorting system, such a signal could be reproduced on a monochrome receiver as a vertical white bar and on a color receiver as a pastel-colored bar, say, for example, a pale green. After passing through the distorting system, the signal would still be reproduced as a white bar on the monochrome receiver with the only apparent error being a luminance distortion, that is, a slight reduction in brightness, which, for the magnitudes shown here, would probably pass unnoticed. The color receiver, however, would receive a signal completely devoid of any color information and would reproduce a white bar in place of the former pale-green one.

The less extreme case is shown in Fig. 59. For the system represented by this characteristic, the slope (incremental gain) does not become zero for inputs above 1 volt but instead falls to one-half its below-1-volt value. The color signal of Fig. 59 would not lose all color in passing through this system, but the amplitude of the subcarrier would become only one-half of its proper value. Since saturation is a function of subcarrier amplitude, the pale green of the undistorted reproduction would, in this case, become a *paler*

green. The luminance distortion would also be less than in the extreme (clipping) case.

It can be seen, then, that unless the incremental gain of a system is constant, that system will introduce compression which will distort the saturation and brightness of reproduced colors. Usually, the error is in the direction of *decreased* luminance and saturation. For certain systems, however, exceptions can be found. For example, the effect that the system represented by Fig. 59 will have on a signal depends on the polarity of the signal. For the signal as shown, the usual *decrease* in luminance and saturation is exhibited. For an inverted signal, however, the subcarrier amplitude would not be reduced, but the luminance signal would still be diminished. The subjective result of this distortion would be an *increase* in saturation. The unusual behavior of this particular system is attributable to its peculiar transfer characteristic, which was drawn with curvature at one end only to simplify the discussion. Most practical system-transfer characteristics exhibit curvature at both ends and therefore have an effect on the signal which is essentially independent of polarity.

Incremental gain can be measured in two ways, the first of which stems from its contribution to luminance distortion and the second, from its contribution to chrominance distortion.

In the first method, an equal-step staircase waveform such as shown in Fig. 60a is applied to the system to simulate a signal having equal luminance increments. If the system has constant incremental gain, the output will, of course, also have equal-step increments. But if the system does not have constant incremental gain, certain steps will be compressed, as in Fig. 60b. If the compression is as in the figure, the *incremental gain distortion* (IGD) is indicated by the distorted amplitude of the last step. Numerically, it can be stated as a percentage:

$$\text{IGD} = 1 - \frac{S_{\text{distorted}}}{S_{\text{undistorted}}} \times 100\%$$

where S is a step amplitude.

For example, if an undistorted step is 0.1 volt and the distorted one is 0.075 volt, then the incremental gain distortion would be 25 percent.

Using the other (chrominance distortion) technique, an input signal consisting of the step wave plus a small, high-frequency sine wave, as shown in Fig. 60c, is applied to the system. After the signal has passed through the system, it is fed through a high-pass filter which removes the low-frequency staircase. The incremental gain distortion then is indicated by the differences in the amplitude of the high-frequency sine waves (see Fig. 60d). In this case, the high-frequency sine

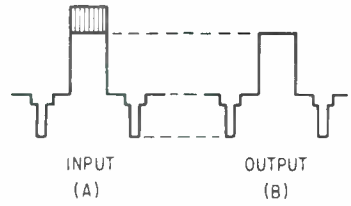


Fig. 58. Extreme case of distortion resulting from passing signal at left (A) through the amplifier represented by Fig. 57. The output (B) has no color information remaining.

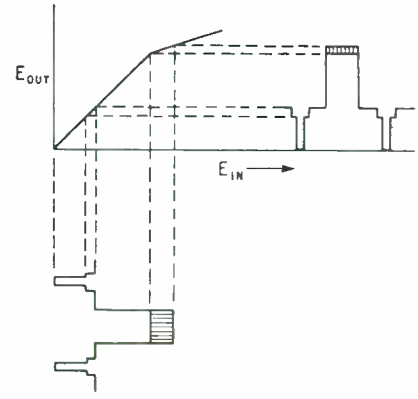


Fig. 59. Diagram showing effect of incremental gain distortion in reducing amplitude of color portion of signal.

wave associated with the top step is shown as having 75 percent of the amplitude of the sine waves associated with the lower steps, which are assumed to be undistorted. Again, the incremental gain distortion is 25 percent.

A most important point must be made regarding the equivalence of these two techniques. Certain systems which show incremental gain distortion when tested by the luminance-step technique may or may not show the same distortion when tested by the high-frequency and high-pass-filter technique. Moreover, a system which shows distortion by the second technique may or may not show distortion by the first. In other words, the incremental gain distortion may be different for different frequencies. Such differences are frequently found in staggered amplifiers, feedback amplifiers, or amplifiers having separate parallel paths for high and low frequencies, such as might be found in stabilizing amplifiers.

A thorough test of a system, therefore, should include test of its incremental gain by both techniques. The staircase-plus-high-frequency waveform can be used to provide *both* tests by observing the system output (for this test waveform input) first through a low-pass filter and then through a high-pass filter. The first test will show

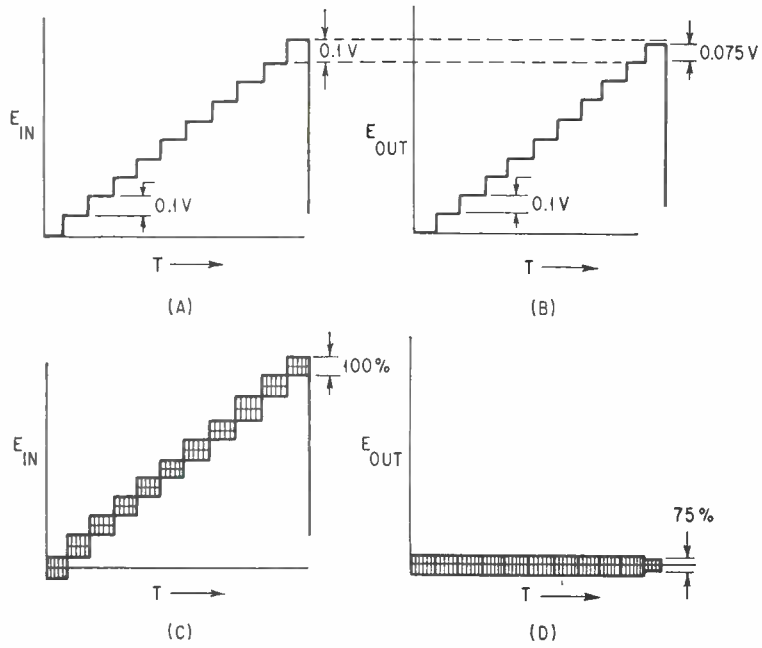


Fig. 60. Diagrams showing two methods of measuring incremental gain distortion, namely, in (A) and (B) by its contribution to luminance distortion and in (C) and (D) chrominance distortion.

low-frequency distortions; the second, high-frequency distortions.

Differential Gain

On the basis of the above discussion of incremental gain distortion, the extremely important concept of *differential gain* can be presented merely as a simple definition. Differential gain is identical with incremental gain distortion when the latter is measured by observing "...the difference in the gain of the system for a small high-frequency sine-wave signal at two stated levels of a low-frequency signal upon which it is superimposed."[4] In other words, differential gain is a special form of incremental gain distortion which describes the IGD of a system for the superimposed high-frequency case only.

One of the reasons for selecting the high-frequency aspect of incremental gain distortion for the IRE definition of differential gain was applied in Fig. 58, when the "...high-frequency sine wave..." of the definition was made equal to color subcarrier. This special case of differential gain explores the system gain linearity in the vicinity of this particularly important frequency. The definition of differential gain was purposely made in the broad terms of a "...high-frequency sine wave..." to allow the greatest possible versatility in devising methods of measurement. In present color-television practice, however, the "...high-frequency sine wave..." is always color subcarrier and the low-frequency signal mentioned in the definition is a 15,750 Hz staircase, sine-wave, or sawtooth. The complete specifications for the signal presently used in this measurement will be found elsewhere in this article.

Another reason for emphasizing high-frequency IGD was implied previously by the sentence "...the signal...would...be reproduced...with the only apparent error being a luminance distortion...which, for the magnitudes shown here, would probably pass unnoticed." The magnitude shown was a 25 percent IGD, which is passing unnoticed, indicating that large incremental gain distortions usually cause no detectable luminance errors. Incremental gain distortion is almost too sensitive a tool to measure luminance distortions. For this purpose, simple gain distortion (compression) is more useful. Therefore, the luminance-distortion aspect of IGD was deliberately omitted from the definition of differential gain.

Incremental Phase and Differential Phase

The phase characteristic sketched in Fig. 49 indicates that the system described by this plot will introduce a certain amount of phase shift for any given frequency. For example, it might be found that a certain system would introduce a phase shift of 60° at 2 MHz. If the system in question were perfectly linear, this 60° phase shift would be produced regardless of how the 2 MHz signal might be applied to the system.

It can be shown, however, that some systems, when presented with a signal of the type shown in Fig. 61, will introduce a delay *different* from 60°, depending on where the zero axis of the sine

wave falls on the transfer characteristic of the system. For the case sketched in the figure, a phase shift of 70° is drawn for the largest zero-axis displacement.

By analogy with the incremental gain and differential gain arguments above, it is possible to define three quantities which pertain to this type of distortion. These quantities are *incremental phase, incremental phase distortion, and differential phase.* It can also be shown that of the three, differential phase is the most important quantity.

Incremental phase is the least exact analog, since it is not very similar in form to incremental gain. Incremental *gain* is a *slope*; incremental phase is simply the absolute value of phase shift. In the above system, the incremental phase was 60° or 70° (or somewhere in between), depending upon the location of the zero axis.

Incremental phase distortion, like its analog *incremental gain distortion*, depends upon the magnitude of the error. It should be zero for a perfect system. In the system of Fig. 61 the 2 MHz signal with 70° incremental phase would be said to have 10° incremental phase distortion, so it is clear that the difference between two phases (one of which is assumed to be "correct") gives the incremental phase distortion.

As previously stated, *differential gain* is identical with *incremental gain distortion* for the superimposed-high-frequency case only. Similarly, *differential phase* is identical with *incremental phase distortion*, but there is no need to limit the definition to the superimposed-high-frequency case, since there is no other case which is meaningful for phase distortion. Without the superimposed sine wave, no phase measurement is possible. Therefore, differential phase is identical with incremental phase distortion. In practical work, the first two terms are seldom used, for the last, differential phase, has been found completely adequate to describe this aspect of a system.

In summary, the differential phase of a system is "the difference in phase shift through the system for a small high-frequency sine-wave signal at two stated levels of a low-frequency signal on which it is superimposed.[5]

It is important that the phrases "differential phase *distortion*" and "differential gain *distortion*" be avoided because differential phase *is* distortion as is differential gain, since they are defined as being identical with incremental phase distortion and incremental gain distortion, respectively. To add the word *distortion* to either is redundant. A sample of proper usage is "this amplifier has a differential gain of 1.5 percent and a differential phase of 0.5°".

Effect of Differential Phase on a Color Picture

The phase of a subcarrier in a composite signal carries information about the *hue* of the signal

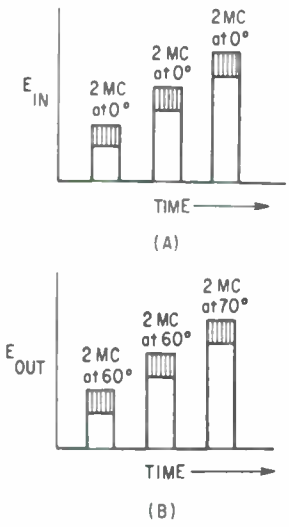


Fig. 61. Graphs illustrating how a signal (A) may undergo different phase shifts (B) depending upon where the zero axis at the sine wave falls on the system transfer characteristic. This distortion is called differential phase.

at that instant. If the signal passes through a system which introduces differential phase, the subcarrier phase (and hence, the hue) at the output will become dependent upon the amplitude of the luminance associated with the hue, since it is the luminance signal which determines the location of the zero axis of the subcarrier. For example, a system introducing 10° of differential phase might be adjusted to reproduce properly a low-luminance hue such as saturated blue or a high-luminance hue such as saturated yellow, but *not both.* One or the other would have to be in error.

State of the Art

The preceding portions of this part have discussed in general terms the possible sources of color errors in a color television system. In no practical system can any of these errors be reduced to zero; therefore, anyone working with practical systems should know how nearly perfect any given parameter should be to be considered acceptable according to the present state of the art.

System Colorimetry

Talking qualitatively about colorimetric accuracy is one thing; assigning numbers and magnitudes is quite another. For the practical purposes of this part, however, we are spared the need to digging deeply into the quantitative aspects of colorimetry by one simple fact: At the present time, color errors attributable to phosphor errors, filter errors, and other basic colorimetric

errors are generally small in comparison with other sources of error.

System Exponent

At the present state of the art, adjusting a system to precompensate for a kinescope exponent of 2.2 is not enforced by the Federal Communications Commission, since this parameter is not yet well established. Adjusting the system to precompensate for this median value, however, can be done with precision. A gamma corrector which uses four or five diodes to make a series of straight-line approximations to a 0.7 exponent can be made so as to have a maximum error of less than 2 percent of the peak signal amplitude. The exponents of the three channels can be made to match within 1 percent of the peak signal amplitude.

Matrix Coefficients

A high-quality matrix, such as would be found in a well-engineered color encoder or studio monitor, uses 0.5 percent precision resistors for all resistances which will influence the values of the coefficients, while inverters and amplifiers are either stabilized by feedback or made adjustable. Errors of greater than 1 percent are rare in such circuits.

While balance in the transmitter matrix, which is a special case of the subject of matrix coefficients, can usually be adjusted and held to a tolerance of the order of 0.5 percent of peak white.

Phase Accuracies

Adjustment of Q subcarrier, I subcarrier, and burst to within 1° of their proper relative phases is easily accomplished using standard commercial equipment and techniques. This accuracy is ten times that required by the Federal Communications Commission.

Subcarrier-Frequency Accuracy

Subcarrier frequency can be easily adjusted to within ±1 Hz the real limit on the accuracy of the adjustment being in the inherent accuracy of the standard used for frequency comparison. Long-term stability of well-engineered equipment should be easily within the required limits of ±10 Hz.

Transmission Characteristics

A single amplifier should have a gain characteristic with less than ±½ dB variation out to 8 MHz. Its envelope-delay error should be of the order of 0.001 μsec at 3.58 MHz, relative to 200 kHz. Differential gain of 0.5 percent and differential phase of 0.25° represent good performance.

Tolerable Color Errors

Sensitivity of the eye to color errors depends upon the manner in which two colors—the original and the reproduction—are compared. For example, if the two colors are placed side by side, the eye becomes a very sensitive indicator of color errors. However, if the comparison is made only by recollection or long term color memory, the eye is far more lenient in its requirements of perfect reproduction. Furthermore, if the reproduced color is one that the eye has not viewed before, the eye requires only that the color relayed to the brain be plausible, that is, that it be a reasonable color for the object.

Fortunately, side-by-side comparison of colors seldom, if ever, occurs in home viewing of color television. However, the system is frequently called upon to reproduce objects whose colors may be well known to the viewer, such as flesh tones or a sponsor's packaged product. Reproductions of these objects must be accurate enough to satisfy the viewer's recollection or color memory. If the system can satisfy the color memory of the viewer, the color-plausibility requirement will be easily met.

Investigations made to determine the sensitivity of the eye to color errors introduced by a deliberate shift of burst phase show that a shift of 10° or more produces perceptible change of hue. With color bar signals a burst phase shift of 3° can just be detected as a hue shift. With typical scenes a phase shift of 5° can be tolerated.

Tests have shown that the eye is much more tolerant of amplitude shifts in R, G, B components, which correspond to changes in color saturation, than it is of phase shifts or changes in hue.

One must distinguish between long-term adaptive errors in viewing of a color television picture and short-term differential color errors. In the first case the eye is quite tolerant of changes or shifts in color balance providing that no direct side-by-side comparisons are involved. Thus a viewer is reasonably well satisfied with color pictures in which white is reproduced within the range of 3200°K to 9500°K. As soon as he views two color TV pictures side-by-side at two different white balance conditions, there will be a much more critical reaction to color fidelity.

For this reason, it is important that color monitors in a broadcasting control room be adjusted to have the same effective white balance, the same color phasing, and the same peak brightness. Since such monitors are usually arranged in a row adjacent to each, great care must be taken so that when the same picture signal is applied to all monitors, there is negligible difference in the color picture displays. Only then can the color monitors be useful in matching and com-

paring color balance of the various camera signal sources.

It is unusual to have more than one color receiver at a home viewing location at a given time. There the absolute color balance problem has little direct impact.

Control of short-term differential color errors is vitally important to the broadcaster. In any broadcast sequence, a given scene is generally viewed from different angles with several color cameras, at various magnifications, and the available video signals are selected from camera to camera to obtain program continuity. The eye views these color scenes in quick succession and is very critical of even small color differences, particularly with regard to skin tone rendition. Variations of the R, G, B or primary color components of 2 percent can be detected. Although the eye can easily adapt to any of the pictures in a few seconds, the viewer will find the abrupt color shifts very disturbing with switching transitions. Thus great care is taken with colorimetric tolerances in color cameras and with color-balancing procedures to provide color matching among cameras which will be precise.

A similar situation exists in the reproduction of color motion pictures. A feature movie having adequate color quality is usually shown in a sequence lasting 15 minutes or more, with the eye having adequate time to adapt to any discrepancies in color balance and skin tones. Commercials spliced into this feature program produce an instantaneous switch to a new and different skin tone balance without time for eye-adaptation. This transition to commercials and back to the feature can exhibit color mismatch to varying degrees, depending on the colorimetric control which has been exercised.

In fact, if the feature film is somewhat misbalanced, and intentionally "corrected" by appropriate use of R, G, B gains or "paint-pot" controls, the transition to the commercial will be more objectionable since the "correction" can then increase the misbalance, even for a "perfectly-balanced" commercial. Effort is going on in the industry to tighten up tolerances on skin tone rendition so that adequate performance can be obtained by purely routine operating methods.

Conclusion

This discussion of color errors indicates *possible* degradations in color fidelity and their probable sources. However, in a properly adjusted color TV system the picture quality is excellent. The various techniques now in development to improve picture quality within the framework of the NTSC system have assured a bright future for color TV.

THE COLOR ENCODER

The color encoder in the color television system performs the required encoding of the R, G, B signals from three-tube cameras or the R, G, B and Y (luminance) signals from four-tube cameras into a single color video signal conforming to FCC specifications. It is the heart of the modern color television system and represents a most ingenious application of many elements of communication circuit theory.

Fig. 62 shows a block schematic of a basic color television system indicating the functions and major components of the color encoder.

A more detailed block diagram of the color encoder showing the matrixing, bandwidth-limiting and quadrature modulation functions is shown in Figs. 36 and 37.

Basic Functions

The principal operations and functions performed by the color encoder are:

1. Matrixing of R, G, B video signals to produced luminance and chrominance signals.
2. Filtering of the chrominance signals to obtain the required bandwidth.
3. Delay compensation to correct for band-limiting time-delay.
4. Modulation of 3.58 MHz carriers by chrominance signals.
5. Insertion of color sync burst.
6. Addition of luminance and chrominance signal to form a complete color signal.
7. Optional addition of sync.

Design and system philosophy determines whether a color encoder is a separate unit or an integral portion of a modular assembly. Present solid state equipment design tends toward the modular concept since it is generally easier to maintain, repair, up-date and revise specific modular units or board assemblies without affecting the overall installation.

The electrical color bar generator which is generally provided for systems test and color encoder alignment is available either as a separately contained unit or as a module in a complete operating assembly.

Color encoders of modern solid state design are inherently stable and require only routine verification or adjustment. Set-up of a color encoder involves the use of color-bars which are electrically generated waveforms of high precision. A color bar generator is capable of producing on a color monitor all of the signal bars illustrated in Fig. 63.

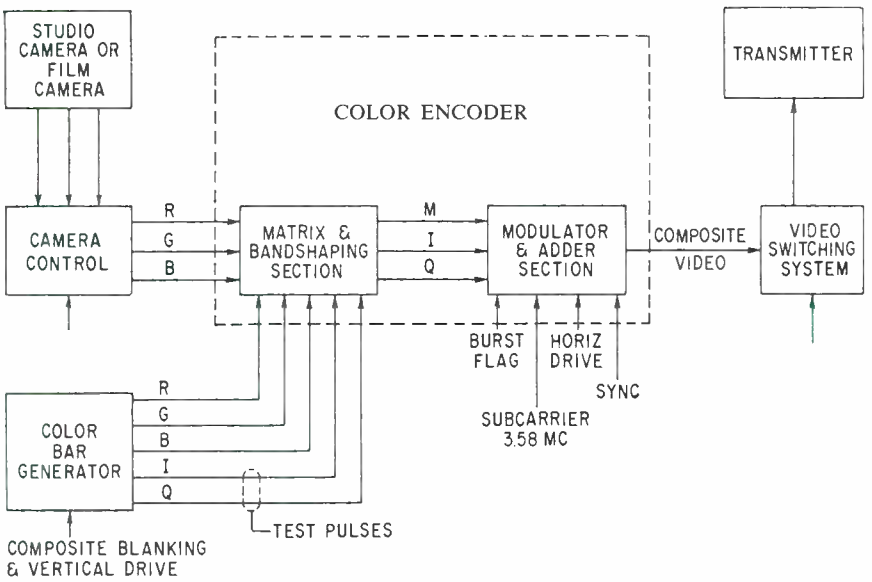


Fig. 62. Basic color-television system showing functions and major components of the color encoder.

Colors at the top of this display pattern are arranged from left to right as white, yellow, cyan, green, magenta, red and blue in their decreasing order of luminance. The lower portion of the pattern contains "I," "100% White," "Q," and black signal areas. The "I and Q" signals simplify subcarrier phase adjustments in the color encoder and the 100 percent white bar facilities white-balance adjustments. The specifications of the standard encoder color bar signal are given in EIA standard RS-189.

Waveforms

Fig. 64 shows the oscilloscope waveforms at a horizontal sweep rate of the color bar signals displayed on the television raster. Note that this is a composite representation of waveforms of the top and bottom areas of the raster. The color sync precedes the color bar pulse information.

Fig. 65 shows the various band-pass response characteristics of the luminance channel and of the "I" and "Q" channels of the color encoder.

A color encoder is set up and adjusted by using the calibrated color bars just described. The color encoder luminance gain is adjusted by using the 75 percent white bar as a reference. By switching off the luminance channel the appropriate "I" and "Q" waveforms are available to set the proper peak amplitudes and the 90° phase separation. Either a wide-band oscilliscope or a vectorscope can be used for display in a variety of specialized set-up procedures. The vector relationship of chrominance components is shown in Fig. 66.

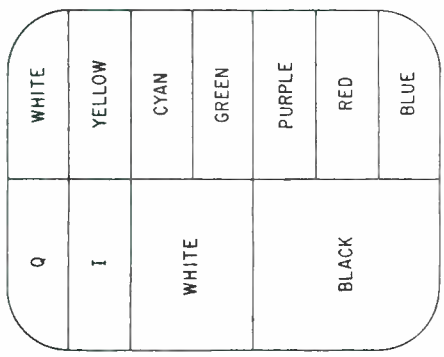


Fig. 63. Diagram showing color monitor display of color and test bars electronically produced by RCA color-bar generator.

Aperture Compensation

Aperture compensation is used in television systems to correct for the decrease in signal output at high frequencies caused by the finite-size limitations of the scanning spot or of equivalent optical lens aperture response. If one considers abrupt or black to white square-wave transitions at 400 TV lines, corresponding to 5 MHz video components, the video signal amplitudes from a Plumbicon or vidicon pick-up tube may be only 30 to 40 percent of the amplitude of low frequency transitions at 40 TV lines or 0.5 MHz. If the signal-to-noise ratio of the output video is good, aperture compensation to give practically 100 percent flat response at 5 MHz can be applied, producing subjectively sharper pictures.

Horizontal aperture correction is done by comparing the amplitude response of a given picture

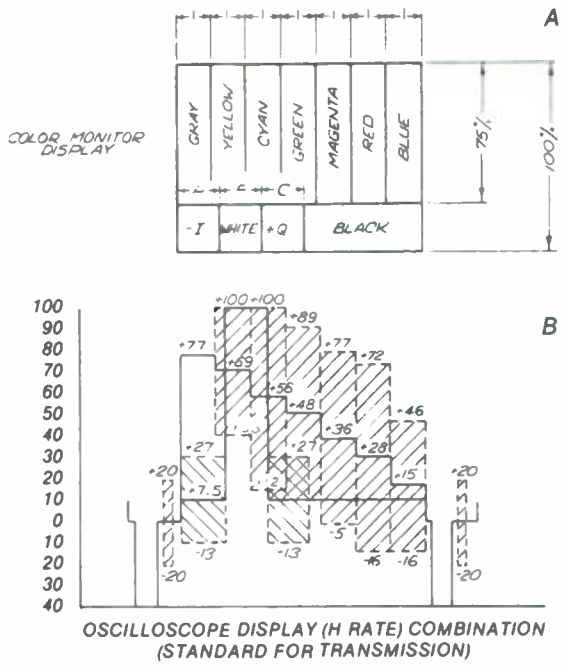


Fig. 64. (A) Color monitor display and (B) Oscilloscope display (H rate).

element with that from adjacent elements by the use of differential amplifiers and electrical delay lines. This difference, suitably amplified and of correct polarity is added to the signal being corrected which increases the sharpness of the transition.

Vertical aperture response can also decrease with increased line number and can similarly be improved by comparing the response of the picture elements on a given TV line with that of line elements preceding and following it. Differential amplifiers compare the video signals obtained from delay lines of a horizontal period (63.6 μsec) in duration with the picture elements of the TV line to be corrected.

Differences between these video responses are obtained from differential or comparison amplifiers amplified and suitably added to the

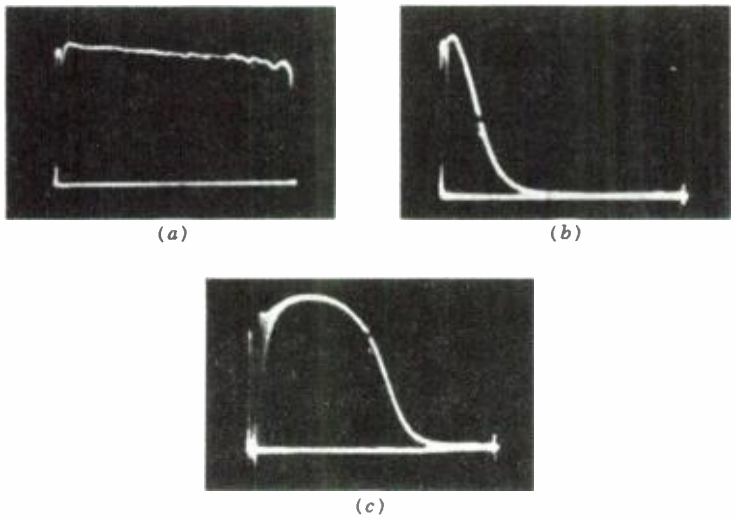


Fig. 65. Waveforms showing response characteristics of colorplexer monochrome, I and Q channels. (a) Response of monochrome channel without aperture correction, marker at 8.0 MHz, (b) output of I filter, marker at 2.0 MHz; (c) output of Q filter, marker at 500 kHz.

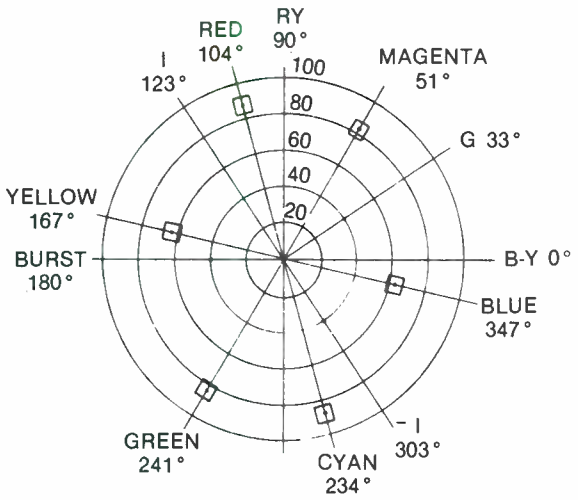


Fig. 66. Vector relationship among chrominance components.

main signal, to improve the vertical transition sharpness.

Judicious use of combined horizontal and vertical aperture correction or enhancement produces marked improvement in subjective picture sharpness. Since the luminance channel of a color system provides the sharpness information, it is generally used as the signal for aperture response improvement.

A block diagram of aperture compensation circuits is given in Fig. 67.

Factors Affecting Color Camera Performance

The following general principles, which outline procedures for the proper alignment and operation of color cameras, are directed toward three-tube color camera models and are presented to assist the station engineer in understanding the effect that each adjustment can have on the composite color picture. No attempt is made to present a step-by-step alignment procedure which, while basically the same for all cameras, will vary in detail depending on the manufacturer and the type of camera.

CAMERA ALIGNMENT

It is important to point out that color camera alignment should be made by viewing the proper test charts for a given adjustment or procedure. Such charts are useful for direct indication of the required camera adjustments. The practice of making an indiscriminate adjustment during a scene to "paint" a pleasing picture should be avoided in any operational procedure. Such an adjustment is usually successful for only isolated

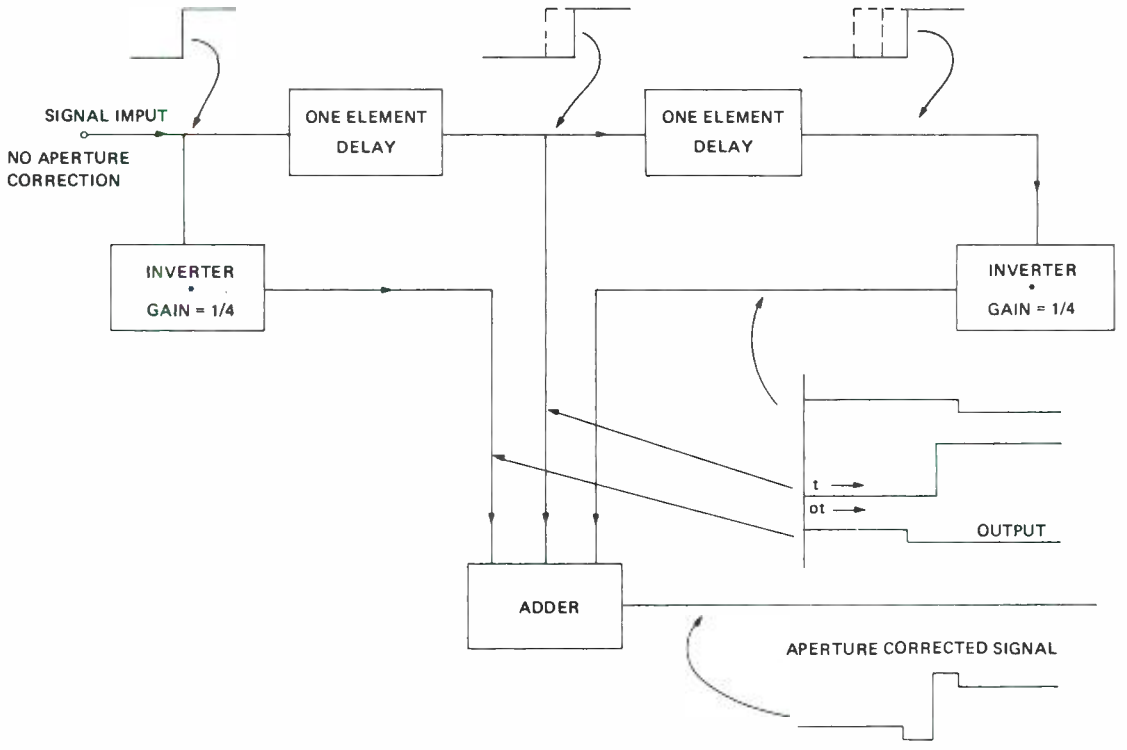


Fig. 67. Generalized aperture corrector.

conditions and may easily produce errors in subsequent scenes. It is also important to note that certain controls in the color cameras when improperly set may give a false indication that other controls are misaligned. Therefore, maximum effort should be given to logical rigorous routine alignment of the controls before program time.

During operation a properly aligned camera should require no more than exposure control using the lens iris as an opening control and an occasional adjustment of pedestal or black level setting.

The Three-Tube Concept

A three-tube camera consists basically of an optical system which "sees" the scene being televised through a dichroic mirror or prism assembly, suitably separated into its red, green, and blue image components. These three red, green, and blue images are focused on the photosensitive layer of the pickup tube in each color channel. By synchronous scanning of the three pickup tubes one obtains three independent video signals which differ only in their amplitude response to the three color images. Thus, we effectively obtain a red signal from the red tube, a green signal from the green tube and a blue signal from the blue tube. With the optical and electrical adjustments available, these three pictures are superimposed or registered on each other within an accuracy of a picture element. In order to carry out this registry process one has access to individual horizontal and vertical size and centering controls, as well as to mechanical rotation of the individual yokes and to "skew" which provides for orthogonal deflection by means of electrical cross-coupling between horizontal and vertical deflection. Thus, in principle one can obtain three independent R, G, and B channels which are effectively superimposed in space at the pickup device and in time by virtue of the synchronous deflection process. One could apply these three signals to the red, green, and blue gun of the color kinescope to produce a replica of the scene being televised. However, certain procedures are necessary to obtain normalized and predictable camera behavior.

Signal-to-Noise and Sensitivity

One must set the gains of the individual video amplifiers in the R, G, B channels to a specific value. Then a given signal current from the Plumbicon will produce the required output level at the required signal-to-noise ratio. The Plumbicon signal-to-noise ratio depends almost entirely on the figure of merit of the external video amplifier. Nominal values of signal current are of the order of 300 to 400 nanoamps. These are obtained at exposures of approximately f:4 with 150 to 200 fc on an average scene. In contrast to the Image Orthicon camera where the signal-to-noise ratio is determined primarily by the signal-to-noise ratio of the image orthicon tube itself, there is a trade-off possible between sensitivity with a 6 dB decrease in signal-to-noise ratio or four times this sensitivity with a 12 dB decrease in signal-to-noise ratio. As long as the signal-to-noise ratio under standard conditions is excellent, in practice about 50 dB before gamma correction, one can tolerate such a degradation to obtain increased sensitivity and still achieve pictures which have adequate signal-to-noise.

Specular Highlights

The signal current magnitude is chosen so as to achieve a compromise between signal-to-noise ratio and the ability of the tube to discharge highlights. A standard procedure is to adjust for a factor of two reserve in the signal current by proper beam bias adjustments. In set-up, the normal scene lens exposure opening is deliberately increased by one f stop, doubling the light to the Plumbicons and the beam currents in the R, G, and B tubes are then adjusted to just discharge the picture highlights. The exposure is then restored to its "normal" setting. With this camera adjustment procedure any increase in peak brightness due to speculars or highlights in a scene which does not exceed this factor of two will be discharged effectively in the Plumbicon by the "available" beam current reserve which has been provided. If one attempts to use larger signal currents than 400 nanoamperes there may be limitations in the gun which cause loss of normal resolution and an inability to supply the required beam current reserve for satisfactory discharge of highlights.

When a camera is operated under conditions of specular highlights and there is motion in the scene, the presence of undischarged areas in the raster will give rise to false color halo effects, generally red, which are usually described as comet tails. This comet-tail effect on motion is called "puddling" by British broadcasters. The two-to-one highlight beam reserve usually controls the comet-tail effect satisfactorily.

Gamma Correction

Since the gamma of the Plumbicon tube is essentially unit, gamma correcting amplifiers must be used to produce a pleasing picture display using modern color kinescopes. The effective gamma characteristic of the color kinescope has

approximately a 2.2 exponent; thus gamma correction of 1/2.2 or 0.45 is needed to obtain an overall gamma or transfer function of unity.

In order to obtain color "tracking" with changes of lighting or exposure, it is important that the transfer characteristics or gamma of the R, G, B channels be indentical. This matching can be achieved by using techniques such as superimposing of the transfer characteristics waveforms on a display oscilloscope, using a standard input sawtooth, and adjusting the individual gamma circuits for the same power law and the individual black levels or capped lens references for zero. A direct check for transfer characteristic adjustment is to use the neutral EIA logarithmic gray scale chart[6] placed directly in the scene viewed by the camera. When the tube and gamma circuits are correctly adjusted to an overall gamma, which is the same for all three channels, and a 0.45 slope value is maintained, the color picture display of the EIA chart on the kinescope will be observed as neutral or shades of gray with no apparent color misbalance over the entire gray scale range.

Aperture Correction

The aperture response of Plumbicon tubes of the 30 mm variety generally used for color TV broadcast is approximately 35 to 45 percent at 400 TV lines or 5 MHz as compared to a 100 percent reference response for low line-number transitions. For this reason it has been almost universal practice to aperture-correct or crispen the picture both horizontally and vertically by the use of omnidirectional aperture correction circuits. The response can be made effectively 100 percent of the time within the 5 MHz TV channel without noticeably deteriorating the signal-to-noise ratio. Such aperture correction techniques are described in the section on color encoder and shown in Fig. 66. Clamping, blanking addition, and clipping of the processed signal, following accepted monochrome picture techniques, are performed on the three channels before they are ready to encode into the NTSC color encoded form adopted for transmission.

Color Matching Techniques

In a color television operation the color-matching of the individual color cameras against each other is of prime importance. Ideally there should be *no* discernible color differences in the color TV pictures from all cameras when viewing the same subject. Experience has shown that by excercising tight control on the production tolerances of dichroic colorimetric components in the optical system and on the electronic components, once can achieve accurate color rendition from any cameras used on a given scene.

In practice each camera is aligned under normalized video gain conditions so as to obtain the required signal-to-noise performance and the same effective sensitivity. Then routine adjustment procedures to obtain the same gamma correction or transfer characteristics in the R, G, B are carried out.

The cameras now view an EIA logarithmic neutral gray scale under standard conditions. If the inputs to the color encoder are standardized and cameras have been well aligned, the gray scales will be reproduced on a color monitor over the complete brightness range as a neutral picture, since the subcarrier amplitude everywhere in the scene should be zero. Such a chart is a very sensitive indicator of small misadjustments and is generally used as a tool for vernier balancing of a color camera.

Any minor discrepancies in color rendition of the cameras used in a studio are corrected by very small changs in either R, B, or G gain provided by "paint pots."

Operationally it has been found that one camera control operator, using a single color monitor, can match four cameras more rapidly and accurately than four operators working independently.

Electronic masking devices such as the RCA Chromacomp and the CBS Color Masking Processor permits color matching cameras to any degree of precision without upsetting white balance.

Flare in Pickup Tubes

Under certain conditions of scene content, an unwanted lift of black level or pedestal can occur in one or more of the color pickup tubes. The effect is due to light scattering in the photoconductive layer of the tube itself and is strongest in the red channel. Thus, for example, if a scene which is predominantly red is viewed by the camera, the red pedestal will rise by 3 or 4 percent producing a red cast in the picture. This can be corrected by manually resetting the red tube black-level control. Automatic circuits which are duty-cycle sensitive are often used to provide a good approximation to black level with changes in scene content without any operator attention. Flare in green is much less than in red and is quite negligible in the blue channel. Light scattering in optical components and lenses will also cause artificial lift of black level.

In a well-designed and well-aligned camera, color balance and color tracking are obtained automatically over a wide range of scene content and exposure.

A special opaque test pattern developed by BBC uses a "super-black" enclosure hole as a reference for black level setting in addition to the usual logarithmic gray scale for gamma checks. American broadcasters often use a square of clean black velvet as a "super-black" for flare-compensation circuit test and adjustment and as a solid black-level reference.

Lighting on the Scene

With Plumbicon cameras the incident lighting required for studio-quality signal-to-noise picture performance generally approaches 250 fc for a lens opening of f:4. The contrast of the scene which the color camera must handle is the product of the incident light and the reflectance of the subject matter. Technically, uniform or flat lighting is easiest to handle since this limits the range to the reflectance of the scene components, generally restricted to a highest white of 60 percent reflectance and a lowlight of 2 to 3 percent, giving a range of 20 or 30 to 1 at most. The rendition in monochrome TV is as important as the rendition in color since many of the TV viewers still look at the picture in monochrome. It is therefore important to select scene materials and surfaces so as to obtain good monochrome separation in the gray scale as well as to provide colorful rendition in the final color picture. Flat lighting, as mentioned previously, is easiest to carry out, but becomes monotonous and boring from the standpoint of the producer. Any departures from flat lighting must be executed with caution. It is necessary to "fill-in" holes and deep shadows in lighting the scene to obtain results which are pleasing from the standpoint of signal-to-noise, range, and lag.

Specular or mirror reflections can be controlled by positioning of lighting and cameras or by "dull-spraying" of the surfaces responsible. Dimming is not an acceptable method of controlled scene lighting, since skin tone balance, which is the key to good performance, is very susceptible to changes in illuminant color temperature. Changes in scene lighting are generally provided by changing the total number of fixtures illuminating the set. Where skin tones are not involved, some liberty can be taken in dimming or fading.

Outdoor Broadcast Pickup

When color cameras view outdoor scenes, such as football and baseball games and other outdoor events, the subject matter and the illumination on the scene are no longer under the direct control of the broadcaster. Thus, for example, in the sunlight and in the shadows the incident illumination can vary 10 to 1, thereby increasing the effective scene range from 200 to 1 or more for a reflectance gamut of 20 to 1. In this case the broadcaster has an option of exposing for proper rendition of detail in the lowlights and compressing the highlights or adjusting for proper highlight exposure and crushing the dark portions of the scene. Fortunately, with mutiple-camera pickups used in sporting events, one can attempt to provide correct exposure for a camera scene with minimal overlap into underexposed or overexposed areas.

Specular Reflections

An annoying problem frequently met in outdoor pickup is specular reflection from shiny surfaces which can effectively direct an image of a light source or the sun itself into the pickup tube. Under such conditions there will be "tailing," "puddling," or "comet-tail" effects during motion due to the fact that it is impractical in standard cameras to provide sufficient beam current to completely discharge such specular highlights. Usual practice is to provide a minimum of twice the normal peak signal reserve for beam current to take care of such specular highlights. The signals themselves, of course, are clipped electrically in the video circuits so as to avoid overload problems in transmission. New developments now underway show promise of providing relief from "comet-tail" effects by providing a very high current discharge beam during horizontal retrace time.

Low-Light Pickup

A frequent color camera problem is the case or providing satisfactory results with insufficient or minimal light on the scene. In this case one trades signal-to-noise ratio in the camera for increased sensitivity. For example, with a reduction of 6 dB in signal-to-noise ratio, an effective gain of 2 in sensitivity can be obtained. Even a factor of 4 gain in sensitivity is quite possible with acceptable signal-to-noise performance. However, at lower values of scene lighting, lag on motion becomes a factor in obtaining satisfactory performance. Under these conditions "bias lighting has been used experimentally in color cameras to provide increased sensitivity with reduced differential color lag on motion. A uniform "light level" applied to the red, green, and blue photocathodes of the Plumbicon tubes so as to increase the dark current to about 8 nanoamperes provides a noteworthy improvement in build-up and decay lag performance, under low-light operating conditions.

Color TV Film Chains

It is a universal American practice to use photoconductive pickup tubes in the reproduction of color film. A powerful reason for this choice is that conventional high reliability, intermittent pull-down motion picture film projectors for 16 and 35 mm film transport can be used. These are generally modified to convert the 24 frames per second motion picture standard to the 60 exposure fields per second required for nominal color TV standards, using the well-known 3-2 intermittent TV motion sequence. With a 3 to 2 intermittent film pull down, one motion picture frame is scanned by three television fields and the next picture frame is scanned by two television fields. Since each field lasts 1/60 second, the five fields take exactly 5/60 seconds or 1/12 second, which is exactly the same time as required to show two motion picture frames, 2/24 or 1/12 second. Thus, we have automatically the 24 frames to 60 field conversion needed for TV.

The use of photoconductive tubes with storage such as the vidicon or the Plumbicon permits nonsynchronous system operation. The projector can be driven from the nominal 60 Hz house power supply even though the color TV field frequency is slightly less than 60 Hz. There is an effective tolerance of ¼ to ½ Hz in the power supply frequency before any disturbing "application bar" effects can be noticed due to the nonsynchronous operation of the projector with respect to the vertical scan rate. Experience has shown that this tolerance is entirely adequate for well-stabilized electrical power systems used in America.

In addition to 16 mm and 35 mm color film, 2 X 2 in. slides are used for program announcements, commercials, and special tests. It is standard practice to provide as many as 3 or even 4 different optical inputs into the same color TV film chain by the use of moving-mirror or fixed-prism multiplexing techniques. Any one of these sources can be selected for color transmission thereby increasing the utilization of the equipment. Practically all modern color film chains use a field lens into which the image if projected. A typical film island is shown in Fig. 68 and a schematic of an optical multiplexer arrangement is shown in Fig. 69.

Network operations rely heavily on 35 mm color films for prime time programs. The local or regional stations use 16 mm color film and it is also used for news programs.

A publication titled, "Color Television" contains reprints or important color TV technical papers from the *Journal of SMPTE*, and is an important reference for the background of some of the fundamental developments in color TV theory, equipment design, and practice. It also provides a reference appendix listing current standards and recommended practices for TV and motion pictures, and a comprehensive bibliography of color television papers published in the SMPTE Journal.

COLOR TEST EQUIPMENT

The color television broadcast station relies heavily on specialized test and monitoring facilities in order to maintain adequate standards of performance and to ensure compliance with FCC regulations. In the early days of monochrome and color TV, the techniques and equipment were cumbersome and difficult to use on a routine basis. In recent years, test signals have become more sophisticated and yield much more information on the performance of monochrome and color TV systems.

A stable high-performance color monitor is an essential element of color test equipment. This, together with a vectorscope and a standard color bar generator for set-up and calibration serves as a means of evaluating performance.

The color monitor, vectorscope, and color bar generator find utilization in rapid routine day-to-day check of the television system adjustments.

Additional test equipment needed for color TV performance evaluation falls into two categories:

(1) equipment to evaluate studio performance and

(2) equipment to evaluate microwave relay and transmitter performance.

The important electrical characteristics to be measured in either category are:

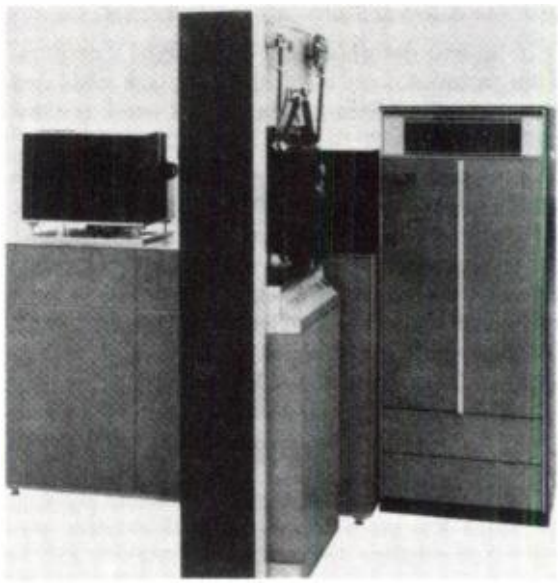


Fig. 68. A typical film island.

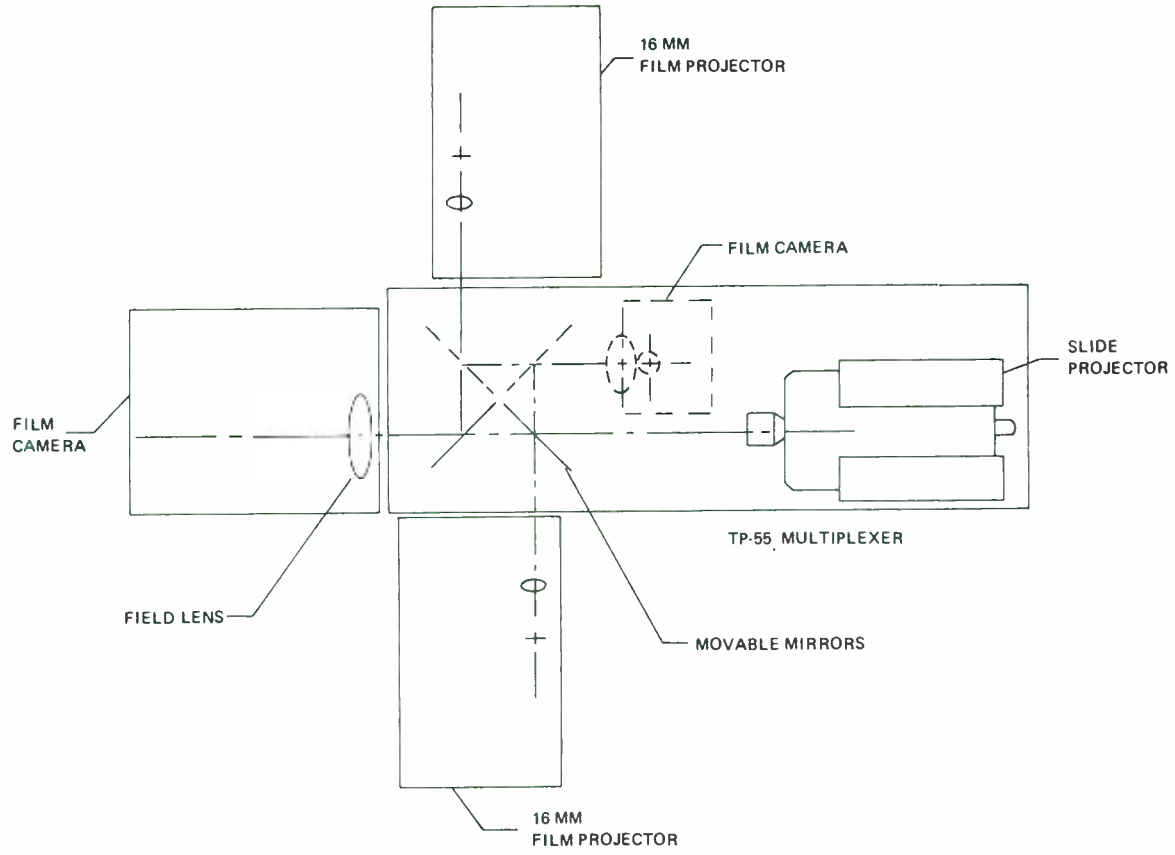


Fig. 69. Schematic of an optical multiplexer.

1. Linearity or differential gain;
2. Frequency response and differential phase performance;
3. Group delay characteristic;
4. Low frequency square-wave response.

Evolutionary developments have followed the requirement that specific test waveforms be made available which are compatible with normal television signal systems and can be introduced easily without disabling or upsetting normal operating conditions. Measurements of such test waveforms after passing through selected portions of the equipment or the complete system under evaluation, will give the required differential gain, phase and group delay information.

Stair-Step Generator

A modulated stair-step generator waveform is shown in Fig. 70. The signal conforms to IEEE standard IEEE 206. It consists of five 20-IRE-unit risers with subcarrier modulation on each transition. The amplitude-linearity or differential gain response of an amplifier can be determined directly from oscilliscope measurements of the output wave display. By the use of a high-pass filter, the differential gain characteristic can be displayed more graphically (Fig. 71, input), (Fig. 72, output) showing appreciable distortion. Differential phase measurements can be obtained by comparison of the subcarrier phase at each discrete level with phase of the color burst. Various oscillographic display techniques for precision phase measurements are available.

Sine-Squared Pulse and Bar

A second specialized waveform which is rapidly gaining popularity in color TV testing is the sine-squared pulse and bar with chrominance subcarrier modulation as shown in Fig. 73. It evolved from the monochrome sine-squared pulse and bar shown in Fig. 74. Use of this color test signal shows presence of differential gain distortions as in Fig 75 and delay distortions as shown in Fig. 76. Operationally the elegance of the method is in the direct-display presentation where distortion limits may be checked by reticle overlay techniques.

Another frequently used waveform is the multiburst signal, Fig. 77, which provides a series of selected frequency, constant-amplitude sine-wave electrical bursts of 0.5 MHz, 1, 2, 3, and 4 sweep

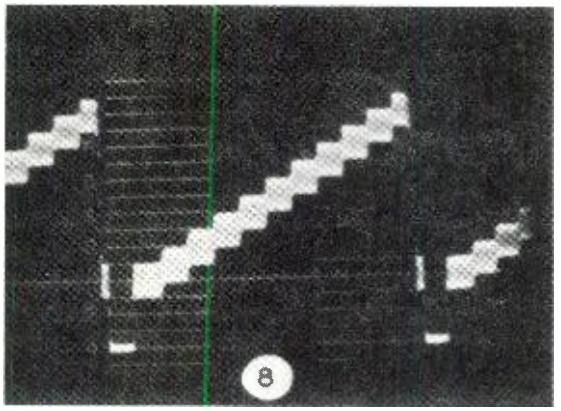


Fig. 70. Modulated stair-step generator waveform. (Picture courtesy of Marconi Instruments, Division of English Electric Corp.)

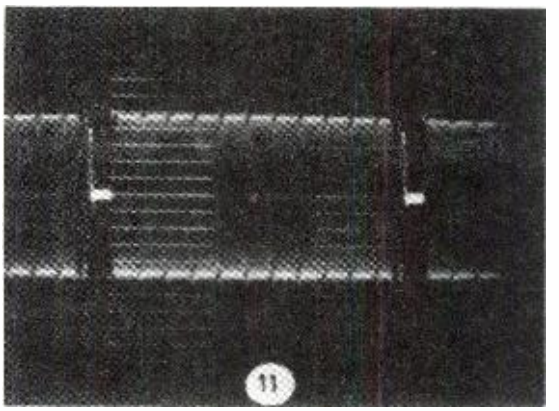


Fig. 71. High pass filter output with modulated stair-step waveform input. (Picture courtesy of Marconi Instruments, Division of English Electric Corp.)

signals which sequentially sample all frequencies in the video pass band. However, it is more convenient to use and to interpret in routine frequency response tests of broadcast equipment.

Vectorscope

The vectorscope[7] is a measurement instrument developed especially for color TV system tests and monitoring. Its essential feature is the polar or vectorial display of chrominance information in which the radial deflection is proportional to saturation of a color and the angular position is equal to the phase angle of that color subcarrier with respect to the color burst. The 360° polar coordinate display corresponds to a complete cycle of color subcarrier or 280 nanoseconds in a time display. By convention, the color burst is normalized at 180°. If the color bar signal described in Fig. 64 and Fig. 66 is applied to the input to the vectorscope and the burst is normalized at 180 , the display shown in Fig. 79 is obtained on the graticule.

It is noted that for standard signal levels each color vector in the color bar sequence falls within its approximately marked box on the graticule. The outer boxes define the FCC maximum permissible errors of ±10° in phase and ±20 percent in amplitude. The inner boxes correspond to ±2.5° phase error and 2.5 percent amplitude error.

A feature of the vectorscope color bar technique is that it gives immediate reassurance on system performance with a color bar test signal display.

By alternating two signal sources at the input, one can obtain direct readings on differential phase and amplitude behavior of any selected picture sources.

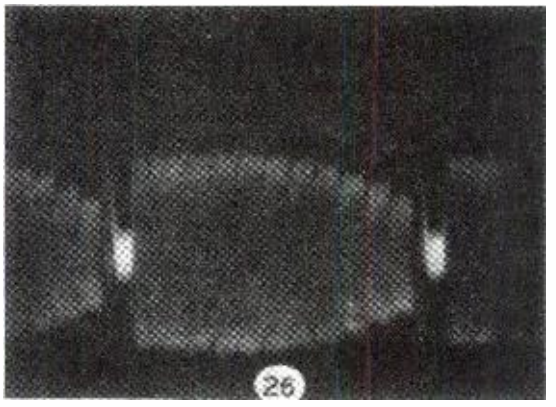


Fig. 72. High pass filter output of modulated stair-step waveform showing large amount of differential gain error in amplifier under test. (Picture courtesy of Marconi Instruments, Division of English Electric Corp.)

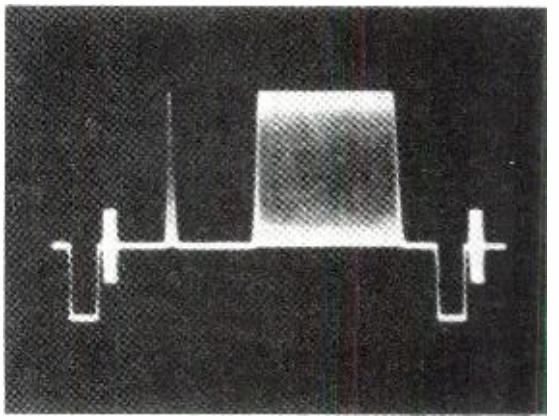


Fig. 73. Combined luminance and chrominance sine-squared pulse and bar. (Picture courtesy of Marconi Instruments, Division of English Electric Corp.)

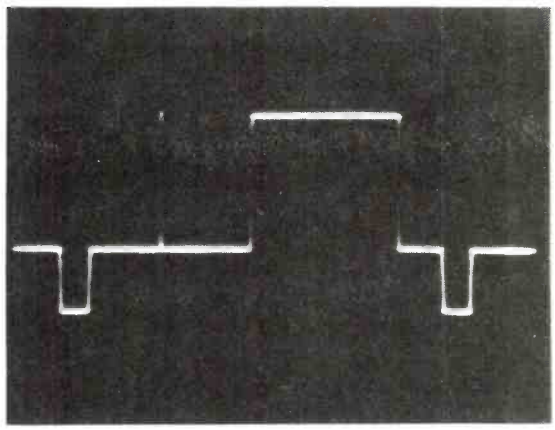


Fig. 74. Monochrome sine-squared pulse and bar. (Picture courtesy of Marconi Instruments, Division of English Electric Corp.)

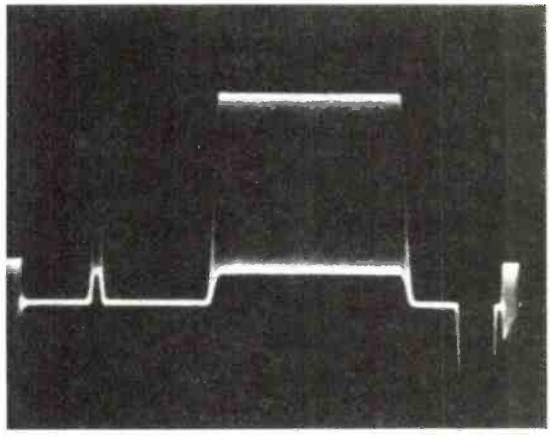


Fig. 75. Gain inequality indicated by combined luminance and chrominance sine-squared pulse and bar. Compare with waveforms of Fig. 73. (Picture courtesy of Marconi Instruments, Division of English Electric Corp.)

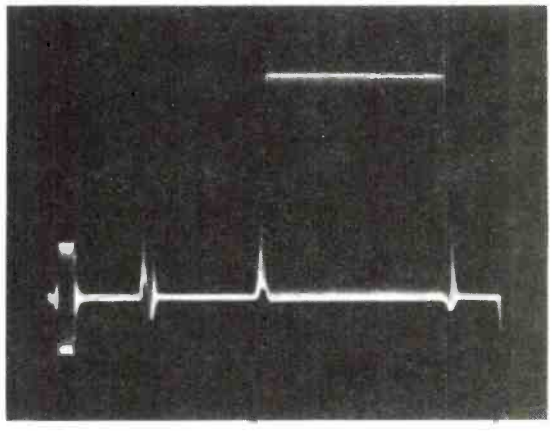


Fig. 76. Delay inequality indicated by the combined luminance and chrominance sine-squared pulse and bar. (Picture courtesy of Marconi Instruments, Division of English Electric Corp.)

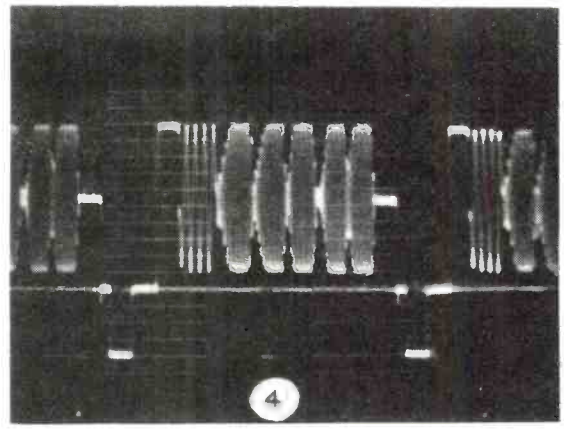


Fig. 77. Multiburst test signal with burst at 0.5 MHz, 1, 2, 3, and 4 MHz. (Picture courtesy of Marconi Instruments, Division of English Electric Corp.)

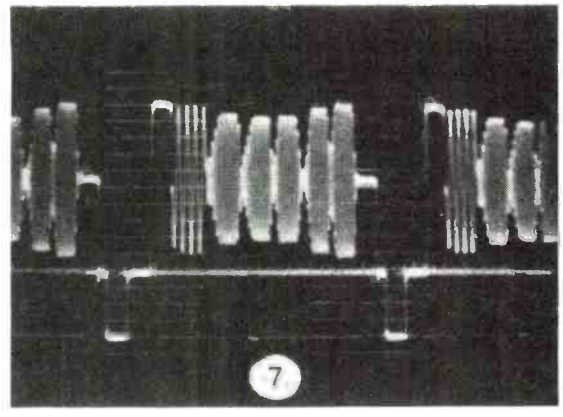


Fig. 78. Multiburst output signal from amplifier having distortion. Compare with Fig. 77. (Picture courtesy of Marconi Instruments, Division of English Electric Corp.)

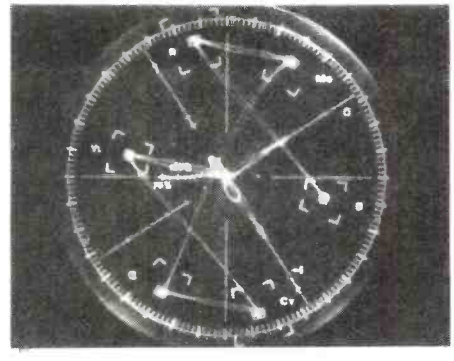


Fig. 79. Vector display. Split field color bars 75 per cent amplitude 100 percent white reference, 10 per cent set up. Conforms to EIA specification RS 189. (Picture courtesy of Tektronix, Inc.)

Vertical Interval Reference and Test Signals

A development which has important long-range possibilities is the use of a special signal transmitted in a specific line of the vertical blanking interval. The Vertical Interval Reference "VIR" signal, consists of a chrominance bar having the same phase as color burst, together with an appropriate luminance pulse and a black level interval. The Vertical Interval Reference signal is added to the main video signal and is in fact a certification that at the time it is added all conditions are normal. If various distortions occur to this Vertical Interval Reference, it can be corrected, with the expectation that the main signal will also be corrected. Thus more rigorous control and compensation of system errors is possible. A "VIT" or Vertical Interval Test signal is used to verify transmission conditions using multiburst, sine-squared or stair-step test signals. Such signals can be used for continuous monitoring of TV system performance, and in the future will probably find application in automatic control or correction of color system performance.

Test Charts

There are available several pictorial charts which serve to optically generate special test signals useful for color camera alignment and system adjustment. These were developed by industry technical committees and are available as opaques from EIA[8] or from equipment manufacturers for live cameras and as 2 X 2 in. slides from SMPTE for color TV film chains.

They are:

- EIA Resolution Chart,
- EIA Linear Gray Scale Chart,
- EIA Logarithmic Gray Scale,
- EIA Registration Chart,
- RCA Multiburst Chart,
- SMPTE Resolution Slide,
- Registration Slide,
- Linearity Slide.

The development of TV test signals and facilities is one which continually strives to increase the information to be obtained on systems performance, preferably on a continuous basis and without taking the system out of service. The "VITS" and "VIPS" concepts appear capable of providing a major step forward in test and measuring techniques.

FOOTNOTES

1. A detailed discussion of colorimetry and perception, and how these factors affect the viewer, is presented in "Color Television Engineering" by John W. Wentworth, McGraw-Hill Book Company, Inc., New York, 1955.
2. If the filters in the system are of the minimum-phase type, only one of the plots is needed, for either plot can be derived from the other for this type of filter. Almost all common interstage coupling networks are of the minimum-phase type.
3. FM systems can have nonlinearity as a result of *passive* networks, but this case is not considered here.
4. From the definition of differential gain by IRE Subcommittee 23.4.
5. From the definintion of differential phase by IRE Subcommittee 23.4.
6. Electronic Industries Association.
7. Tektronics Model 520 vectorscope is widely used for these measurements.
8. EIA—Electronic Industries Association.

REFERENCED TO FCC PART 73.699

	TIMING MEASUREMENTS	DEFINITION	RANGE			EIA RS-170A TENTATIVE STANDARDS SPECIFICATIONS APPLICABLE TO STUDIO FACILITIES	NOTES
			MINIMUM	NOMINAL	MAXIMUM		
1	H SYNC WIDTH	THE HORIZONTAL SYNC PULSE IS MEASURED BETWEEN THE -4 IRE POINTS ON THE LEADING AND TRAILING EDGES OF THE WAVEFORM.	4.45 μ SEC, @ -4 IRE	4.76 μ SEC, @ -4 IRE	5.08 μ SEC, @ -4 IRE	4.7 μ SEC ±0.1 μ SEC, @ -20 IRE	FCC REQUIRES THAT THE HORIZONTAL SYNC PULSE MUST BE BETWEEN 4.45 AND 5.08 μ SEC.
2	FRONT PORCH	THE FRONT PORCH IS MEASURED BETWEEN BLANKING AND THE LEADING EDGE OF H SYNC. THIS COMPONENT IS MEASURED FROM THE +4 IRE LEVEL AT BLANKING TO THE -4 IRE LEVEL ON THE LEADING EDGE OF THE H SYNC PULSE.	1.27 μ SEC, SEE NOTE	1.54 μ SEC, @ -4 IRE	1.60 μ SEC, @ -4 IRE	1.5 μ SEC ±0.1 μ SEC, @ +4 IRE -20 IRE	THE FCC SPECIFIES THAT THE FRONT PORCH, MUST BE NO LESS THAN 1.27 μ SEC MEASURED FROM THE +4 IRE LEVEL AT BLANKING TO THE -4 IRE LEVEL ON THE LEADING EDGE OF H SYNC.
3	SYNC TO START OF VIDEO DURATION	THIS INTERVAL IS MEASURED FROM THE -4 IRE POINT ON THE LEADING EDGE OF H SYNC TO THE +4 IRE POINT ON THE TRAILING EDGE OF BLANKING.	9.22 μ SEC, SEE NOTE	9.4 μ SEC, SEE NOTE	9.61 μ SEC, SEE NOTE	9.4 μ SEC ±0.1 μ SEC, @ -20 IRE +4 IRE	THE FCC SPECIFIES 0.145 H MINIMUM DURATION, FOR THIS COMPONENT.
4	SYNC TO END OF BURST DURATION	THIS SECTION IS MEASURED FROM THE -4 IRE POINT ON THE LEADING EDGE OF H SYNC TO THE TRAILING ZERO CROSSING OF THE LAST BURST EXCURSION EXCEEDING 50% OF BURST AMPLITUDE.	7.07 μ SEC, SEE NOTE	7.50 μ SEC, SEE NOTE	7.94 μ SEC, SEE NOTE	7.80 μ SEC ±0.1 μ SEC, @ -20 IRE TO LAST CYCLE OF BURST EXCEEDING 50% AMPLITUDE	THE FCC SPECIFIES 0.125 H MAXIMUM DURATION, FOR THIS COMPONENT.
5	H BLANKING	THE FCC DEFINES HORIZONTAL BLANKING AS MEASURED BETWEEN POINTS ON THE WAVEFORM AT +4 IRE UNITS, WITH A DURATION OF 10.49 μ SEC. THE MAXIMUM WIDTH SPECIFICATION FOR H BLANKING DEFINED BY THE FCC, IS 11.44 μ SEC MEASURED AT 90 IRE UNITS.	10.49 μ SEC, @ 4 IRE	10.8 μ SEC, @ 20 IRE	11.44 μ SEC, @ 90 IRE	10.9 μ SEC ±0.2 μ SEC @ +20 IRE	THE MAXIMUM WIDTH SPECIFICATION FOR H BLANKING IS MEASURED AT 90 IRE UNITS ABOVE BLANKING. IT IS INTERESTING TO NOTE THAT MANY VIDEO SIGNALS DO NOT REACH 90 IRE IMMEDIATELY AFTER BLANKING.
6	COLOR BURST WIDTH	THE COLOR BURST IS MEASURED FROM THE LEADING ZERO CROSSING OF THE FIRST BURST EXCURSION EXCEEDING 50% OF THE BURST AMPLITUDE TO THE TRAILING ZERO CROSSING OF THE LAST BURST EXCURSION EXCEEDING 50% OF THE BURST AMPLITUDE.	8 CYCLES	9 CYCLES	10 CYCLES	9 CYCLES	FCC STANDARDS REQUIRE A MINIMUM OF 8 CYCLES OF COLOR BURST. THE NEW STANDARD WHICH IS NOW BEING USED IN THE INDUSTRY IS 9 CYCLES OF COLOR BURST.
7	BREEZEWAY WIDTH	THE BREEZEWAY IS DEFINED AS THE PERIOD BETWEEN THE TRAILING EDGE OF THE HORIZONTAL SYNC PULSE AND THE FIRST CYCLE OF COLOR BURST. THIS IS MEASURED FROM THE -4 IRE POINT ON THE TRAILING EDGE OF H SYNC TO THE LEADING ZERO CROSSING OF THE FIRST BURST EXCURSION EXCEEDING 50% AMPLITUDE	381 nSEC, SEE NOTE	600 nSEC, SEE NOTE	900 nSEC, SEE NOTE	600 nSEC ±100 nS, @ -4 IRE TO FIRST CYCLE OF COLOR BURST EXCEEDING 50% AMPLITUDE	THE FCC SPECIFIES THAT THE BREEZEWAY MUST BE NO LESS THAN 381 μ SEC, MEASURED FROM THE TRAILING EDGE OF HORIZONTAL SYNC PULSE A -4 IRE POINT, TO THE FIRST CYCLE OF COLOR BURST.
8	SUBCARRIER FREQUENCY	THE FREQUENCY OF THE COLOR SUBCARRIER, 3.579545 MHZ, IS AN ODD MULTIPLE OF HALF-LINE FREQUENCY, I.E., HORIZONTAL LINE FREQUENCY/2. $\frac{15734.264\ HZ}{2} = 7867.132$ FOR NTSC COLOR TELEVISION. (7867.132) (455) = 3.579545 MHZ	3.579535 MHZ	3.579545 MHZ	3.579555 MHZ	3.579545 MHZ, ±10 HZ	THE FREQUENCY OF THE COLOR SUBCARRIER MUST BE HELD WITHIN 10 HZ OF 3.579545 MHZ. NOTE, SHORT TIME DURATION OF BURST SIGNAL MAKES DIRECT FREQUENCY COUNTING INACCURATE.
9	H SYNC RISE AND FALL TIMES	THE RISE AND FALL TIMES OF THE HORIZONTAL SYNC PULSE ARE MEASURED BETWEEN THE 10 AND 90% POINTS ON THE LEADING AND TRAILING EDGES OF THE WAVEFORM.	———	<250 nSEC, SEE NOTE	250 nSEC, SEE NOTE	0.14 μ SEC ±0.02 μ SEC MEASURED BETWEEN 10 AND 90% POINTS ON THE LEADING AND TRAILING EDGES OF THE PULSE	FCC REQUIRES THAT RISE TIME OF H SYNC BE LESS THAN 0.250 μ SEC ASSUMING 40IRE UNITS OF H SYNC AMPLITUDE, 10% CORRESPONDS TO -4IRE AND 90% CORRESPONDS TO -36IRE.
10	SERRATION WIDTH	THE SERRATIONS ARE LOCATED IN THE VERTICAL SYNC PULSE AND MEASURED AT THE -4 IRE POINTS.	3.81 μ SEC, -4 IRE SE@NOTE	4.45 μ SEC, @ -4 IRE SEE NOTE	5.08 μ SEC, @ -4 IRE SEE NOTE	4.7 μ SEC ±0.1 μ SEC, @ -20 IRE	THE SERRATIONS IN THE V SYNC PULSE MUST BE BETWEEN 3.8 AND 5.08 μ SEC, MEASURED AT -4 IRE LEVEL. THE RISE AND FALL TIMES OF THE SERRATIONS MUST BE LESS THAN 250 nSEC.
11	RISE AND FALL TIMES OF EQUALIZERS AND SERRATIONS	THE RISE AND FALL TIMES OF THE EQUALIZERS AND SERRATIONS ARE MEASURED BETWEEN THE 10 AND 90% POINTS ON THE LEADING AND TRAILING EDGES OF THE WAVEFORMS.	———	250 nSEC, SEE NOTE	250 nSEC, SEE NOTE	0.14 μ SEC ±0.02 μ SEC MEASURED BETWEEN 10 AND 90% POINTS ON THE LEADING AND TRAILING EOGES OF THE PULSE	FCC SPECIFIES RISE AND FALL TIMES OF EQUALIZERS AND SERRATIONS MUST BE LESS THAN 250 nSEC. THE 10% AND 90% POINTS CORRESPOND TO -4 IRE AND -36 IRE UNITS, RESPECTIVELY.
12	EQUALIZING PULSE WIDTH	THE EQUALIZING PULSES PRECEDE AND FOLLOW THE VERTICAL SYNC PULSE INTERVAL. THEY ARE MEASURED AT THE -4 IRE LEVEL.	2.00 μ SEC, @ -4 IRE	2.26 μ SEC, @ -4 IRE	2.54 μ SEC, @ -4 IRE	2.3 nS ± 0.1 μ SEC, @ -20 IRE	THE TOLERANCE ON EQUALIZING PULSES, IS THAT THE AREA OF THESE PULSES MUST BE BETWEEN 45 AND 50% OF THE AREA OF THE HORIZONTAL SYNCHRONIZING PULSE.
13	V BLANKING WIDTH	VERTICAL BLANKING INTERVAL IS THE TIME BETWEEN THE LAST PICTURE INFORMATION AT THE BOTTOM OF ONE FIELD TO THE FIRST PICTURE INFORMATION AT THE TOP OF THE NEXT FIELD.	19 LINES	20 LINES	21 LINES	FIELD I = 20 LINES FIELD II = 19.5 LINES	IN TERMS OF TIME, VERTICAL BLANKING MUST BE GREATER THAN 1.17 mSEC, BUT LESS THAN 1.33 mSEC. NOTE, THE BROADCAST INDUSTRY NOW FAVORS A MAXIMUM OF 20 LINES OF VERTICAL BLANKING.
14	V SYNC PULSE INTERVAL	THE VERTICAL SYNC PULSE SHOULD HAVE A DURATION EQUAL TO THREE HORIZONTAL LINES. THE SERRATIONS IN THE VERTICAL SYNC PULSE SHOULD BE BETWEEN 3.8 TO 5.1 μ SEC, MEASURED AT -4 IRE LEVEL.	———	3H	———	3H H = 1 HORIZONTAL LINE H = 63.55 μ SEC	FCC REQUIRES THE VERTICAL SYNC PULSE TO HAVE A DURATION OF THREE HORIZONTAL LINES. IN TERM OF TIME, 3 H = 190.67 μ SEC. THE VERTICAL SYNC PULSE IS TO BE EXACTLY 3 HORIZONTAL LINES.

FCC time-base specifications for NTSC-M color television.

Developed and Prepared By:
MICHAEL J. SCHUMILA
Senior Member Engineering Staff
Systems Engineering
RCA American Communications
Princeton, New Jersey 08540

7.1

Color Television

Part II: Worldwide Color Television Standards— Similarities and Differences*

D. H. Pritchard
J. J. Gibson
RCA Laboratories, David Sarnoff Research Center
Princeton, New Jersey

WORLDWIDE COLOR TELEVISION STANDARDS

Introduction

A simple, concise summary of the similarities and differences in the ever-changing color television system techniques and standards employed throughout the world is difficult to achieve, as evidenced by the efforts of the CCIR (International Radio Consultative Committee) in attempting to establish the elusive "universal" system. Nevertheless, it is hoped that this tutorial review and up-date may be useful for those who desire a conceptual overview of the technical situation.

The picture performance of a motion picture system in one location in the world is generally the same as in any other location. Thus, international exchange of film programming is comparatively straightforward.

Not so in the case of broadcast color television systems. The lack of compatibility has its origins in many factors such as constraints in communications channel allocations and techniques, differences in local power source characteristics, network requirements, pickup and display technology, and political considerations relating to international telecommunications agreements. The intent of this paper is to provide a tutorial review of the technical standardization characteristics pertinent to the problem of international exchange of images—not a system's performance comparison.

Background

The most outstanding as well as the most controversial effort of the Eleventh Plenary Assembly of the CCIR, held in Oslo in 1966, was an attempt at standardization of color television systems by the contributing countries of the world. The discussions pertaining to the possibility of a universal system proved inconclusive. Therefore, the CCIR, instead of issuing a unanimous recommendation for a single system, was forced to issue only a report describing the characteristics and recommendations for a variety of proposed systems. It was, therefore, left to the controlling organizations of the individual countries to make their own choice as to which standard to adopt.

This outcome was not totally surprising since one of the primary requirements for any color television system is compatibility with a coexisting monochrome system. In many cases, the monochrome standards, already existed and were dictated by such factors as local power line frequen-

*Reprinted with the permission of the Society of Motion Picture and Television Engineers. This was originally published in the *SMPTE Journal*

NOTE: Superscript numbers refer to references at the end of this chapter.

cies—relevant to field and frame rates—as well as radio frequency channel allocations and pertinent telecommunications agreements.

Thus, such technical factors as line number, field rate, video bandwidth, modulation technique, and sound carrier frequencies were predetermined and varied in many regions of the world. The ease with which international exchange program material may be accomplished is thereby hampered and is accomplished at present by means of standards conversion techniques, or "transcoders," with varying degrees of loss in quality.

On the other hand, these techniques have provided surprisingly good service in more recent years with the growing use of "satellite relays" coupled with the advances in digital signal processing technology in both the video and audio domains. In view of this rapidly changing situation and considering that more and more countries, particularly in Latin America (Region II), arrive at the point of deciding on a color system, it becomes apparent that a clear understanding of the implications of system variations has a high order of priority for those involved in international live television broadcast and film/videotape programming exchange.

The data quoted herein is referenced to the recent recommendations of the Fourteenth Plenary Assembly of the CCIR held in Kyoto, Japan in 1978. It should be recognized that the situation is of a continually shifting nature and future decisions can and no doubt will alter some of the details.

"Monochrome-Compatible" Color TV Systems

In order to achieve success in the introduction of a color television system, it is essential that the color system be fully compatible with the existing black-and-white system. That is, monochrome receivers must be able to produce high-quality black-and-white images from a color broadcast, and color receivers must produce high-quality black-and-white images from monochrome broadcasts. The first such color television system to be placed into commercial broadcast service was developed in the United States. On 17 December 1953, the Federal Communications Commission (FCC) approved transmission standards and authorized broadcasters, as of 23 January 1954, to provide regular service to the public under these standards. This decision was the culmination of the work of the NTSC (National Television System Committee) upon whose recommendation the FCC action was based.[1] Subsequently, this system, now referred to as the NTSC system, was adopted by Canada, Japan, Mexico, and others.

That 26 years later, in 1980, these standards are still providing color television service of good quality testifies to the validity and applicability of the fundamental principles underlying the choice of specific techniques and numerical standards.

The previous existence of monochrome television standards was two-edged in that it provided a foundation upon which to build the necessary innovative techniques while simultaneously imposing the requirement of compatibility. Within this framework, an underlying theme—that which the eye does not see does not need to be transmitted nor reproduced—set the stage for a variety of fascinating developments in what has been characterized as an "economy of representation."[1]

The countries of Europe delayed the adoption of a color television system, and in the years between 1953 and 1967, a number of alternative systems that were compatible with the 625-line, 50-field existing monochrome systems were devised. The development of these systems was to some extent influenced by the fact that the technology necessary to implement some of the NTSC requirements was still in its infancy. Thus, many of the differences between the NTSC and other systems are due to technological rather than fundamental theoretical considerations.

Most of the basic techniques of NTSC are incorporated into the other system approaches. For example, the use of wideband luminance and relatively narrowband chrominance, following the teachings of the principle of "mixed highs," is involved in all systems. Similarly, the concept of providing horizontal interlace for reducing the visibility of the color subcarrier(s) is followed in all approaches. This feature is required to reduce the visibility of signals carrying color information that are contained within the same frequency range as the coexisting monochrome signal, thus maintaining a high order of compatibility.

An early system that received approval was one proposed by Henri de France of the Compagnie de Television of Paris. It was argued that if color could be relatively band-limited in the horizontal direction, it could also be band-limited in the vertical direction. Thus, the two pieces of coloring information (hue and saturation) that need to be added to the one piece of monochrome information (brightness) could be transmitted as subcarrier modulation that is sequentially transmitted on alternate lines—thereby avoiding the possibility of unwanted crosstalk between color signal components. Thus, at the receiver, a one-line memory, commonly referred to as a 1-*H* delay element, must be employed to store one line to then be concurrent with the following line. Then a linear matrix of the "red" and "blue" signal components (*R* and *B*) is used to produce

the third "green" component (*G*). Of course, this necessitates the addition of a line-switching identification technique. Such an approach, designated as SECAM (*S*equential *C*ouleur *A*vec *M*emoire, for sequential color with memory) was developed and officially adopted by France and the USSR, and broadcast service began in France in 1967.

The implementation technique of a 1-*H* delay element led to the development, largely through the efforts of Walter Bruch of Telefunken Company, of the *P*hase *A*lternation *L*ine or PAL system. This approach was aimed at overcoming an implementation problem of NTSC that requires a high order of phase and amplitude integrity (skew-symmetry) of the transmission path characteristics around the color subcarrier to prevent color quadrature distortion. The line-by-line alternation of the phase of one of the color signal components averages any colorimetric distortions to the observer's eye to that of the correct value. The system in its simplest form (simple PAL), however, results in line flicker (Hanover bars). The use of a 1-*H* delay device in the receiver greatly alleviates this problem (standard PAL). PAL systems also require a line identification technique.

The standard PAL system has been adopted by numerous countries in continental Europe as well as in the United Kingdom. Public broadcasting began in 1967 in Germany and the United Kingdom using two slightly different variants of the PAL system (to be described shortly).

NTSC, PAL, and SECAM Systems Overview

In order to properly understand the similarities and differences in systems used today, a familiarization with the basic principles of NTSC, PAL, and SECAM is required. As previously stated, because many basic techniques of NTSC are involved in PAL and SECAM, a thorough knowledge of NTSC is necessary in order to understand PAL and SECAM.

The same *R*, *G*, and *B* pickup devices and the same three primary color display devices are used in all systems. The basic camera function is to analyze the spectral distribution of the light from the scene in terms of its red, green, and blue components on a point-by-point basis as determined by the scanning rates. The three resulting electrical signals must then be transmitted over a band-limited communications channel to control the three-color display device to make the *perceived* color at the receiver appear essentially the same as the *perceived* color at the scene.

It is useful to define color as a psycho-physical property of light—specifically, as the combination of those characteristics of light that produces the sensations of brightness, hue, and saturation as shown in Fig. 1. Brightness refers to the relative intensity; hue refers to that attribute of color that allows separation into spectral groups perceived as red, green, yellow, etc. (in scientific terms, the dominant wavelength); and saturation is the degree to which a color deviates from a neutral gray of the same brightness—the degree to which it is "pure," or "pastel," or "vivid," etc. These three characteristics represent the total information necessary to define and/or recreate a specific color stimulus.

This concept is useful to communication engineers in developing encoding and decoding techniques to efficiently compress the required information within a given channel bandwidth and to subsequently recombine the specific color signal values in the proper proportions at the reproducer. The NTSC color standards define the first commercially broadcast process for achieving this result.

A preferred signal arrangement was developed that resulted in reciprocal compatibility with monochrome pictures and is transmitted within the existing monochrome channel as shown in

BRIGHTNESS (Luminance):

RELATIVE INTENSITY OF THE COLOR

HUE

THE ATTRIBUTE THAT ALLOWS DESIGNATION IN TERMS OF RED, YELLOW, BLUE, etc. (Dominant wavelength).

SATURATION

DEGREE TO WHICH A COLOR DEVIATES FROM A NEUTRAL GRAY OF THE SAME BRIGHTNESS – PURITY, PASTEL, VIVIDNESS, etc.

Fig. 1. Basic definition of "color."

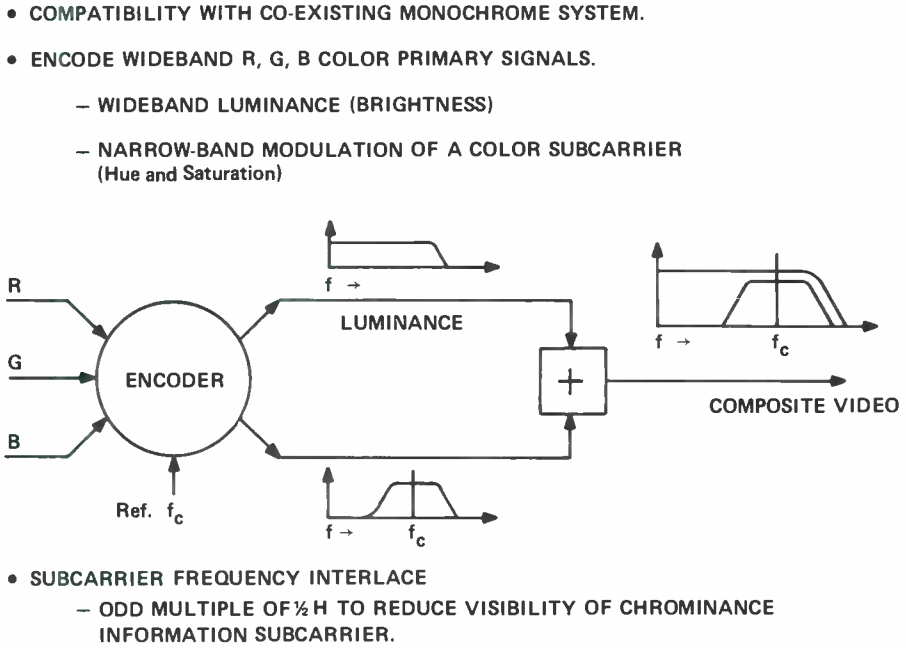


Fig. 2. Basic communications channel principles applied to color television.

Fig. 2. Thus, one signal (luminance) is chosen in all approaches to occupy the wide-band portion of the channel and to convey the *brightness* as well as the detail information content. A second signal, termed the chrominance signal, representative of the chromatic attributes of *hue* and *saturation*, is assigned less channel width in accordance with the principle that in human vision full three-color reproduction is not required over the entire range of resolution—commonly referred to as the "mixed-highs principle."

Another fundamental principle employed in all systems involves arranging the chrominance and luminance signals within the same frequency band without excessive mutual interference. Recognition that the scanning process, being equivalent to sampled-data techniques, produces signal components largely concentrated in uniformly spaced groups across the channel width, led to introduction of the concept of horizontal frequency interlace (dot interlace). The color subcarrier frequency is so chosen as to be an odd multiple of one-half the line rate (in the case of NTSC) such that the phase of the subcarrier is exactly opposite on successive scanning lines. This substantially reduces the subjective visibility of the color signal "dot" pattern components.

Thus the major differences among the three main systems of NTSC, PAL, and SECAM are in the specific modulating processes used for encoding and transmitting the chrominance information. The similarities and differences are briefly summarized in Fig. 3.

The following four sections discuss the basic color television systems in some technical detail, including some never actually implemented. For a summary and comparison of system standards and specifications, the reader is referred to a later section.

The NTSC Color System

The importance of the colorimetric concepts of brightness, hue, and saturation comprising the three pieces of information necessary to analyze or recreate a specific color value becomes evident in the formation of the composite color television NTSC format.

The luminance, or monochrome, signal is formed by addition of specific proportions of the red, green, and blue signals and occupies the total available video bandwidth of 0-4.2 MHz. The NTSC, PAL, and SECAM systems all use the same luminance (Y) signal formation, differing only in available bandwidths.

The "Y" signal components have relative voltage values representative of the brightness sensation in the human eye. Therefore, the red (E'_R), green (E'_G), and blue (E'_B) voltage components are tailored in proportion to the standard luminosity curve at the particular values of the dominant wavelengths of the three color primaries chosen for color television. Thus, the luminance signal makeup for all systems, as normalized to white, is described by

- ALL SYSTEMS:
  - THREE-PRIMARY ADDITIVE COLORIMETRIC PRINCIPLES
  - SIMILAR CAMERA PICK-UP AND RECEIVER DISPLAY TECHNOLOGY
  - WIDEBAND LUMINANCE AND NARROW-BAND COLOR
- COMPATIBILITY WITH CO-EXISTING MONOCHROME SYSTEM:
  INTRODUCES FIRST ORDER DIFFERENCES
  - LINE NUMBER
  - FIELD/FRAME RATES
  - BANDWIDTH
  - FREQUENCY ALLOCATION
- MAJOR DIFFERENCES IN COLOR TECHNIQUES
  - NTSC – PHASE AND AMPLITUDE QUADRATURE MODULATION OF INTERLACED SUBCARRIER
  - PAL – SIMILAR TO NTSC BUT WITH LINE ALTERNATION OF "V" COMPONENT
  - SECAM – FREQUENCY MODULATION OF LINE SEQUENTIAL COLOR SUBCARRIERS

Fig. 3. General comparison of worldwide television systems.

$$E'_Y = 0.299\ E'_R + 0.587\ E'_G + 0.114\ E'_B \quad [1]^*$$

Fig. 4 also indicates the equations for the chrominance signal components. Signals representative of the chromaticity information (hue and saturation) that relate to the differences between the luminance signal and the basic red, green, and blue signals are generated in a linear matrix. This new set of signals is termed *color-difference* signals and is designated as $R-Y$, $G-Y$, and $B-Y$. These signals modulate a subcarrier that is combined with the luminance component and passed through a common communications channel. At the receiver, the color difference signals are determined, separated, and individually added to the luminance signal in three separate paths to recreate the original R, G, and B signals according to the equations

$$\begin{aligned} E'_Y + E'_{(R-Y)} &= E'_Y + E'_R - E'_Y = E'_R \\ E'_Y + E'_{(G-Y)} &= E'_Y + E'_G - E'_Y = E'_G \quad [2] \\ E'_Y + E'_{(B-Y)} &= E'_Y + E'_B - E'_Y = E'_B \end{aligned}$$

In the specific case of NTSC, two other color-difference signals, designated as "I" and "Q", are formed at the encoder and used to modulate the color subcarrier, indicated in Fig. 4. The reason for the choice of I and Q signals is discussed later.

It may be noted that the $B-Y$, $R-Y$, and $G-Y$ color signal modulation components are the same in NTSC, PAL, and SECAM.

Another reason for the choice of signal values in the NTSC system is that the eye is more responsive to spatial and temporal variations in luminance than it is to variations in chrominance. Therefore, the visibility of luminosity changes due to random noise and interference effects may be reduced by properly proportioning the relative chrominance gain and encoding angle values with respect to the luminance values. Thus, the "principle of constant luminance"** is incorporated into the system standards.[1, 2]

The voltage outputs from the three camera tubes are adjusted to be equal when a scene reference white or neutral gray object is being scanned for the color temperature of the scene ambient. Under this condition, the color subcarrier also automatically becomes zero. The colormetric values have been formulated by assuming that the reproducer will be adjusted for "Illuminant C," representing the color of average daylight.

*The signal of Equation [1] would be exactly equal to the output of a linear monochrome camera tube with ideal spectral sensitivity if the red, green, and blue camera tubes were also linear devices with theoretically correct spectral-sensitivity curves. In actual practice, the red, green, and primary signals are deliberately made nonlinear to accomplish gamma correction (adjust the slope of the input/output transfer characteristic). The prime mark (') is used to denote a gamma-corrected signal.

**The IEEE Standard Dictionary of Electrical and Electronics Terms notes that in constant-luminance signal and no control of luminance is provided by the chrominance signal. Noise signals falling within the bandwidth of the chrominance channel produce only chromaticity variations, which if they are coarse-structured are subjectively less objectionable than correspondingly coarse-structured luminance variations.

LUMINANCE:

$$E'_Y = 0.299\ E'_R + 0.587\ E'_G + 0.114\ E'_B$$

(Common for all systems)

CHROMINANCE:

NTSC

$$E'_I = -0.274\ E'_G + 0.596\ E'_R - 0.322\ E'_B$$

$$E'_Q = -0.522\ E'_G + 0.211\ E'_R + 0.311\ E'_B$$

$$B\text{-}Y = 0.493\ (E'_B - E'_Y)$$

$$R\text{-}Y = 0.877\ (E'_R - E'_Y)$$

$$G\text{-}Y = 1.413\ (E'_G - E'_Y)$$

PAL

$$E'_U = 0.493\ (E'_B - E'_Y)$$

$$\pm E'_V = \pm 0.877\ (E'_R - E'_Y)$$

SECAM

$$D'_R = -1.9\ (E'_R - E'_Y)$$

$$D'_B = 1.5\ (E'_B - E'_Y)$$

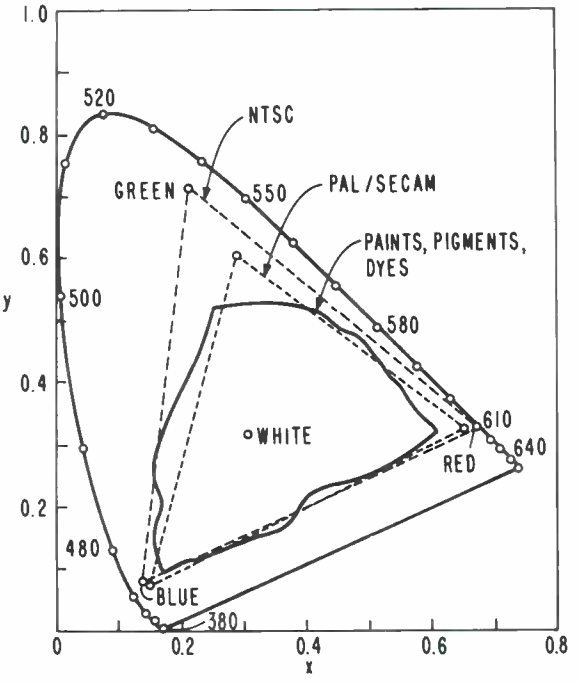
Fig. 4. Electronic color signal values for NTSC, PAL, and SECAM.

Fig. 5 is a CIE chromaticity diagram (CIE = Commission Internationale de l'Eclairage) indicating the primary color coordinates for NTSC, PAL, and SECAM. It is interesting to compare the television available color gamut relative to that of all color paint, pigment, film, and dye processes.

In NTSC color standards, the chrominance information is carried as simultaneous amplitude and phase modulation of a subcarrier chosen to be in the high frequency portion of the 0-4.2 MHz video band and specifically related to the scanning rates as an odd multiple of one-half the horizontal line rate as shown by the vector diagram in Fig. 6. The hue information is assigned to the instantaneous phase of the subcarrier. Saturation is determined by the *ratio* of the instantaneous amplitude of the subcarrier to that of the corresponding luminance signal amplitude value. For details of the derivation, the reader is directed to References 2, 3, and 4.

The choice of the I and Q color modulation components relates to the variation of color acuity characteristics of human color vision as a function of the field of view and spatial dimensions of objects in the scene. The color acuity of the eye decreases as the size of the viewed object is decreased and thereby occupies a small part of the field of view. Small objects, represented by frequencies above about 1.5 to 2.0 MHz, produce no color sensation ("mixed-highs"). Intermediate spatial dimensions (approximately 0.5- to 1.5 MHz range) are viewed satisfactorily if reproduced along a preferred orange-cyan axis. Large objects (0–0.5 MHz) require full three-color reproduction for subjectively pleasing results. Thus, the I and Q bandwidths are chosen accordingly and the preferred colorimetric reproduction axis is obtained when only the "I" signal exists by rotating the subcarrier modulation vectors by 33°. In this way, the principles of "mixed-highs" and "I, Q color-acuity axis" operation are exploited.

At the encoder, the "Q" signal component is band-limited to about 0.6 MHz and is representative of the green-purple color-axis information. The "I" signal component has a bandwidth of about 1.5 MHz and contains the orange-cyan color axis information. These two signals are then



		x	y
NTSC	R	0.67	0.33
	G	0.21	0.71
	B	0.14	0.08
PAL/SECAM	R	0.64	0.33
	G	0.29	0.60
	B	0.15	0.06
WHITE: NTSC (ILL. C)		0.310	0.316
PAL/SECAM (D6500)		0.313	0.329

Fig. 5. CIE chromacity diagram-system comparison.

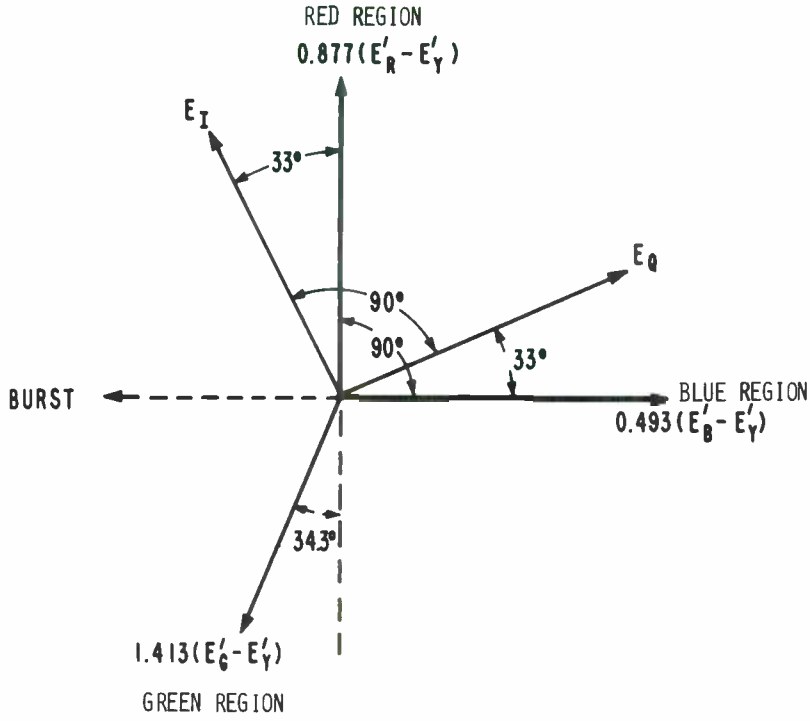


Fig. 6. NTSC color modulation phase diagram.

used to individually modulate the color subcarrier in two balanced modulators operated in phase quadrature. The "sum products" are selected and added to form the composite chromaticity subcarrier. This signal in turn is added to the luminance signal along with the appropriate horizontal and vertical synchronizing and blanking signals to include the color-synchronization burst. The result is the total composite color video signal.

Quadrature synchronous detection is used at the receiver to identify the individual color signal components. When individually recombined with the luminance signal, the desired R, G, and B signals are recreated. The receiver designer is free to demodulate either at I and Q and matrix to form $B-Y$, $R-Y$, and $G-Y$, or as in nearly all present-day receivers, at $B-Y$ and $R-Y$ and maintain 500-kHz equiband color signals.

The chrominance information can be carried without loss of identity provided that the proper phase relationship is maintained between the encoding and decoding processes. This is accomplished by transmitting a reference "burst" signal consisting of eight or nine cycles of the subcarrier frequency at a specific phase $[-(B-Y)]$ following each horizontal synchronizing pulse as shown in Fig. 7.

The specific choice of color subcarrier frequency in NTSC was dictated by at least two major factors. First, the necessity for providing horizontal interlace in order to reduce the visibility of the subcarrier requires that the frequency of the subcarrier be precisely an odd multiple of one-half the horizontal line rate. Fig. 8 shows the energy spectrum of the composite NTSC signal for a typical stationary scene. This interlace provides line-to-line phase reversal of the color subcarrier, thereby reducing its visibility (and thus

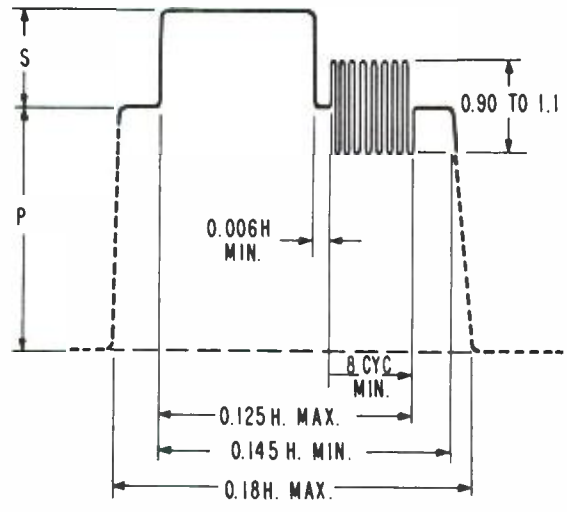


Fig. 7. NTSC color burst synchronizing signal.

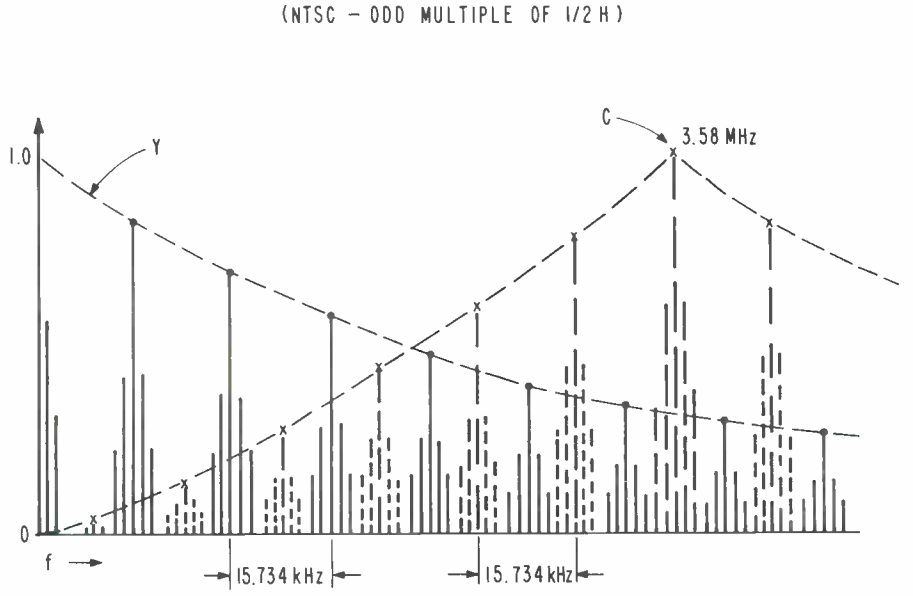


Fig. 8. Luminance/chrominance horizontal frequency interlace principle.

improving compatibility with monochrome reception). Second, it is advantageous to also provide interlace of the beat-frequency (about 920 kHz) occurring between the color subcarrier and the average value of the sound carrier. For total compatibility reasons, the sound carrier was left unchanged at 4.5 MHz and the line number remained at 525. Thus, the resulting line scanning rate and field rate varied slightly from that of the monochrome values, but stayed within the previously existing tolerances. A good rule of thumb is that the difference is exactly one part in a thousand. The exact specifications and method of calculating the frequencies are shown in Fig. 9.

CHOICE OF EXACT FREQUENCIES

$$f_{LINE} = \frac{4.5 \times 10^6}{286} \text{ cps} = 15{,}734.26 \text{ cps}$$

$$f_{FIELD} = \frac{f_{LINE}}{525/2} \text{ cps} = 59.94 \text{ cps}$$

$$f_{SC} = \frac{13 \times 7 \times 5}{2} \times f_{LINE}$$

$$f_{SC} = \frac{455}{2} \times f_{LINE}$$

$$f_{SC} = \frac{455}{2} \times \frac{4.5 \times 10^6}{286} \text{ cps}$$

$$= 3.579545 \text{ MHz}$$

Fig. 9. Calculation of NTSC specific line, field, and color subcarrier frequencies.

It is seen that the line rate is 15.734 kHz, the field rate is 59.94 Hz and the color subcarrier is 3.579545 MHz.

The NTSC system fundamentals have been reviewed in some detail since it was the first truly compatible system placed in commercial use and because the other systems subsequently proposed make use of most of the basic principles, differing mainly in the techniques of color encoding primarily to overcome early implementation difficulties.

PAL Color System

Except for some minor details, the color encoding principles for PAL are the same as those for NTSC. However, the phase of the color signal, $E_v = R - Y$, is reversed by 180° from line-to-line. This is done for the purpose of averaging, or cancelling certain color errors resulting from amplitude and phase distortion of the color modulation sidebands. Such distortions might occur as a result of equipment or transmission path problems.

The NTSC chroma signal expression within the frequency band common to both I and Q is given by

$$C_{NTSC} = \frac{B - Y}{2.03} \sin \omega_{sc} t + \frac{R - Y}{1.14} \cos \omega_{sc} t \quad [3]$$

The PAL chroma signal expression is given by

$$C_{PAL} = \frac{U}{2.03} \sin \omega_{sc} t \pm \frac{C}{1.14} \cos \omega_{sc} t \quad [4]$$

where U and $\pm V$ have been substituted for $B - Y$ and $R - Y$ signal values, respectively.

The PAL employs equal bandwidths for the U and V color-difference signal components which are about the same as the NTSC I signal bandwidth (1.3 MHz at 3 dB). There are slight differences in the U and V bandwidth in different PAL systems due to the differences in luminance bandwidth and sound carrier frequencies as discussed later under the heading of Summary and Comparisons. Reference is made to the CCIR documents[5] for specific details.

The *"V"* component was chosen for the line-by-line reversal process because it has a lower gain factor than *"U"* and therefore is less susceptible to switching rate ($\frac{1}{2} f_H$) imbalance. Figure 10 indicates the vector diagram for the PAL quadrature modulated and line-alternating color modulation approach.

The result of the switching of the V signal phase at the line rate is that any phase errors produce complementary errors from V into the U channel. In addition, a corresponding switch of the decoder V channel results in a constant V component with complementary errors from the U channel. Thus, any line-to-line averaging process at the decoder, such as the retentivity of the eye (simple PAL) or an electronic averaging technique such as the use of a 1-H delay element (standard PAL), produces cancellation of the phase (hue) error and provides the correct hue but with somewhat reduced saturation—this error being subjectively much less visible.

Obviously, the PAL receiver must be provided with some means by which the V signal switching sequence may be identified. The technique employed is known as A B sync, PAL sync, or "swinging burst" and consists of alternating the phase of the reference burst by $\pm 45°$ at a line rate as shown in Fig. 10. The burst is constituted from a fixed value of U phase and a switched value of V phase. Because the sign of the V burst component is the same sign as the V picture content, the necessary switching "sense" or identification information is available. At the same time, the fixed-U component is used for reference carrier synchronization.

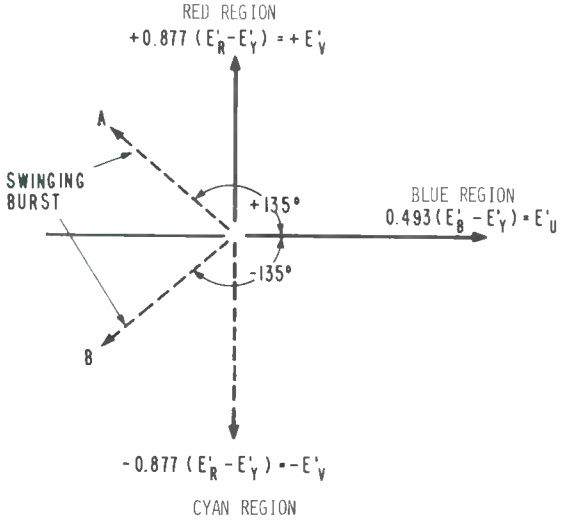


Fig. 10. PAL color modulation phase diagram.

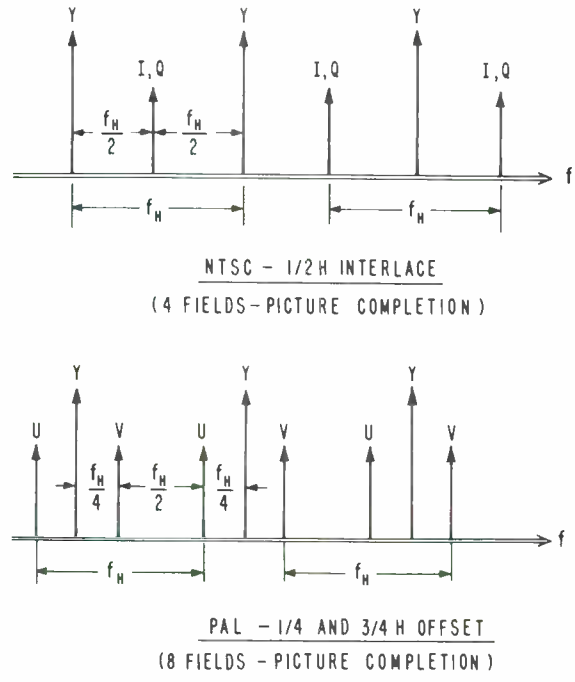


Fig. 11. NTSC and PAL frequency interlace relationship.

Figure 11 explains the degree to which horizontal frequency (dot) interlace of the color subcarrier components with the luminance components is achieved in PAL and may be summarized as follows: In NTSC, the Y components are spaced at f_H intervals due to the horizontal sampling (blanking) process. Thus the choice of a color subcarrier whose harmonics are also separated from each other by f_H (as they are odd multiples of $\frac{1}{2} f_H$) provides a half-line offset and results in a perfect "dot" interlace pattern that moves upward. Four complete field scans are required to repeat a specific picture element "dot" position.

In PAL, the luminance components are also spaced at f_H intervals. Because the V components are switched symmetrically at half the line rate, only odd harmonics exist, with the result that the V components are spaced at intervals of f_H. They are spaced at half-line intervals from the U components which, in turn, have f_H spacing intervals due to blanking. If half-line offset were used, the U components would be perfectly

interlaced but the V components would coincide with Y and thus not be interlaced, creating vertical, stationary dot patterns.

For this reason, in PAL, a ¼-line offset for the subcarrier frequency is used as shown in Fig. 11. The expression for determining the PAL subcarrier specific frequency for 625-line/50-field systems is given by

$$f_{SC} = \frac{1135}{4} f_H + \frac{1}{2} f_V \qquad [5]$$

The additional factor $\frac{1}{2}f_V$ = 25 Hz is introduced to provide motion to the color dot pattern thereby reducing its visibility. The degree to which interlace is achieved is therefore not perfect, but is acceptable, and eight complete field scans must occur before a specific picture element "dot" position is repeated.

One additional function must be accomplished in relation to PAL color synchronization. In all systems, the burst signal is eliminated during the vertical synchronization pulse period. Because, in the case of PAL, the swinging burst phase is alternating line-by-line, some means must be provided for ensuring that the phase is the same for the first burst following vertical sync on a field-by-field basis. Therefore, the burst reinsertion time is shifted by one line at the vertical field rate by a pulse referred to as the "meander" gate. The timing of this pulse relative to the A vs. B burst phase is shown in Fig. 12.

The transmitted signal specifications for PAL systems include the basic features discussed above. Although description of a great variety of receiver decoding techniques is outside the scope and intent of this paper, we should here review at least briefly the following major features: "Simple" PAL relies upon the eye to average the line-by-line color switching process and can be plagued with line beats call Hanover bars caused by the system nonlinearities introducing visible luminance changes at line rate. "Standard" PAL employs a 1-H delay line element to separate U color signal componenets from V color signal components in an averaging technique coupled with summation and subtraction functions. Hanover bars can also occur in this approach if imbalance of amplitude or phase occurs between the delayed and direct paths.

For an excellent discussion of the variety of other decoder approaches such as Chroma Lock, Super PAL, New PAL or PAL (not to be confused with N(PAL)), readers are referred to Vol. 2 of *Colour Television* by Carnt and Townsend.[3]

In a PAL system, vertical resolution in chrominance is reduced as a result of the line averaging processes. The visibility of the reduced vertical color resolution as well as the vertical time coincidence of luminance and chrominance transitions differs depending upon whether the total system, transmitter through receiver, includes one or more averaging (comb filter) processes.

Thus PAL provides a similar system to NTSC and has gained favor in many areas of the world, particularly for 625-line/50-field systems.

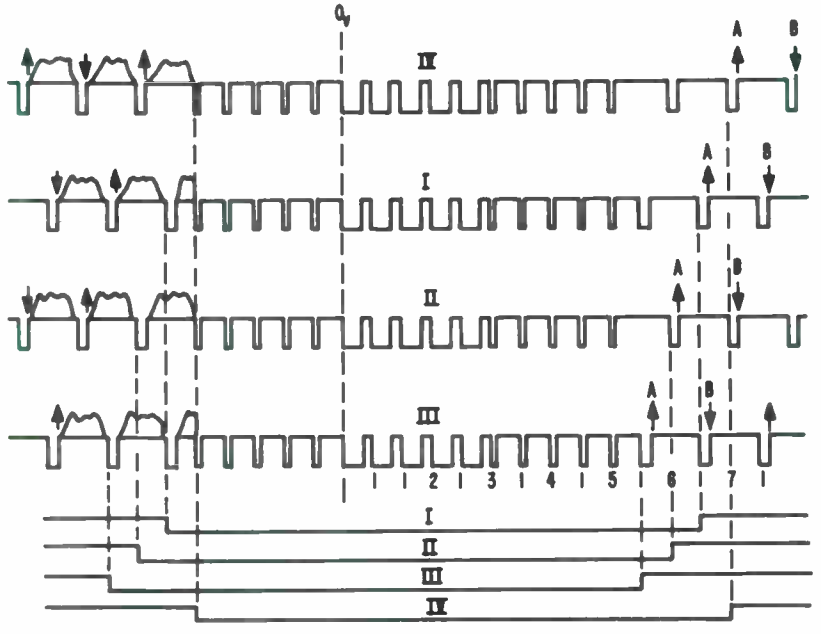


Fig. 12. PAL "meander" burst blanking gate timing diagram for *B, G, H,* and *I* PAL.

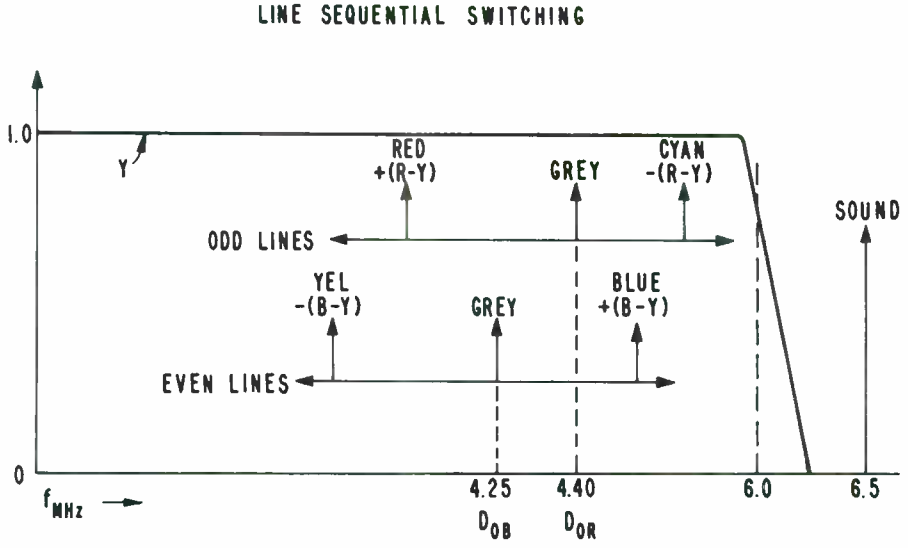


Fig. 13. SECAM FM color modulation system.

SECAM Color System

The "optimized" SECAM system, called SECAM III, is the system adopted by France and the USSR in 1967. The SECAM method has several features in common with NTSC such as the same E'_Y signal and the same $E'_B - E'_Y$ and $E'_R - E'_Y$ color-difference signals. However, this approach differs considerably from NTSC and PAL in the manner in which the color information is modulated onto the subcarrier(s).

First, the $R-Y$ and $B-Y$ color difference signals are transmitted alternately in time sequence from one successive line to the next—the luminance signal being common to every line. Since there is an odd number of lines, any given line carries $R-Y$ information on one field and $B-Y$ information on the next field. Second, the $R-Y$ and $B-Y$ color information is conveyed by frequency-modulation of different subcarriers. Thus, at the decoder, a 1-H delay element, switched in time synchronization with the line switching process at the encoder, is required in order to have simultaneous existence of the $B-Y$ and $R-Y$ signals in a linear matrix to form the $G-Y$ component.

The $R-Y$ signal is designated as D'_R and the $B-Y$ signal as D'_B. The undeviated frequency for the two subcarriers, respectively, is determined by

$$f_{0B} = 272 f_H = 4.250000 \text{ MHz}$$
$$f_{0R} = 282 f_H = 4.406250 \text{ MHz} \qquad [6]$$

These frequencies represent zero color difference information (zero output from the FM discriminator), or a neutral gray object in the televised scene.

As shown in Fig. 13, the accepted convention for direction of frequency change with respect to the polarity of the color difference signal is opposite for the D_{0B} and D_{0R} signals. A positive value of D_{0R} means a decrease in frequency whereas a positive value of D_{0B} indicates an increase in frequency. This choice relates to the idea of keeping the frequencies representative of the most critical color away from the upper edge of the available bandwidth to minimize the instrumentation distortions.

The deviation for D'_R is ± 280 kHz and D'_B is ± 230 kHz. The maximum allowable deviation, including preemphasis, for $D'_R = -506$ kHz and $+350$ kHz while the values for $D'_B = -350$ kHz and $+506$ kHz.

Two types of preemphasis are employed simultaneously in SECAM. First, as shown in Fig. 14, a conventional type of preemphasis of the low-frequency color difference signals is introduced. The characterisitic is specified to have a reference level break-point at 85 kHz (f_1) and a maximum emphasis of 2.56 dB. The expression for the characteristic is given as

$$A = \frac{1 + j(f/f_1)}{1 + j(f/3f_1)} \qquad [7]$$

A second for of preemphasis (Fig. 14) is introduced at the subcarrier level where the amplituded of the subcarrier is changed as a function of the frequency deviation. The expression for this inverted "bell" shaped characteristic is given as

$$G = M_0 \frac{1 + j16\left(\frac{f}{f_c} - \frac{f_c}{f}\right)}{1 + j1.26\left(\frac{f}{f_c} - \frac{f_c}{f}\right)} \quad [8]$$

Where:
f_0 = 4.286 MHz and $2M_0$ = 23% of the luminance amplitude (100 IRE).

This type of preemphasis is intended to further reduce the visibility of the frequency modulated subcarriers in low luminance level color values and to improve the signal-to-noise ratio in high luminance and highly saturated colors. Thus, monochrome compatibility is better for pastel average picture level objects but sacrificed somewhat in favor of S/N in saturated color areas.

Of course, precise interlace of frequency modulated subcarriers for all values of color modulation cannot occur. Nevertheless, the visibility of the interference represented by the existence of the subcarriers may be reduced somewhat by the use of two separate carriers, as is done in SECAM. Fig. 15 indicates the line-switching sequence in that at the undeviated "resting" frequency situation, the two-to-one vertical interlace in relation to the continuous color difference line-switching sequence produces adjacent line pairs of f_{0B} and f_{0R} signals. In order to further reduce the subcarrier "dot" visibility, the phase of the subcarriers (phase carries no picture information in this case) is reversed 180° on every third line and between each field. This, coupled with the "bell" preemphasis, produces

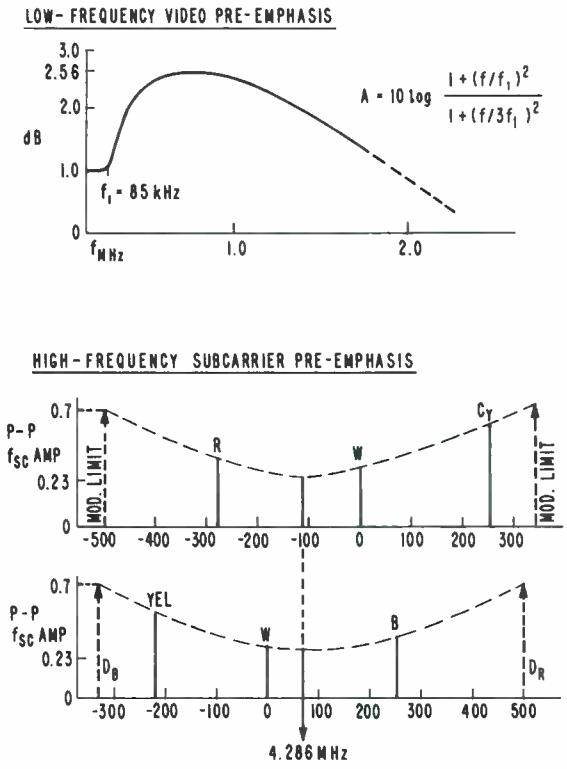


Fig. 14. SECAM color signal pre-emphasis.

a degree of monochrome compatibility considered subjectively adequate.

As in PAL, the SECAM system must provide some means for identifying the line-switching sequence between the encoding and decoding processes. This is accomplished, as shown in Fig. 16, by introducing alternate D_R and D_B color iden-

FIELD	LINE #	COLOR	SUBCARRIER Ø	
ODD (1)	n	f_{OR}	0°	
EVEN (2)	n + 313	f_{OB}		180°
ODD (3)	n + 1	f_{OB}	0°	
EVEN (4)	n + 314	f_{OR}		0°
ODD (5)	n + 2	f_{OR}	180°	
EVEN (6)	n + 315	f_{OB}		180°
ODD (7)	n + 3	f_{OB}	0°	
EVEN (8)	n + 316	f_{OR}		180°
ODD (9)	n + 4	f_{OR}	0°	
EVEN (10)	n + 317	f_{OB}		0°
ODD (11)	n + 5	f_{OB}	180°	
EVEN (12)	n + 318	f_{OR}		180°

Note: • 2 frames (4 fields) for picture completion.
• Subcarrier interlace is field-to-field and line-to-line of same color.

Fig. 15. Color vs. line and field timing relationship for SECAM.

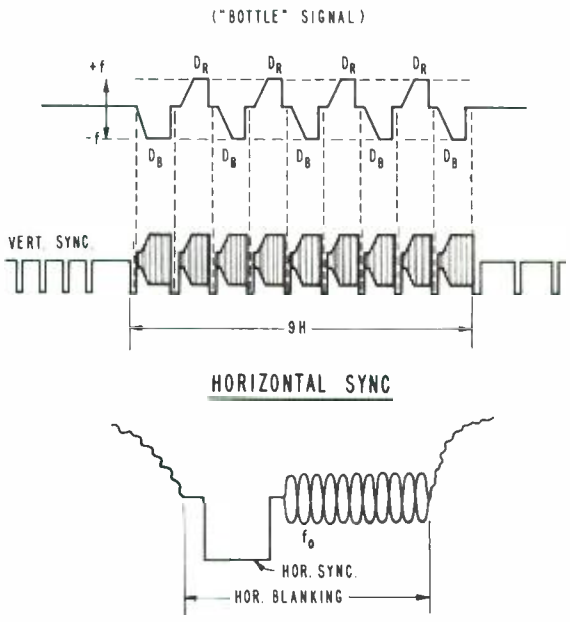


Fig. 16. SECAM line identification signal.

tifying signals for nine lines during the vertical blanking interval following the equalizing pulses after vertical sync. These "bottle" shaped signals occupy a full line each and represent the frequency deviation in each time sequence of D_B and D_R at zero luminance value. These signals can be thought of as fictitious green color that is used at the decoder to determine the line-switching sequence.

During horizontal blanking, the subcarriers are blanked and a burst of f_{0B}/f_{0R} is inserted and used as a gray level reference for the FM discriminators, to establish their proper operation at the beginning of each line.

Thus the SECAM system is a line sequential color approach using frequency modulated subcarriers. A special identification signal is provided to identify the line-switch sequence and is especially adapted to the 625-line/50-field wideband systems available in France and the USSR.

It should be noted that SECAM, as practiced, employs amplitude modulation of the sound carrier as opposed to the FM sound modulation in other systems.

Additional Systems of Historical Interest

Of the numerous system variations proposed over the intervening years since the potential development of the NTSC system, at least two others, in addition to PAL and SECAM, should be mentioned briefly. The first of the these was ART (Additional Reference Transmission) which involved the transmission of a continuous reference pilot carrier in conjunction with a conventional NTSC color subcarrier quadrature modulation signal. A modification of this scheme involved a "multiburst" approach that utilized three color bursts, one at black level, one at intermediate gray level, and one at white level, to be used for correcting differential phase distortion.

Another system, perhaps better known, was referred to as *NIR* or SECAM IV. Developed in the USSR (*NIR* = *N*auchni *I*ssledovatelskaia *R*abota or Scientific Discriminating Work), this system consists of alternating lines of (1) an NTSC-like signal using an amplitude and phase modulated subcarrier and (2) a reference signal having *"U"* phase to demodulate the NTSC-like signal. In the linear version the reference is unmodulated, and in the nonlinear version, the amplitude of the reference signal is modulated with chrominance information.

To the author's knowledge, neither ART nor NIR were ever implemented or used for commercial broadcast. Still, they are of theoretical and historical interest; details may be found in Ref. 3.

Summary and Comparisons of Systems Standards and Specifications

History has shown that it is apparently impossible to obtain total international agreement on "universal" television broadcasting standards. Even with the first scheduled broadcasting of monchrome television in 1936 in England, the actual telecasting started using two different systems on alternate days from the same transmitter. The Baird system was 250 lines (noninterlaced) with a 50 Hz frame rate while the EMI (Electric and Musical Industries) system was 405 lines (interlaced) with a 25 Hz frame rate.

These efforts were followed in 1939 in the United States by broadcasting a 441 line interlaced system at 60 fields per second (the Radio Manufacturers Association—RMA—system). In 1941, the NTSC initiated the present basic monochrome standards in the U.S. of 225 lines (interlaced) at 60 fields per second, designated as system M by the CCIR. In those early days, the differences in power line frequency were considered as important factors and were largely responsible for the proliferation of different line rates versus field rates as well as the wide variety of video bandwidths. However, the existence and extensive use of monochrome standards over a period of years soon made it a top-priority matter to assume reciprocal compatibility of any developing color system.

The CCIR documents[5] define recommended standards for worldwide color television systems in terms of the three basic color approaches—NTSC, PAL, and SECAM—as shown in Fig. 17. The variations —at least 13 of them—are given alphabetical letter designations; some represent

THREE BASIC SYSTEMS
- **NTSC**
- **PAL**
- **SECAM**

THIRTEEN VARIATIONS OR SUBSYSTEMS:
A*, M, N, C*, B, G, H, I, D, K, KI, L, E*

SYSTEMS A (405 LINES), C (625 LINES) AND E (819 LINES) NOT RECOMMENDED FOR NEW SERVICE*

98 COUNTRIES LISTED BY CCIR AS EMPLOYING ONE OR MORE SYSTEMS

Fig. 17. CCIR worldwide color television designations.

major differences while others signify only very minor frequency allocation differences in channel spacings or the differences betweeen the VHF and UHF bands. In 1978, at least 98 countries were listed as either employing or considering one or more of the proposed systems in monochrome and/or color format.

The key to understanding the CCIR designations lies in recognizing that the letters refer primarily to *local monochrome standards* for line and field rateds, video channel bandwidth, and audio carrier relative frequency. Further classification in terms of the particular color system then adds to NTSC, PAL, or SECAM as appropriate. For example, the letter "M" designates a 525-line/60-field, 4.2-MHz bandwidth, 4.5-MHz sound carrier monochrome system. Thus, M(NTSC) describes a color system employing the NTSC technique for introducing the chrominance information within the constraints of the above basic monchrome signal values. Likewise, M(PAL) would indicate the same line/field rates and bandwidths but employ the PAL color subcarrier modulation approach.

In another example, the letters "I" and "G" relate to specific 625-line/50-field, 5.0 or 5.5 MHz bandwidth, 5.5 or 6.0 Mhz sound carrier monochrome standards. Thus, G(PAL) would describe a 625-line/50-field,5.5 Mhz bandwidth, color system utilizing the PAL color subcarrier modulation approach. The letter "L" refers to a 625-line/50-field, 6.0 Mhz bandwidth system to which the SECAM color modulation method has been added (often referred to as SECAM III).

System E is an 819-line/50-field, 10 MHz bandwidth, monochrome system. This channel was used in France for early SECAM tests and for system E transmissions.

Some general comparison statements can be made about the underlying monochrome systems and existing color standards:

1. There are four different scanning standards: 405-lines/50-fields, 525-lines/60-fields, 625-lines/50-fields, and 819-lines/50-fields.
2. There are six different spacings of video-to-sound carriers, namely 3.5, 4.5, 5.5, 6.0, 6.5, and 11.15 MHz.
3. Some systems use FM and others use AM for the sound modulation.
4. Some systems use positive polarity (luminance proportional to voltage) modulation of the video carrier while others, such as the U.S. (M)NTSC system, use negative modulation.
5. As previously discussed, there are also differences in the techniques of color subcarrier encoding represented by NTSC, PAL, and SECAM, and of course, in each case there are many differences in the details of various pulse widths, timing, and tolerance standards. It is evident that one must refer to the CCIR documents for accurate information on the combined monochrome/color standards. Fig. 18 presents a comparison of the relative bandwidths, color subcarrier frequencies, and sound carrier spacing for the major color systems used in the world today.

The signal in the M(NTSC) system occupies the least total channel width, which when the vestigial sideband plus guard bands are included, requires a minimum radio frequency channel spacing of 6 Mhz. The L(III) SECAM system signal occupies greater channel space with a full 6 MHz luminance bandwidth. Signals from the tow ver-

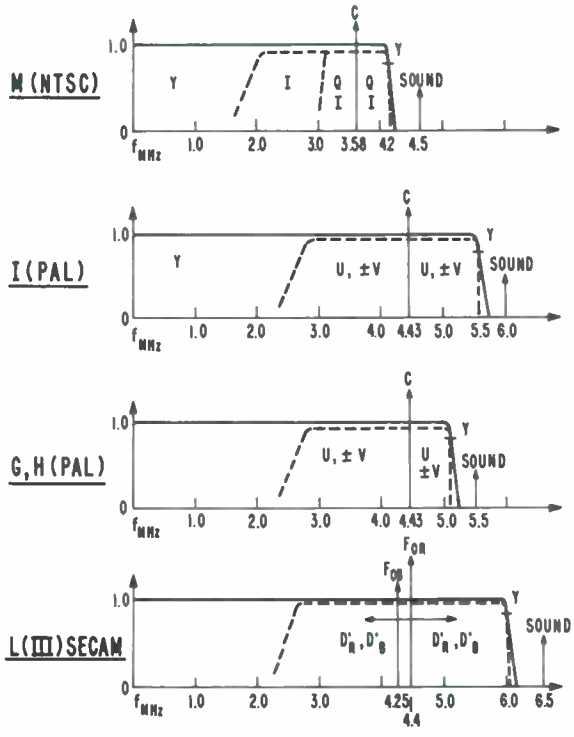


Fig. 18. Bandwidth comparison between NTSC, PAL, and SECAM.

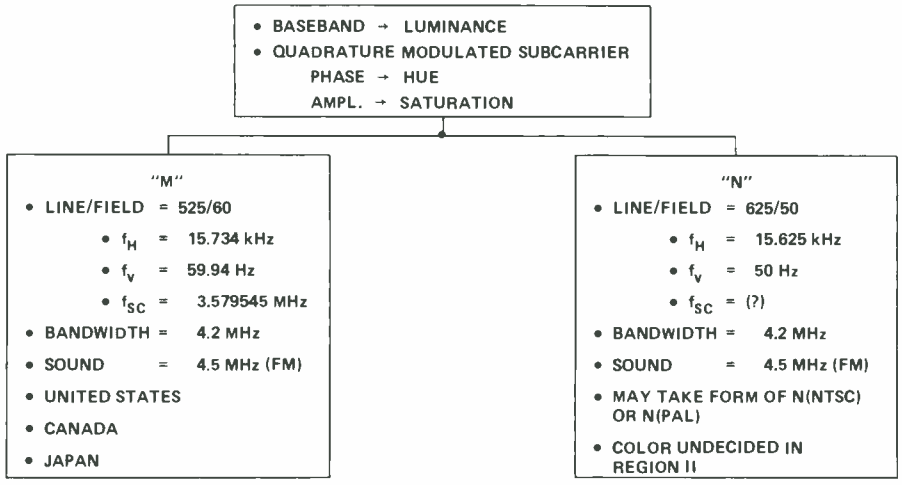


Fig. 19. CCIR designation for NTSC system—summary.

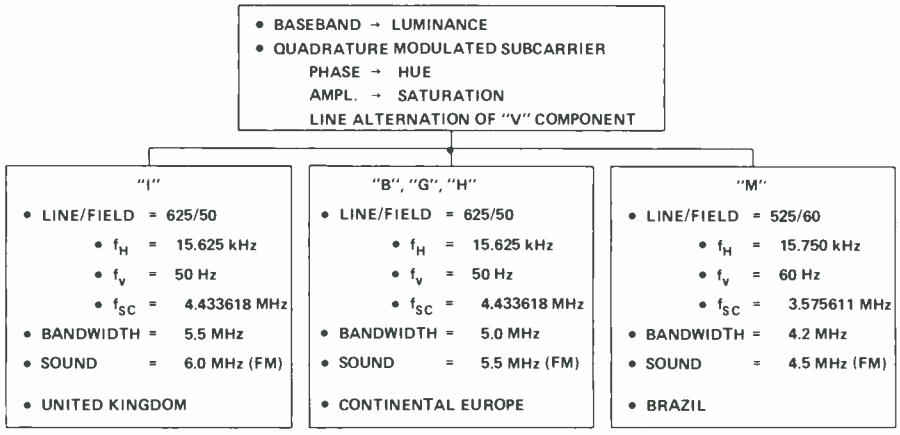


Fig. 20. CCIR designation for PAL system—summary.

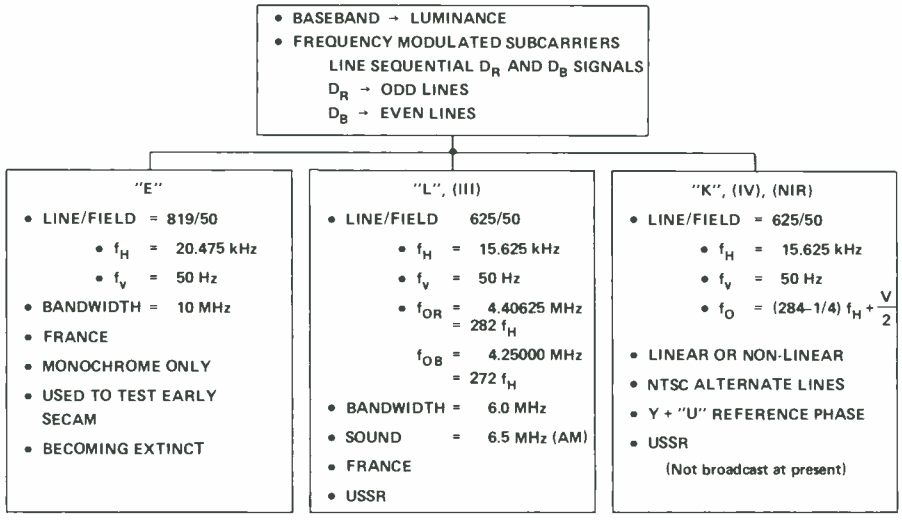


Fig. 21. CCIR designation for SECAM system—summary.

	NTSC	PAL	SECAM
TV SYSTEM	M	G, I	L
FIELD RATE (f_V Hz)	59.94	50	50
TV LINES	525	625	625
LINE RATE (f_H kHz)	15.734	15.625	15.625
LUMA BANDWIDTH (MHz)	4.2	(5.0) (5.5)	6.0
SOUND (MHz)	4.5 (F 3)	(5.5) (6.0) (F 3)	6.5 (A 3)
VERTICAL INTERLACE	2:1	2:1	2:1
GAMMA	2.2	2.8	2.8
WHITE	ILL. "C" (D6500)	D6500	D6500

Fig. 22. General system technical summary—Part I.

sions of PAL also occupy greater channel widths (though less than SECAM signal) and vary in vestigial sideband width as well as color and luminance bandwidths. NTSC is the only system to incorporate the *I, Q* color acuity bandwidth variation. PAL minimizes the color quadrature phase distortion effects by line-to-line averaging, and SECAM avoids this problem by only transmitting the color components sequentially at a line-by-line rate.

Figs. 19 through 24 summarize, in "organization chart" form, the CCIR designations for NTSC, PAL, and SECAM basic system identifications and characteristics. In Fig. 19, M(NTSC) identified the system used in the United States, Canada, Japan, Mexico, the Philippines and several other Central American and Caribbean area countries. The N system may be implemented in color either in the NTSC or the PAL format. At present, many Latin American countries are in the process of adopting one or the other version of this approach.[6] Fig. 20 provides a summary of the PAL systems. PAL systems in one or another of the 625-line formats are predominately used in Continental Europe, the United Kingdom, some African countries, and China. An "M" (525-line) version of PAL has been in use in Brazil.

Fig. 21 summarizes the SECAM III system, which is in use primarily in France and the USSR. The SECAM IV system, as a proposal,[1] almost gained favor in 1966 as a universal European approach but to the authors' knowledge has never been used for normal broadcasting. The E system, mentioned in connection with early SECAM tests in France, is limited to monochrome broadcasts and is slowly becoming extinct even in this application.

	NTSC	PAL	SECAM
COLOR SUBCARRIER (MHz)	3.579545	4.433618	4.250000 = f_{OB} 4.406500 = f_{OR}
f_{SC} MULTIPLE OF f_H	$\frac{455}{2} f_H$	$\frac{1135}{4} f_H + \frac{f_v}{2}$	272 f_H = f_{OB} 282 f_H = f_{OR}
CHROMA ENCODING	PHASE & AMP. QUAD. MOD.	PHASE & AMP. QUAD. MOD. (LINE ALTERNATION)	FREQUENCY MODULATION (LINE SEQUENTIAL)
COLOR DIFFERENCE SIGNALS	I, Q, (1.3 MHz) (0.6 MHz)	U, ± V (1.3 MHz) (1.3 Mhz)	D_R (f_{OR}) (> 1.0 MHz) D_B (f_{OB}) (> 1.0 MHz)
COLOR BURST PHASE	-(B-Y)	U and ± V	f_{OR} AND f_{OB} 180° PHASE SWITCH EVERY 3rd LINE AND EVERY FIELD
COLOR SWITCH IDENT.	NOT REQUIRED	SWINGING BURST ± 45°	9 LINES OF D_R AND D_B DURING VERTICAL INTERVAL
ADDITIONAL SIGNALS	NONE	"MEANDER" GATE $f_{H/2}$	$f_{H/2}$, $f_{H/4}$, f'_v, $f_{v/2}$

Fig. 23. Chrominance encoding systems comparison—Part II.

Fig. 22 (Systems Comparison Summary—Part I) provides a "summary-at-a-glance" of the major color television system general characteristics as presently practiced, whether it be monochrome only or including the addition of chrominance information. Fig. 23 (Part II) characterizes the fundamental features relating to the differences between NTSC, PAL, and SECAM in the critical areas of color encoding techniques. Similarily, Fig. 24 (Part II) indicates the color encoding line-by-line color sequence operation for the three systems.

The information conveyed in these last seven charts (Fig. 18-24) highlights the technical equalities and differences among the systems and attempts to show some kind of order as an aid to understanding the existing worldwide situation. It serves as well to point out the difficulties of entertaining the notion of a "universal" system.[7]

Comments on International Exchange of Images

The international exchange of images in broadcast television in the face of the variety of standards is difficult. It should be remembered that all TV systems, both monochrome and color, can be operated from movie film. Special television camera chains have been developed and manufactured that are capable of operating at 655-lines and 48-field rate—the field rate purposely being made to be compatible with the 24-frame rate motion picture standards.

It is comparatively straightforward to exchange television program material by tape, microwave, or satellite between areas employing the same scanning rates: the video bandwidths are, of course, not equivalent but the differences do not result in major image degradation. Electronic standards converters have been developed and used for converting between 50-fields/s and 60 fields/s systems.

The direct exchange of color television programs between the three major systems is obviously more complex. Special transcoding systems have been developed to translate color subcarrier frequencies between similar color systems having different scanning rates. More complex transcoders are possible which translate from one color technique to another, although always at the cost of some degradation of resolution or reduction of performance. Even simultaneous translation between different scanning rates and different color systems, such as between 525-line NTSC and 625-line PAL, has been accomplished.

As previously stated, the advent of satellite worldwide television relay, coupled with recent advances in digital processing of television signals, has given new importance to standards conversion relative to the exchange of program material on an international basis. Thus, the intent of this worldwide color systems standards review is to highlight the similarities as well as the major differences for those who desire an overview of the related television concepts and standards. A thorough understanding of those concepts and standards by many people is essential if effective international exchange of programming is to grow.

Acknowledgements

The authors would like to acknowledge the aid and suggestions provided by A. Lind of the RCA Broadcast Products Division, and are especially

	LINE (N)	LINE (N + 1)	LINE (N + 2)	LINE (N + 3)
NTSC:				
CHROMA:	I, Q	I, Q	I, Q	I, Q
BURST PHASE:	-(B-Y)	-(B-Y)	-(B-Y)	-(B-Y)
PAL				
CHROMA:	$U_1 + V$	$U_1 - V$	$U_1 + V$	$U_1 - V$
BURST PHASE:	$-U + V = +135°$	$-U - V = +225°$	$-U + V = +135°$	$-U - V = +225°$
SECAM: (FM)				
CHROMA:	$D_R \pm 280$ kHz	$D_B \pm 230$ kHz	$D_R \pm 280$ kHz	$D_B \pm 230$ kHz
BURSTS:	(D_R DEVIATION = $^{+350\text{ kHz}}_{-500\text{ kHz}}$)		(D_B DEVIATION = $^{+500\text{ kHz}}_{-350\text{ kHz}}$)	

CHROMA SWITCH IDENT. LINES DURING VERTICAL INTERVAL

LINE #:	7	8	9	10	11	12	13	14	15
	320	321	322	323	324	325	326	327	328
INDENT SIGNALS:	D_R	D_B	D_R	D_B	D_R	D_B	D_R	D_B	D_R

(NOTE: Phase reversed 180° every 3rd line and every field).

Fig. 24. Line-to-line chroma signal sequence comparison—Part III.

grateful for the assistance and information provided by R. Mills and E. Rutishauser of the Laboratories RCA Ltd., Zurich.

REFERENCES

1. J. W. Herbstreit and J. Pouliquen, "International Standards for Color Television," *IEEE Spectrum*, March 1967.
2. Donald G. Fink (Ed.), *Color Television Standards*, McGraw-Hill Book Co., New York, 1955.
3. P. S. Carnt and G. B. Townsend, *Colour Television—Volume 1: NTSC; Volume 2: PAL and SECAM,* ILIFFE Bookes Ltd. (Wireless World), London, 1969.
4. D. H. Pritchard, "U.S. Color Television Fundamentals—A Review," *SMPTE Journal,* 86: 819/828, November 1977.
5. "CCIR Characteristics of Systems for Monochrome and Colour Television—Recommendations and Reports," Recommendations 470-1 (1974-1978) of the Fourteenth Plenary Assembly of CCIR in Kyoto, Japan, 1978.
6. C. J. Hirsch, "Color Television Standards for Region 2," *IEEE Spectrum,* February 1968.
7. J. Roizen, "Universal Color Television: An Electronic Fantasia," *IEEE Spectrum,* March 1967.

7.2

Using Operational Amplifiers in Broadcasting

William B. Sacks
President,
Straight Wire Audio, Inc.
Arlington, Virginia

This chapter is a brief, practical guide for the broadcast engineer in the use of operational amplifiers, or "opamps". Understanding the opamp, which has been the fundamental building block of broadcast audio equipment since the mid-1970s, provides a basic understanding of how most analog audio equipment in a modern broadcast facility operates.

The operational amplifier concept is essentially one of a truly universal amplifier, shown schematically as a triangle with a differential input and single-ended output, whose operational characteristics are determined soley by feedback provided by external components. The original opamps were developed as universal computational blocks for use in analog computers and performed many functions including addition, subtraction, inversion, differentiation, and integration. These first opamps were built with vacuum tubes so that reliability and stability were not very good. Integrated circuit opamps first appeared commercially in the 1960's at which time the concept of a universally insertable, standardized amplifier for computational blocks had already evolved. The ideal characteristics of these standardized amplifiers were and are:

Infinite gain;

Infinite bandwidth (dc to daylight);

Perfectly balanced differential input with infinite common mode rejection;

Infinite input impedance (zero input current);

Zero output impedance, a true voltage source with infinite output current capability;

Zero dc offset;

Low cost.

The ideal characteristics described above are not available in the real world; but technology continues to improve and sometimes the deviation from the ideal becomes almost inconsequential. This is true for certain low noise and low offset input stages and certain high current output stages. Unfortunately the average piece of broadcast equipment is not constructed with these enhanced opamps.

Lack of adequate open loop gain bandwidth and excessive loading of output stages are common problems in broadcast equipment made with opamps. The earliest broadcast equipment built with opamps has to be upgraded to keep the facility competitive. By carefully following the recommendations in this chapter, older broadcast equipment can be made to sound competitive with, if not better than, some new broadcast equipment.

The opamps commonly encountered in broadcast equipment are monolithic integrated circuits (ICs), although some are hybrids. There are also some made with discreet components, such as the JE 990, and various potted opamps from companies such as Datatronics (API), Modular Audio

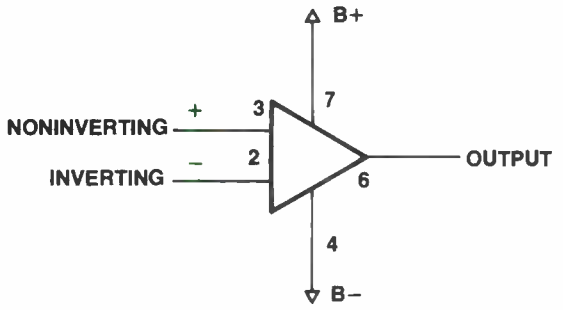


Fig. 1. Standard "741" pin connections.

Products, and Melcor (no longer produced). These discreet component modules, for the most part, have better input noise figures and lower output impedances than monolithic ICs. Many times broadcast products are built with monolithic opamps supporting a discreet output stage, which is considered to be part of the opamp triangle even though it is not shown that way on the schematic. It is also common to have a discreet low noise input stage (also considered to be part of the triangle), either FET or bipolar, to improve the noise performance of a monolithic (IC) opamp.

These low noise differential input stages should also be considered as part of the triangle unless they are very special open-loop differential input stages used for esoteric applications. Unless the input stage is this kind of open loop front end or, the circuit is designed as an oscillator, the feedback will appear only on the inverting input.

Monolithic opamps have become somewhat standardized in terms of their pin connections. The most common arrangement for single opamp devices is known as the "741 pinout" shown in Fig. 1.

Our illustrations will use this pinout for convenience. The unity gain noninverting voltage follower shown in Fig. 2 is the simplest opamp configuration in terms of component count. R_{bias} provides the reference operating voltage for the stage, bias current to the input transistor of the opamp, and sets the input impedance of the stage, since it is in parallel with the noninverting input which, in this configuration, has a theoretically infinite input impedance. There is a direct connection without attenuation from the output to the inverting input which provides 100% negative feedback, forcing the output voltage to follow the input voltage exactly. This configuration is useful as an impedance buffer since the input impedance is infinite (actually, the normally high value of R_{bias}) and output impedance is theoretically zero and is in actual practice a very low value.

A non-inverting amplifier with gain is shown in Fig. 3. The stage voltage gain is set by the ratio of R_{fb} plus R_{in} divided by R_{in}. This formula assumes that the open loop voltage gain of the opamp is more than the voltage gain called for by the divider, as do all of the formulas for gain. The input and output impedance characteristics and value of R_{bias} are essentially the same as the noninverting voltage follower configuration.

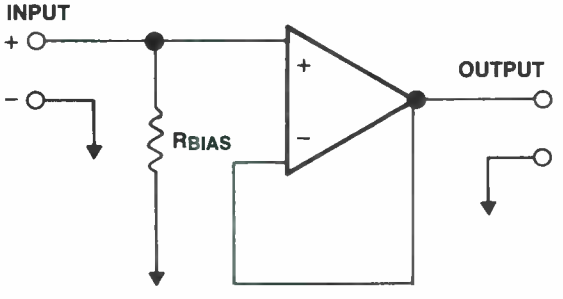


Fig. 2. The simplest opamp configuration is the noninverting voltage follower.

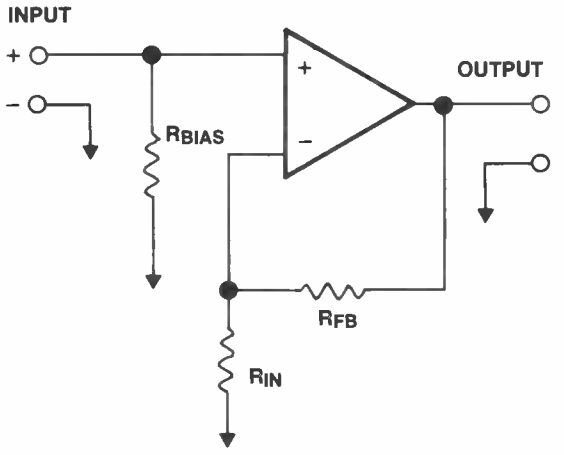


Fig. 3. This noninverting amplifier has voltage gain which is determined by the input and feedback resistor values.

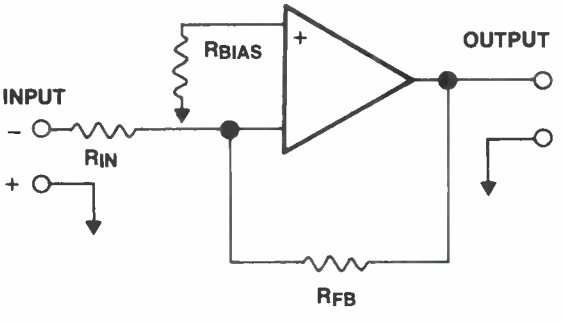


Fig. 4. The output of this amplifier is inverted. Source impedance affects gain as a component of R_{IN}.

The inverting amplifier is shown in Fig. 4. The gain of this stage is the feedback resistor divided by the input resistor. This gain formula assumes a zero source impedance signal driving the circuit. Any output series resistance of the driving stage must be added to the value of R_{in} when calculating amplifier gain. Feeding this circuit directly with a reactive source such as a transformer, dynamic microphone, tape head, or phono cartridge will cause frequency response errors because the source output resistance changes with frequency. The stage's input impedance is approximately equal to the input resistor, since the inverting input with feedback applied is a "virtual ground." It is called a "virtual ground" because all the signal currents in the circuit meet here to produce zero (or very close to zero) signal voltage. This is also referred to as the "summing point." The actual impedance of this virtual ground is the feedback resistor divided by the product of the open-loop gain (which varies with frequency) and the closed loop gain.

Notice that, once again, the noninverting input is connected to ground through R_{bias}, which in this configuration, has no effect on the voltage gain of the stage. The value of R_{bias} should be the parallel resistance of R_{in} and R_{fb} in order to minimize undesirable dc shifts on the output caused by input offset. Many times in broadcast audio equipment applications where dc parameters are not critical, R_{bias} is omitted and the noninverting input is brought directly to ground. Sometimes R_{bias} will have a capacitor in parallel with it. This is to shunt the small amount of ac noise generated in the resistor to ground. Without the capacitor, this resistor's ac noise would be amplified along with the desired signal. This problem is particularly troublesome in high impedance circuits.

The most basic differential input opamp configuration is shown in Fig. 5. This circuit appears in a wide variety of broadcast equipment misnamed "active balanced input". It is a differential input, but it is not balanced to ground. The input impedance of the MINUS input is the value of R1 (plus the actual summing point impedance, see the description of the inverting amplifier, above). The input impedance of the PLUS input is R1 plus R2. This circuit therefore creates a longitudinal imbalance to any line across which it is placed. The voltage gain of the circuit is equal to the ratio of R2 divided by R1. R1 must match R1' as closely as possible and, similarly, R2 must match R2'. The degree of matching of these resistors is the primary determinant of common mode rejection ratio (CMRR). Allowing one percent deviation in the value of these resistors could result in a common mode rejection ratio of only 40 dB. One tenth of 1% deviation in resistor value matching provides a common mode rejection

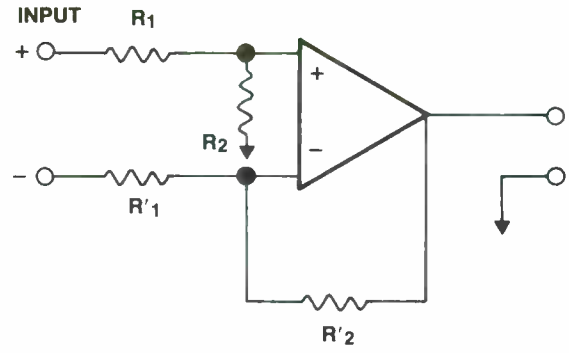


Fig. 5. This basic differential input amplifier is often mislabeled as "balanced."

ratio of 60 dB. As in the above circuit, these figures are based on the assumption that the circuit is fed by a perfectly balanced source exhibiting a very low output impedance. For this reason this circuit should not be used to bridge outside circuits coming into the broadcast facility such as telephone lines. It is, however, an ideal alternative to unbalanced wiring within a control room where there are relatively short interconnections and known driving sources.

The circuit in Fig. 6 is known as an instrumentation amplifier with a cross-coupled differential preamplifier which has a true electronically balanced input. It is a logical progression of the basic differential input amplifier in Fig. 5. The input impedance is fully symmetrical to ground and is set by the values of R_{bias} and R_{bias}' which is matched to R_{bias}'. Their matching determines the symmetry of the input. The circuit common mode rejection is not affected by minor longitudinal imbalances of the line feeding it because of the impedance buffering action of U1

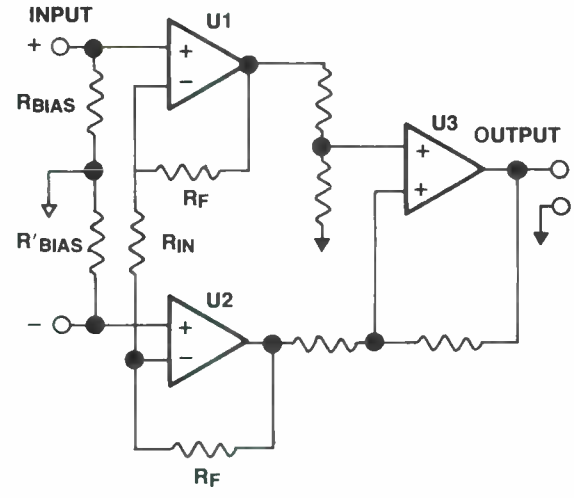


Fig. 6. In this configuration, the differential inputs are balanced and cross-coupled.

and U2. The circuit around U3 is identical in operation to Fig. 5 but since it is fed directly from the outputs of U1 and U2, common mode rejection characteristics are controlled, making the use of a laser trimmed resistor network a practical means of optimizing common mode rejection. The differential gain of the first stage is R_{in} plus $2R_f$ divided by R_{in}, but the common mode gain of this stage remains unity for all values of differential gain. This characteristic of cross coupling the summing points with a single input resistor using opposite summing points as returns, combines synergistically with the impedance buffering characteristics of the two opamps in front of the differential amplifier to provide levels of common mode rejection ratio beyond what can be offered with transformers (until input overload occurs). Another advantage of this configuration for broadcast audio applications is that the input impedance of the stage is set by the value of R bias because both inputs are noninverting opamps with a theoretical input impedance of infinity. A very high impedance, absolutely balanced bridging circuit can be achieved using this technique, allowing many inputs to be simultaneously connected to the same low impedance balanced program line without loading or disturbing the balance of the line. The line noise will remain low assuming a near zero source impedance of an active differential drive. Please note that the traditional 600 ohm line impedance power transmission system can be interfaced with these circuits if required. The system that we are describing here is known as a Voltage Transmission System and has better noise immunity that the traditional 600 ohm power transmission system. The Voltage Transmission System with its low source impedances and high input impedances is capable of extremely large fanouts, i.e. a considerable number of equipment inputs can be driven with one program source without loading considerations. Maintaining ground symmetry (balance) is the most important consideration in a Voltage Transmission System and the cross-coupled input preamplifier differential configuration (the three opamp instrumentation amplifier described above) is an essential element in building large systems. The simple differential input consisting of a single opamp and four resistors is adequate for smaller systems with just a few inputs connected to each output and short, predictable cable runs.

The circuit shown in Fig. 7 is an optimal driver for the balanced line system described above. U1 provides an unbalanced input with high impedance (set by R_{bias}) and provides impedance buffering for U3 and input bias for U2. U1 can also be configured as a gain stage by adding the appropriate feedback divider network. Opamp U2 is a noninverting unity gain buffer with an output source impedance of R_{output}. U3 is configured as a unity gain inverting amplifier, R_{in} equals R_f. The output source impedance of U3 is determined by R_{output}. The differential output impedance is twice the value of R_{output}. R_{output} should be closely matched to R_{output}' for best line balance. The value of R_{output} is chosen to be the minimum amount necessary to isolate the output stage of the opamp from the reactive effects of the line. A good practical value for R_{output} in a typical broadcast plant when using opamps such as 5534s into 22 AWG twisted shielded pairs is approximately 60 ohms, producing a differential source impedance of 120 ohms. This value assumes terminations with cross-coupled differential amplifiers such as Fig. 6 with R bias values 10k ohms or higher and no 600 ohm terminations across the line. When the output impedance of the driving stage is known to be low, a more practical and commonly found implementation of Fig. 7 is shown in Fig. 8. U1 is a unity gain noninverting amplifier and U2 is a unity gain inverting amplifier.

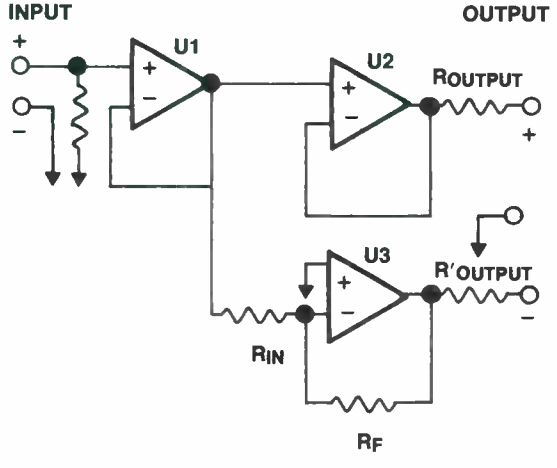


Fig. 7. Ideal differential output stage.

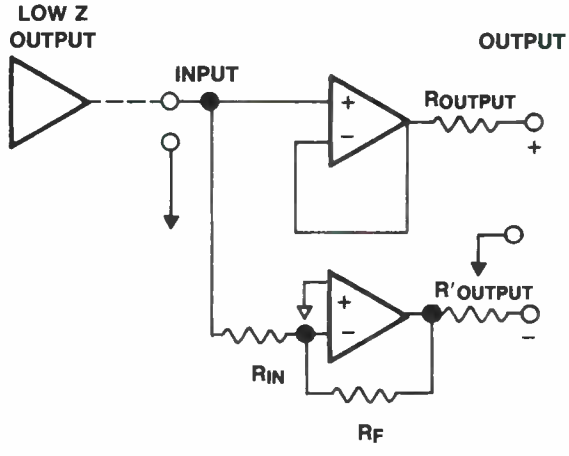


Fig. 8. Practical differential output stage.

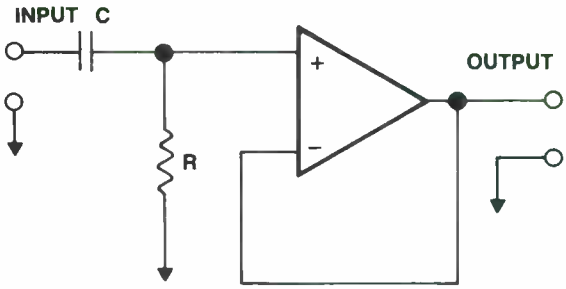
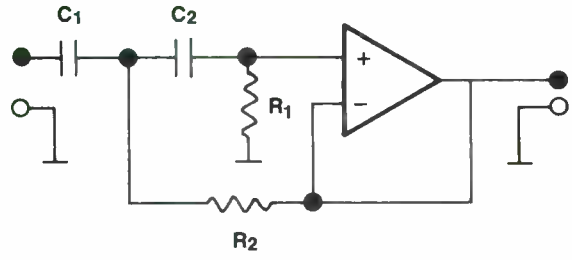


Fig. 9. High pass filter, single pole.



$$F_c = \frac{1}{2\pi C_1 (R_1 \cdot R_2)^{1/2}}$$

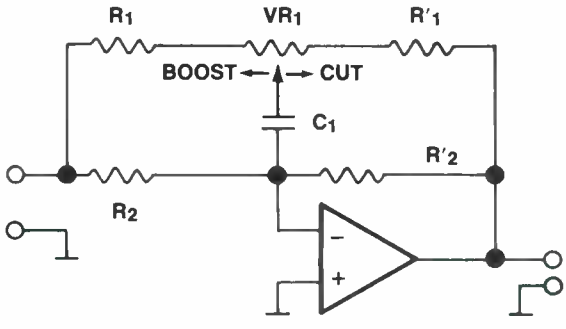
$C_1 = C_2$, $R_2 = .5 \cdot R_1$

Fig. 10. High pass filter, two pole.

ACTIVE FILTERS AND EQUALIZERS

Another common use of opamps in broadcast equipment is shaping program frequency response, phase delay or both. The IC opamp, with its small package, low price, good availability, and simple operating rules, has made the realization of very complex active networks a practical reality. The high input impedance and low output impedance of the opamp make it ideal for assisting in virtually every filter application, from being an impedance buffer stage to simulating the energy storage characteristics of bulky inductors. Fig. 9 illustrates the most basic opamp filter application as an impedance buffer. The high pass filter configuration consisting of C and R will exhibit the ideal charateristics of the formula shown without loading interaction caused by the next stage's input impedance.

Fig. 10 illustrates a second order high pass filter which is realized without the use of inductors. The opamp serves not only as a buffer but simulates the energy storage of the inductive element. Its resonant frequency calculation is shown with the illustration. Transposing the R and C elements produces a low pass filter. Basic shelf-type tone controls with a 20 dB boost or cut are shown in Fig. 11. The circuits in Fig. 12 illustrate the manipulation of phase without affecting frequency response. This configuration is also known as a first order (or single pole) all-pass filter. Multiple pole all-pass filters are sometimes referred to in the broadcast plant as phase scramblers and are used to process an audio signal



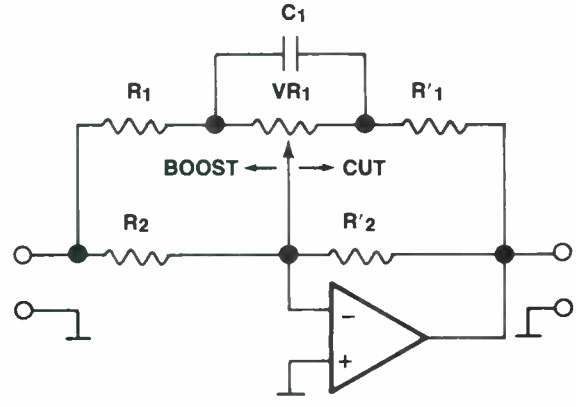
MAX BOOST OR CUT $= \frac{R_2 || VR_1}{R_1 || R_2}$

$$F = \frac{1}{2\pi R_2 C_1}$$

BASS $R_2 = R'_2$ $R_1 = R'_1$

$R_2 = 10 \cdot R_1$ $VR_1 = 5 \cdot R_2$
FOR 20 dB BOOST OR CUT

Fig. 11A. Shelf-type tone control: bass.



$$F = \frac{1}{2\pi R_1 C_1}$$

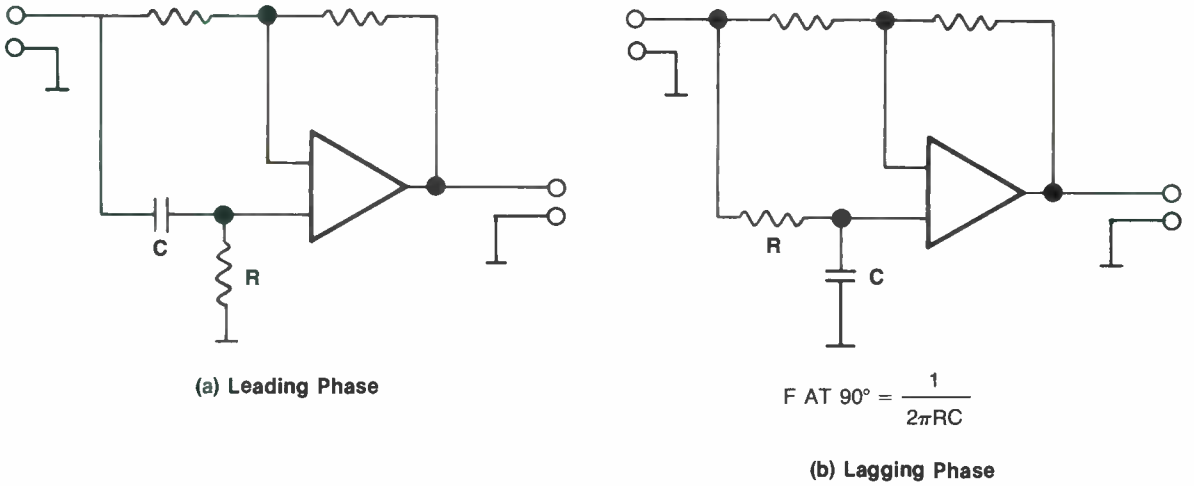
$R_1 = R'_1$

$R_2 = R'_2$

FOR 20 dB BOOST OR CUT: $VR_1 = 5 \cdot R_2$, $R_2 = 10 \cdot R_1$

MAX BOOST OR CUT $= \frac{R_2 || VR_1}{R_1 || R_2}$

Fig. 11B. Shelf-type tone control: treble control.



(a) Leading Phase

(b) Lagging Phase

Fig. 12. All pass filters, single pole.

so that the peaks are symmetrical about the base line of the signal. The first phase-scrambler packaged for use in broadcast plants was the Kahn Symmetra Peak introduced in the 1960s. The Symmetra Peak is a multi-pole passive all pass filter.

A full discussion of active filter techniques is beyond the scope of this chapter. Please see suggested readings below.

IMPROVING OLDER EQUIPMENT

Broadcast equipment produced with the first generation of monolithic opamps sounds inferior to the last commercial generation of vacuum tube broadcast equipment. As of this writing some manufacturers are still using first generation monolithic opamps, but this equipment can be upgraded by the broadcast engineer in the field for relatively low cost. Monolithic opamps have, for the most part, maintained the basic pinouts of earlier generations. The most common single-circuit-per-package 8 pin mini-DIP pinout is known in the industry as the 741 pinout. Some of the more common first generation device numbers in this single package genre which exhibit poor performance and should be replaced are 741, 301, 310, MC1456, CA3140, and OP-01. An exception to this replacement rule is the 318/518 opamp which is still considered an excellent device by today's standards.

The 741 pinout is usually followed for round can packages, sometimes referred to with a "T" suffix in the part number. All of these devices employ Pin 3 for the noninverting input, Pin 2 for the inverting input, and Pin 6 for the output. The power supply connections are positive to Pin 7 and negative to Pin 4. There is some variation in dc offset adjustment and frequency compensation techniques. Many broadcast audio circuits will use opamps without external frequency compensation or dc offset nulling, so that the devices listed below can generally be inserted without any circuit changes (other than the occassional requirement of additional high frequency bypass capacitors at the appropriate IC pins should the original circuit be deficient in this area). Caution should be taken and manufacturer's specification sheets should be consulted before replacing any operational amplifier IC in a circuit which has frequency compensation or an offset nulling potentiometer.

Two general types of plug-in replacements are available for the 741 pinout devices. Circuits which require low bias current, i.e. operate with a high impedance input circuit, and are driving a load which is greater than 2,000 ohms benefit from the use of commonly available BiFET (Field Effect Transistor input stage with a Bi-polar output stage) devices such as the TLO71, TLO81, or LF351. These BiFET devices are inexpensive, have high slew rates, and are audibly superior to the opamps they are replacing, but have poor dc performance and are relatively noisy (high 1/F noise figures). The LF411 and AD611 types are more costly but offer much improved dc performance when this parameter is important. When optimum noise performance and the ability to drive low impedance loads are requirements, the NE5534 bipolar input devices are the best choice. For best stability, the 5534 must be compensated with a 22 pF capacitor between Pins 8 and 5 when the circuit has an ac voltage gain of less than 3 (10 dB). Ceramic capacitors are not recommended for audio applications. Some other high performance bipolar input devices include the OP27, OP37, and the AD518.

Replacing single package dual opamp devices listed below on a pin for pin basis is much easier than the single opamp per package devices because compensation and offset pins are not available in these packages. The original dual 8 pin minidip packaged devices are the MC1458, MC4558, and CA3240. The pinout for this family is: first amplifier—noninverting input Pin 3, inverting input Pin 2, first amplifier output Pin 1. Second amplifier - noninverting input Pin 5, inverting input Pin 6, second amplifier output pin 7. Power supply connections are positive on Pin 8, negative to Pin 4. Some of the dual BiFET replacements are TLO72, TLO82, and LF353.

There are two standard pinouts for quad opamps in a 14 pin package. All 14 pin quads are internally compensated. Some early quad devices with the same pinout are the HA4741, HA4605, and the OP11. The positive supply is Pin 4, the negative supply (sometimes ground) is Pin 11. The first opamp uses Pin 2 for its inverting input, Pin 3 for the noninverting input, and Pin 1 as its output. The second opamp uses Pin 6 for its inverting input, Pin 5 for its noninverting input, and Pin 7 for its output. The third opamp uses Pin 9 for its inverting input, Pin 10 for its noninverting input and pin 8 for its output. The fourth opamp in this package has its inverting input appearing on Pin 13, its noninverting input on Pin 12, and its output on Pin 14. To improve the performance of earlier equipment, these quads can be pin for pin replaced with the TL074 and LF347 BiFET opamps. The other popular quad pinout is known as the 4136 pinout which can be directly replaced by the TLO75 quad BiFET. The 4136 pinout is as follows: the first opamp's inverting input is Pin 1, its noninverting input is Pin 2, and its output is Pin 3. The second opamp uses Pin 6 for its inverting input, Pin 5 for its noninverting input and Pin 4 for its output. The third opamp employs Pin 8 for its inverting input, Pin 9 as its noninverting input, and Pin 10 for the output. The inverting input of the fourth opamp is connected to Pin 14, Pin 13 is the noninverting input and the output of the fourth opamp appears on Pin 12. The positive supply is applied to Pin 11 and the negative supply (sometimes ground) is connected to Pin 7.

It is also a good idea to install sockets when changing opamps, if no socket was in the original equipment. This brief treatment of opamps should give you a base to work from. Some additional reading material is referenced below for those interested in further pursuing the subject.

SELECTED BIBLIOGRAPHY ON OP AMPS

1. *IC Op-Amp Cookbook* by Walter Jung, Howard Sams & Co., Second Edition, 1980, down-to-earth and practical paperback.
2. *Linear Integrated Circuit Applications* by George B. Clayton, The Macmillan Press Ltd., London, 1975.
3. *Modern Operational Circuit Design,* by J. I. Smith, John Wiley & Sons, Inc., 1971.
4. *Nonlinear Circuits Handbook,* edited by D. H. Sheingold. 1976. Analog Devices, Box 796, Norwood, MA 02062.
5. *Operational Amplifiers and Linear IC's,* by R. F. Coughlin and F. F. Driscoll, Prentice-Hall, Second Edition, 1982, Practical textbook.
6. *Operational Amplifiers, Theory and Practice,* by J. K. Roberge, J. Wiley & Sons, 1975. Authoritative book on op amp principles and circuitry; contains extensive material on compensation to optimize dynamic performance.
7. *Transducer Interfacing Handbook,* edited by D. H. Sheingold. 1980. Analog Devices, Box 796, Norwood, MA 02062.

7.3

AC Power Systems

Jerry Whitaker
Editor
Broadcast Engineering Magazine
Overland Park, Kansas

We all take the utility company power system for granted. If you want ac service, you just call the local office and order a power drop. You expect the utility company lines to be operating all day, every day. But how is this intricate ac power system designed? How is it interfaced to user equipment? What problems can it present to broadcasters?

An understanding of the answers to these questions is important to proper planning of a broadcast facility. Like any other area of engineering, the first requirement in system planning is an understanding of the basic principles involved.

THE UTILITY POWER SYSTEM

The details of power distribution in the United States vary from one utility company to another, but the basics are the same. See Fig. 1.

Power from a generating station or distribution grid comes into an area substation at 115 kV or higher. The substation will deliver output voltages around 60 kV to subtransmission circuits which feed distribution substations. These substations convert the energy to approximately 12 kV and provide voltage regulation and switching arrangements that permit "patching around" a problem. The 12 kV lines power the pole- and surface-mounted transformers, which supply various voltages (generally 208-240 V 3 phase) to the individual loads.

Fuses and circuit breakers are included at a number of points in the 12 kV distribution system to minimize fault-caused interruptions of service. Ground-fault interrupters are also included at various points in the 12 kV system to open the circuit if excessive ground currents begin to flow on the monitored line. In addition, reclosers may be included as part of overcurrent protection of the 12 kV lines. They will open the circuit if excessive currents are detected, and re-close after a preset length of time. The recloser will perform this trip off-reset action several times before being locked out.

In some areas, the actions of circuit breakers, pole-mounted switched and reclosers are controlled by two-way radio systems that allow status interrogation and switching of the remotely-located devices from a control center. Some utilities use this method sparingly, others make extensive use of it.

Depending on the geographic location, varying levels of lightning protection are included as part of the ac power system design. Most service drop transformers (12 kV to 208 V) have integral lightning arresters. In areas of severe lightning activity, a ground wire will be strung between the top insulators of each pole, thus attracting lightning to the grounding wire, and away from the hot leads.

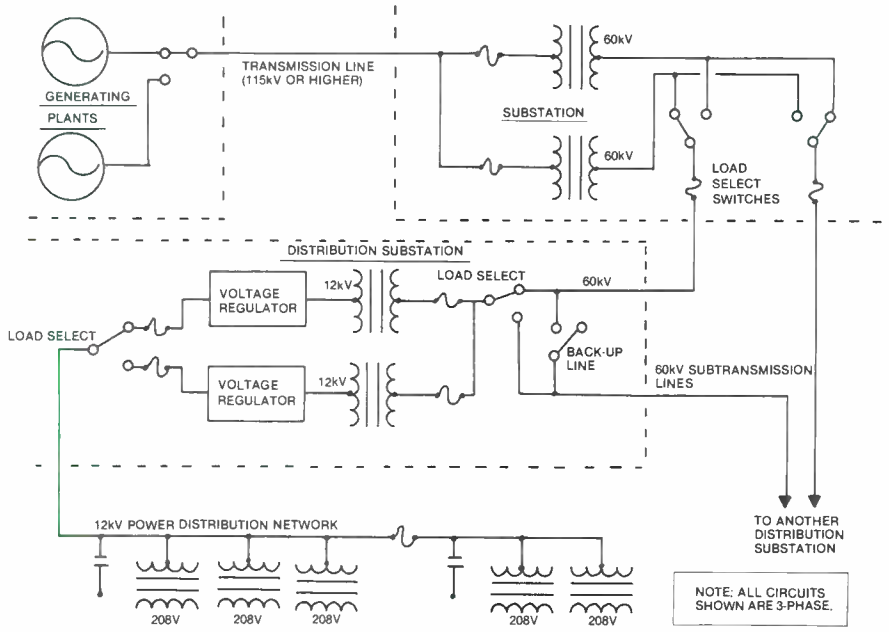


Fig. 1. A simplified block diagram of a basic utility company power distribution system. The devices shown as fuses could be circuit breakers or reclosers, which function as automatic-resetting circuit breakers. All circuits shown are three phase. The capacitors perform power factor correction duty.

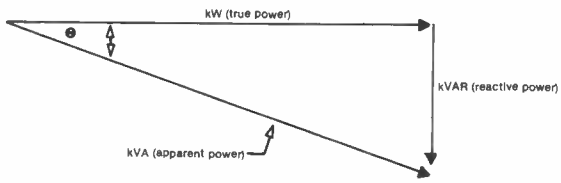
Power Factor

Capacitor banks are placed at various locations in the 12 kV distribution system. The number of banks and where they are located in the system is determined by the load distribution and *power factor* of the circuit. The capacitors will improve the short-term line voltage regulation (in the millisecond range) and reduce transient activity on the line. Spikes are reduced because the capacitors will present a high impedance to the 60 Hz line voltage frequency, but a low impedance to a high frequency transient. The capacitors are placed on the line in order to keep the power factor as close to unity (100%) as possible. Transient suppression is simply a by-product.

Power Factor (PF) is defined as the ratio of *true power* to *apparent power.* It is generally expressed in percent. Reactive loads (inductive or capacitive) act on power systems to shift the current out of phase with the voltage, and the cosine of the resulting angle between the current and voltage is the power factor. A utility line that is looking into an inductive load (which is most often the case) is said to have a *lagging power factor*, while a line feeding a capacitive load has a *leading power factor*. Fig. 2 illustrates the concept.

A poor power factor will result in excessive losses along utility company feeder lines because more current is required to supply a particular load with a low power factor than would be demanded if the load had a power factor close to 100%.

For example, a motor requiring 5 kW from the line is connected to the utility service entrance. If the motor has a power factor of 86%, the actual amount of power demanded by the load will be 5 kW divided by 86%, or better than 5,800 watts. 5 kW is the true power, 5.8 kW is the apparent power. The same amount of work is being done by the motor, but the closer the power factor is to unity, the more efficient the system will be.



$$\cos\theta = \frac{kW}{kVA} = PF$$

$$\sin\theta = \frac{kVAR}{kVA}$$

θ = the phase angle, a measure of the net amount of inductive reactance in the circuit.
kW = the true power that performs the "real work" done by the electrical circuit (measured in kilowatts).
kVA = the apparent power drawn by a reactive load (measured in kilowatts).
kVAR = the kilovolt-ampers-reactive component of an inductive circuit. The kVAR component (also known as the *phantom power*) provides the magnetizing force necessary for operation of inductive loads.

Fig. 2. The mathematical relationships of an inductive circuit as they apply to power factor (PF) measurements. Reducing the KVAR component of the circuit causes θ to diminish, improving the PF. When KW is equal to KVA the phase angle is zero and the power factor is unity (100%).

In an effort to keep the power factor as close to 100% as possible, utility companies place capacitor banks at various locations in the 12 kV distribution system, thereby offsetting the inductive loading (lagging power factor) of most user equipment. The idea is to create an equal amount of leading PF in the system to match the load's lagging PF. When a balance is made, the power factor is unity.

In practice this is seldom attainable, since loads are switched on and off at random times, but utilities routinely (through much effort) maintain a power factor of approximately 99%. To accomplish this, capacitor banks are switched in and out of the system automatically to compensate for changing load conditions. The actual power factor of a particular system is determined by a complicated series of steps that involves measuring line parameters and correlating them with various charts and look-up tables.

Utility Company Interfacing

Most utility company connections in this country are the standard Delta-Wye type, as illustrated in Fig. 3. The transformer is usually connected with the Delta side facing the high voltage and the Wye side facing the load. This type of configuration provides good isolation of the load from the utility and retards somewhat the transmission of transients from the primary to the secondary. The individual three phase loads are denoted by Z-1, Z-2, and Z-3. They carry load currents as shown.

Some utility connections, on the other hand, use the Open-Delta arrangement shown in Fig. 4. Problems are often encountered when operating a sensitive three phase load from such a connection because of the system's poor voltage regulation characteristics under varying load conditions. The Open-Delta configuration is also subject to high third harmonic content and transient propagation. The three loads and their respective load currents are shown in the diagram.

Several other primary power connection arrangements are possible, such as Wye-to-Wye or Delta-to-Delta, and like the Delta-to-Wye configuration, they are not susceptible to the problems that can be experienced with the Open-Delta (or V-V) service.

The Open-Delta system can develop a considerable imbalance between the individual phases in either voltage or phase or both. Such an occurrence can introduce a strong 120 Hz ripple frequency in three phase power supplies, which are designed to filter out a 360 Hz ripple. The effects of this imbalance can be increased output noise from the supply, overheating of transformers, and possible damage to protection devices across power supply chokes.

Depending on the loading of an Open-Delta transformer arrangement, high third harmonic energy can be transferred to the load, producing transients (of up to 300% of the normal voltage)

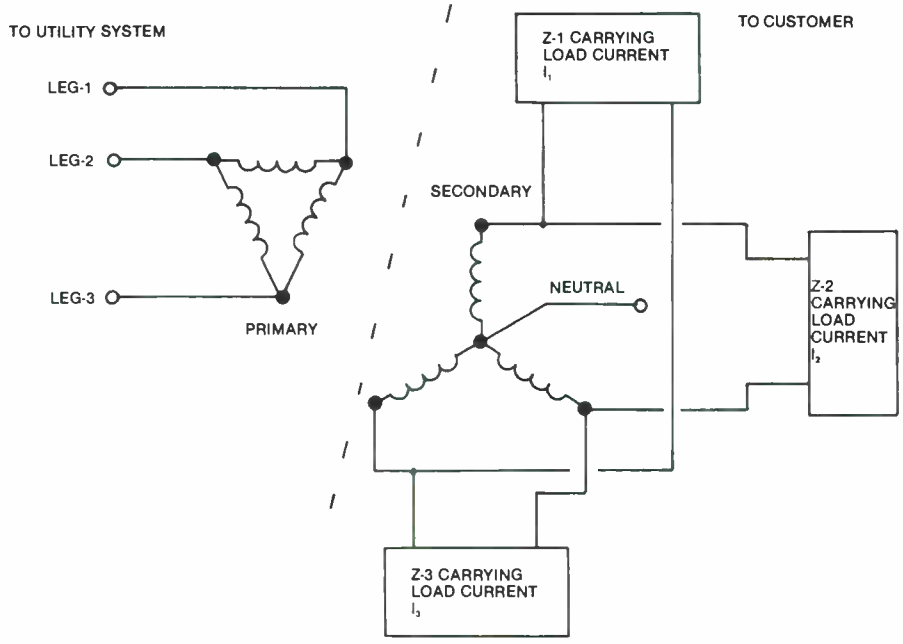


Fig. 3. The Delta-Wye transformer configuration for utility company power distribution. This common type of service connection transformer provides good isolation of the load from the 12KV distribution system line.

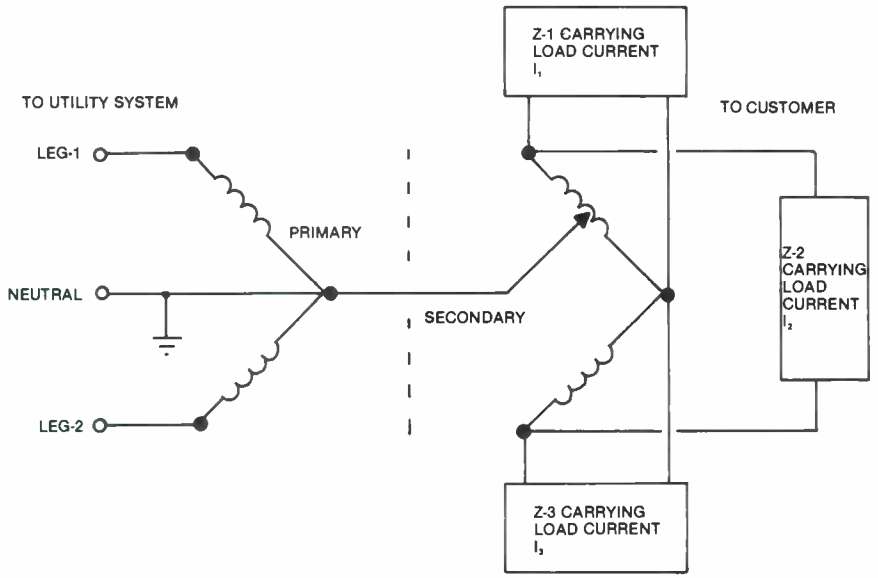


Fig. 4. The Open-Delta (or V-V) utility company service connection transformer. Use of this configuration is not recommended due to the tendency of the design to provide poor voltage regulation, high third harmonic content and transient disturbance propagation.

which severely strain rectifiers, capacitors and inductors in the power supply, as well as adding to the supply's output noise.

The phase-to-phase voltage balance of a utility company line is important to a broadcast facility not only because of the increased power supply ripple it may cause, but also because of the heating effects that may result. Even simple 3-phase devices such as motors should be operated from a power line that is well balanced (preferably within 1%). Studies have shown that a line imbalance of just 3.5% can produce a 25% increase in the heat generated by a 3-phase motor. A 5% imbalance can cause a potentially destructive temperature increase of 50% above normal. Similar heating can also be observed in the windings of a 3-phase power transformers used in broadcast equipment.

Phase-to-phase voltage balance can be accurately measured over a period of several days with a slow-speed chart recorder. The causes of imbalanced operation are generally large single-phase power users on the 12 kV distribution line. Uneven currents through the utility company power distribution system will result in uneven line-to-line voltages at the customer's service drop entrance.

It is important when using a Wye-connected system that the building neutral lead be tied to the mid-point of the transformer windings, as shown in Fig. 3. The neutral line provides a path for the removal of any harmonic currents that may be generated in the system due to rectification of the secondary voltages.

AC Line Disturbances

The ac power line into a broadcast plant is the lifeblood of any operation. It is also, however, a frequent source of equipment malfunctions and component failures. The utility company ac feed contains not only the 60 Hz power needed to run the facility, but also a variety of voltage sags, surges and transients. These abnormalities cause different problems for different types of equipment.

An ac voltage *sag* is generally defined as a decrease of 10-35% below the normal line voltage for a period of 16 milliseconds to 30 seconds. A *surge*, on the other hand, is a voltage increase of 10-35% above normal lasting 16 millisecond to 30 seconds. See Fig. 5. Sags and surges may occasionally result in operational problems for the equipment on-line, but generally automatic protection (or correction) circuits will take appropriate actions to ensure there is no equipment damage. *Transients*, however, are not so easily identified or eliminated. Many devices commonly used to correct for sag and surge conditions, such as ferroresonant transformers or motor-driven auto transformers, are of limited value in protecting a load from high energy, fast rise-time spikes on the ac line.

The Scope of the Problem

Transient suppression is important to broadcasters because the sensitive, high-speed solid state equipment in use today can be disrupted, or even destroyed by random short-duration spikes riding on the ac waveform. If not attenuated, these brief

pulses (sometimes only a few microseconds in duration) can destroy semiconductors, disturb logic operations or latch-up microcomputer routines.

Experience in the computer industry has shown that the vast majority of unexplained problems resulting in disallowed states of operation are actually caused by transient overvoltages on the utility feed. With the increased use of microcomputers in broadcasting, this warning cannot be ignored. The threat to broadcast facilities is compounded by the fact that microcomputers are being used at critical stages in the transmission chain, including program automation equipment and transmitter control systems.

The subject of transient overvoltages has been extensively studied in the computer industry. A pioneering effort by the IBM Systems Development division in 1974 (conducted by George Allen and Donald Segall), showed that voltage spikes lasting between 10 and 100 μs in a frequency range of 10-100 kHz occur on an average of better than 50 times per month in a typical commercial environment.

Other more recent studies have shown that power line transients caused by utility company switching, distribution system faults, large loads going on- and off-line and lightning, can occur as often as 900 times per month. These spikes can reach 2 kV (or more) and last up to 30 milliseconds.

Assessing the Threat

Someone once jokingly said that the best transient eliminator is a transient monitor. Anyone who has monitored primary power service lines with an oscilloscope for any length of time would surely agree with that statement. Recent developments in digital technology, however, have moved the business of assessing the threat posed by unprocessed ac from an educated guess to a fine science.

Sophisticated monitoring equipment can give the user a complete, detailed look at what is coming in from the power company. Such monitoring devices can provide a wealth of information on the problems that can be expected when operating data processing, transmitting or other sensitive electronic equipment from an unprotected ac line. Typically the power at a facility to be protected is monitored for a week or more, after which an assessment is made as to whether ac processing equipment is needed at the installation.

As a case in point, a recently-completed study for a San Francisco Bay area company planning to install a new data processing center graphically demonstrates the scope of the transient problem.

The firm wanted to determine the extent of transient activity that could be expected at the new site so that an informed decision could be made on the type of power conditioning needed. A Dranetz Engineering Laboratories model 606-3 ac line monitor was connected to the 480 V dedicated drop at the new facility for a period of 6 days. During this time the monitor recorded *thousands* of spikes, many exceeding 2 kV, on one or more of the three phase inputs. The transient recording threshold was 460 V *above* the nominal ac voltage level of 480 V, phase-to-phase.

An expert from the report summary states that, on one particular day, the facility was plagued by many high-level transient periods, stretching from 8:30 a.m. until 3:00 p.m. In fact, the transient counters overflowed on the monitor's daily summary printout. The highest voltage recorded

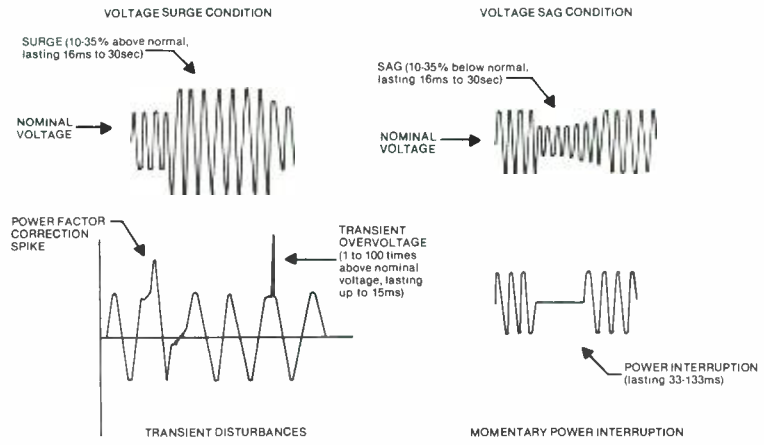


Fig. 5. Various classifications of power-line disturbances. Voltage sags and surges can garble data and stress hardware components. Momentary power interruptions can cause a complete loss of volatile memory and severely stress hardware components, especially if the ac supply is allowed to surge-back automatically. Transient disturbances can cause a wide variety of operational problems, from logic errors to complete system failure.

```
C  1792V  IMPULSE
A  0544V  IMPULSE
C  1984V  IMPULSE
A  0592V  IMPULSE
C  1856V  IMPULSE
A  0544V  IMPULSE
C  1824V  IMPULSE
A  0560V  IMPULSE
C  1488V  IMPULSE
A  0496V  IMPULSE
C  1664V  IMPULSE
A  0528V  IMPULSE
C  1600V  IMPULSE
A  0544V  IMPULSE
B  2480V  IMPULSE
11:19:11
```

Fig. 6. A portion of the ac monitor readout from the San Francisco area power quality study. The first column indicates on which phase (A, B or C) the spike occurred. The second column is an actual readout of the transient (impulse) magnitude in volts.

during this period was 4.08 kV. (This transient activity occurred, by the way, during periods of good weather.)

Fig. 6 is part of the printout from this study. The data covers transients exceeding more than twice the normal line voltage that occurred within a period of just *30 seconds*. Even though these transients were very brief in duration, any sensitive equipment connected to the power line would suffer damage in a very short period of time.

While this is certainly a worst-case example of dirty ac, it points up the need for a minimal amount of spike protection on all incoming power lines. Studies such as the one detailed here should not be construed to be an indictment of utility company engineering standards. Very few power drops are as bad as the one analyzed in this study. Further, most transient activity on ac lines is generated by power customers, not utility companies.

Standards of Measurement

It is difficult to assess the threat posed by transient disturbances without a guideline on the nature of spikes in ac power systems. To this end, a Working Group of the Institute of Electrical and Electronic Engineers (IEEE) has suggested two waveforms, one unidirectional and the other oscillatory, for measurement and testing of transient suppression components and systems in ac power circuits with rated voltages of up to 277 V line-to-ground. The guidelines also recommend specific source impedance or short-circuit current values for transient analysis.

The voltage and current amplitudes, waveshapes and source impedance values suggested in the IEEE Guide (now ANSI/IEEE Standard C62.41-1980) are designed to approximate the vast majority of high-level transient disturbances, but are not intended to be worst case conditions—a difficult parameter to predict. The timing of a transient overvoltage with respect to the power line wave is also an important parameter in the examination of ac disturbances. Certain types of semiconductors exhibit failure modes that are dependent on the position of a transient on the 60 Hz ac system sine wave.

Fig. 7 shows the ANSI/IEEE representative waveform for an *indoor-type spike* (for 120-240 V ac systems). Field measurements, laboratory observations and theoretical calculations have shown that the majority of transient disturbances in low-voltage indoor ac power systems have oscillatory waveshapes, instead of the unidirectional wave most often thought to represent a transient overvoltage. The oscillatory nature of the indoor transient waveform is caused by the natural resonant frequencies of the ac distribution system. Studies by the IEEE show that the oscillatory frequency range of such disturbances extend from 30 Hz to 100 kHz, and that the waveform changes depending upon where in the power distribution system it is monitored.

The waveform shown in Fig. 7 is the result of extensive study by the IEEE and other independent organizations of various ac power circuits. The representative waveshape for 120 and 240V systems is described as "a 0.5 μs-100 kHz ring wave." This standard indoor spike has a rise time of 0.5 μs and then decays while oscillating at 100 kHz. The amplitude of each peak is approximately 60% of the preceding peak.

Fig. 8 shows the ANSI/IEEE representative waveform for an *outdoor-type spike*. The classic

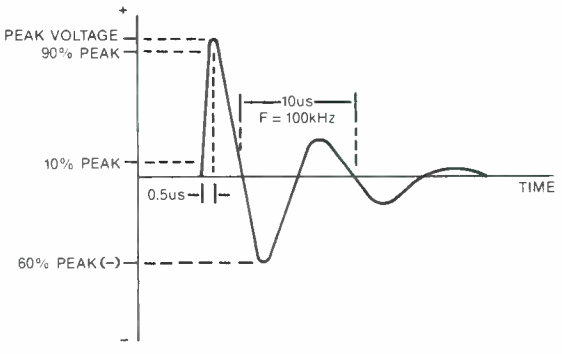


Fig. 7. The suggested IEEE indoor-type transient overvoltage test waveform (0.5 μs-100 kHz ring wave, open-circuit voltage).

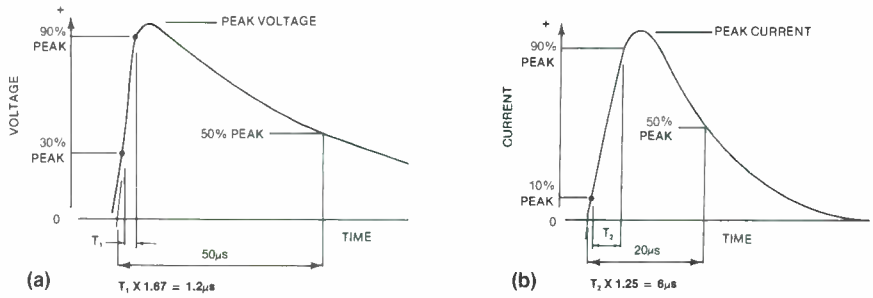


Fig. 8. The unidirectional waveshape for outdoor-type transient overvoltage test analysis based on ANSI Standard C62.1. Figure (a) shows the open-circuit waveform and Figure (b) shows the discharge current waveform.

lightning overvoltage pulse has been established as 1.2/5 50 μs waveshape for a voltage wave and a 8/20 μs waveshape for a current wave. Accordingly, the ANSI/IEEE standard waveshape is defined as "1.2/50 μs for the open-circuit voltage (voltage applied to a high-impedance device), and 8/20 μs for the discharge current (current in a low-impedance device)."

The outdoor waveshapes, while useful in analysis of components and systems, are not meant to represent all transient patterns seen in low voltage ac circuits. Lightning discharges can cause oscillations, reflections and other disturbances in the utility company power systems that can appear at the service drop entrance as decaying oscillations.

Equipment Performance Recommendations

The susceptibility of computer equipment to failure because of disturbances on the ac power line was analyzed in a far reaching study conducted between 1968 and 1978 by Lieutenant Thomas Key of the Naval Facilities Engineering Command, Washington, D. C. The work identified three distinct categories of recurring disturbances on the utility company power system. See Table 1. Note that the duration of the disturbance, not the magnitude of the voltage, determines the classification.

The study found that most computer failures caused by ac line disturbances occurred during periods of bad weather. In fact, according to a report on the findings of the study*, the incidence of thunderstorms in a given area may be used in predicting future equipment failures.(**The Effects of Power Disturbances on Computer Operation*, IEEE Industrial and Commercial Power Systems Conference Paper, delivered in Cincinnati, Ohio, June 7, 1978.)

The type of power transmission system used by the utility company was also found to have an effect on the number of disturbances observed on power company lines. For example, an analysis of utility system problems in Washington,

TABLE 1. The three types of power line disturbances identified in the research by Key, and the characteristics of each classification.

DEFINITION	TYPE 1 Transient and oscillatory overvoltage	TYPE 2 Momentary undervoltage or overvoltage	TYPE 3 Power outage
CAUSES	Lightning, power network switching, operation of other loads	Power system faults, large load changes, utility company equipment malfunctions	Power system faults, unacceptable load changes, utility equipment malfunctions
THRESHOLD*	200 to 400% of rated RMS voltage or higher (peak instantaneous above or below rated RMS)	Below 80-85% and above 110% of rated RMS voltage	Below 80-85% of rated RMS voltage
DURATION	Spikes 0.5 to 200 μs wide and oscillatory up to 16.7ms at frequencies of 200Hz-5kHz and higher	From 4 to 60 cycles depending on type of power system distribution equipment	From 2 to 60 seconds if correction is automatic; from 15 minutes to 4 hours if manual

*The approximate limits beyond which the disturbance is considered to be harmful to the load equipment.

D.C., Norfolk, Virginia, and Charleston, South Carolina showed that underground power distribution systems experienced only ⅓ as many failures as overhead lines in the same area.

Based on his research, Key developed a voltage tolerance envelope for computer equipment, shown in Fig. 9. It is designed as a guide for computer manufacturers in system tolerance design and in diagnosing power-related equipment failures.

Other Considerations

Another fault condition associated with the utility company ac power supply is single-phasing. This is caused when one or more lines of a multiphase system is (are) open. Multi-phase equipment, particularly motors, not protected against such occurrences will generally overheat, and sometimes fail.

Unfortunately, the power quality problems affecting many areas of the nation are becoming worse, not better. Broadcasters cannot depend upon power suppliers to solve the transient problems that exist. Utility companies are rarely interested in discussing ac disturbances that are measured in the microseconds or nanoseconds. The problem must be solved instead, at the input point of sensitive loads.

Utilities have traditionally checked the quality of a customer's service drop by connecting a chart recorder to the line for a period of several days. The response time of such recorders, however, is far too slow to document any transient spike. Slow-speed analog recorders will only show long-term surge and sag conditions (as earlier defined), which can generally be dealt with by the regulated power supplies or high voltage protection systems normally used in broadcast equipment.

The degree of protection afforded a radio or television facility is generally a compromise between the line abnormalities that will account for better than 90% of the expected problems, and the amount of money available to spend on that protection. Each installation is unique and requires an assessment of the importance of keeping the system up and running at all times, the threat posed by the utility company feed and the budget available for protection devices and systems.

Suppression Devices

The decision on how to proceed with a transient protection program is not an easy one, but it is made somewhat less complicated by the economics involved. Most commonly-available discrete protection devices can be purchased for $5.00 to $20.00 each and installed by station personnel at critical points in the transmission plant. The alternative method is to purchase a transient suppressor system designed for connection to the utility company primary input lines at the protected facility. The *systems* approach is certainly

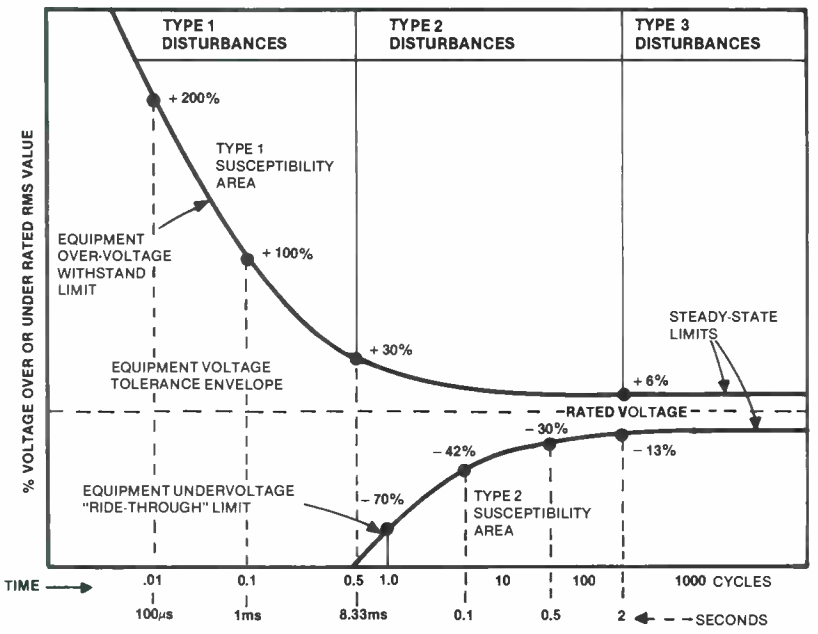


Fig. 9. The recommended voltage tolerance envelope for computer equipment. This chart is based on pioneering work done by the Naval Facilities Engineering Command. The study identified how the magnitude *and* duration of a transient pulse must be considered in determining the damaging potential of a spike. The design goals illustrated in the chart are recommendations to computer manufacturers for implementation in new equipment.

TABLE 2. The use of ac interface equipment in controlling disturbances on ac power line inputs. (Based on the research by Key.)

TYPE OF DISTURBANCE	UPS SYSTEM AND STANDBY GENERATOR	UPS SYSTEM	SECONDARY SPOT NETWORK[1]	SECONDARY SELECTIVE NETWORK[2]	MOTOR-GENERATOR	SHIELDED ISOLATION XFMR	SUPPRESSORS, FILTERS, LIGHTNING ARRESTERS	SOLID-STATE LINE-VOLTAGE REGULATOR
#1	ALL SOURCE TRANSIENTS	ALL SOURCE TRANSIENTS	NONE	NONE	ALL SOURCE TRANSIENTS	MOST SOURCE TRANSIENTS	MOST TRANSIENTS	MOST SOURCE TRANSIENTS
	NO LOAD TRANSIENTS	NO LOAD TRANSIENTS			NO LOAD TRANSIENTS	NO LOAD TRANSIENTS		NO LOAD TRANSIENTS
#2	ALL	ALL	NONE	MOST	MOST	NONE	NONE	SOME, DEPENDING ON RESPONSE TIME OF SYSTEM
#3	ALL	ALL OUTAGES SHORTER THAN BATTERY SUPPLY DISCHARGE TIME	MOST	MOST	ONLY "BROWN-OUTS"	NONE	NONE	ONLY "BROWN-OUTS"

NOTES:
1. Dual power feeder network.
2. A dual power feeder network using a solid-state switch to select which line is fed to the load.

TABLE 3. Approximate costs for various methods of ac power processing. It should be emphasized that these values are only approximate, and may vary substantially depending on the installation requirements and vendor chosen.

BASIS OF COMPARISON[1]	UPS SYSTEM AND STANDBY GENERATOR	UPS SYSTEM	DUAL POWER FEEDERS	MOTOR-GENERATOR	SHIELDED ISOLATION XFMR	SUPPRESSORS, FILTERS, LIGHTNING ARRESTORS	SOLID-STATE LINE-VOLTAGE REGULATOR
INSTALLATION AND EQUIPMENT COSTS	$1,500 to $2,000 per kVA	$1,100 to $1,500 per kVA	Installation cost will vary greatly depending on site	$250 to $400 per kVA	$50 to $150 per kVA	$1 to $10 per kVA	$250 to $280 per kVA
MAINTENANCE COSTS	$2,000 to $4,000 per year	$1,100 to $3,000 per year	NONE	Less than $1,000 per year	NONE	NONE	Less than $1,000 per year
OPERATING EFFICIENCY[2]	80-85%	80-85%	100%	80-90%	Up to 98%	100%	90-98%

NOTES:
1. A power conditioning system rated for approximately 25kVA is assumed.
2. Efficiency applies to the ac power conditioning equipment only. Losses in environment support systems are not taken into account.

the more effective way to prevent damaging transient overvoltages from entering a broadcast plant. It is also however, the more expensive way.

The amount of money a broadcaster is willing to spend on transient protection is generally a function of how much money is available in the engineering budget and how much the station has to lose. An expenditure of $10,000 for transient protection for a major-market station, where spot rates can run into the hundreds or thousands of dollars, is easily justifiable. At small or medium market stations, however, justification is not so easy to come by.

Tables 2 and 3 show the various options available to station engineers to protect sensitive broadcast equipment from disturbances on the ac line, and the approximate costs of that protection. Because each installation is unique, a detailed investigation of the station's exact needs should be made before any ac line protection equipment is purchased.

The high-performance end of transient suppression equipment available to broadcasters is occupied by motor-generated units, uninterruptable power systems and various types of power line filters.

Motor-Generator Units (MGU)

As the name implies, a motor-generator unit consists of a motor powered by the ac utility supply that is mechanically tied to a generator, which feeds the load. Transients on the utility line will have no effect on the load when an arrangement such as this is used. Further, the addition of a flywheel to the motor-to-generator shaft will provide protection against brief power dips (up

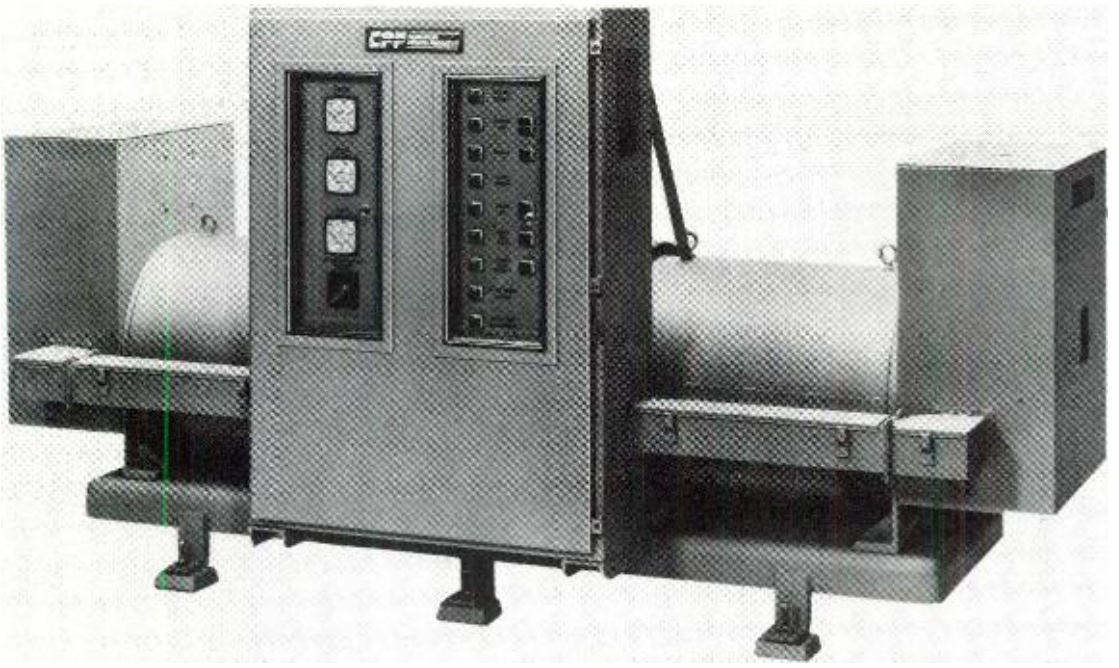


Fig. 10. The design layout of a typical motor-generator unit. The MGU shown is manufactured by Computer Power Products, Inc., of Los Angeles. Systems performing similar functions are also manufactured by several other companies.

to ½ second on many models). Fig. 10 shows the construction of a typical MGU.

Other features available from a motor-generator unit include output voltage and frequency regulation, ideal sine wave output, elimination of common-mode and transverse mode noise, elimination of utility company power factor correction problems and true 120 degree phase shift for 3 phase models. The efficiency of a typical MGU ranges from 65% to 89%, depending on the size of the unit and the load.

Uninterruptable Power Systems (UPS)

Another method guaranteed to eliminate spikes on utility company power lines is the rectifier-inverter combination, used in many Uninterruptable Power Systems. As shown in Fig. 11, ac from the utility is rectified to a given voltage, such as 120 volts dc, across which floats a bank of a batteries connected in series to yield slightly less than 120 volts. This dc power drives a closed-loop inverter, which provides voltage and frequency regulation. The output of the inverter is generally a sine wave, or pseudo sine wave (really a stepped square wave). If the utility voltage should drop or disappear, current is drawn from the batteries. When the ac power is restored, the batteries are re-charged.

Many UPS systems incorporated a standby diesel generator that is started as soon as the utility company feed is interrupted. With this arrangement, the batteries are called upon to supply the operating current for only 10 seconds or so, until the generator gets up the speed.

Processing Line Filters

Processing systems for ac power are available from a number of manufacturers in a variety of configurations and designs. Some use shunt elements to clip transient overvoltages, and others use a series element—in addition to the shunt—to absorb the transient energy. Another type of filter commonly found is the high-performance isolation transformer.

Transients, as well as noise (RF and low level spikes) can pass through transformers not only by way of the magnetic lines of flux between the primary and the secondary, but through resistive and capacitive paths between the windings as well. Increasing the physical separation of the pirmary and secondary windings will reduce the resistive and capacitive couplings, however, it will also reduce the inductive coupling, and thus decrease the power transfer. A better solution is to shield the primary and secondary windings from each other and thereby divert much of the primary noise current to ground, while leaving the inductive coupling basically unchanged. This idea can be carried a step further by placing the primary winding in a shielding box that shunts noise current to ground and reduces the capacitive coupling between the windings.

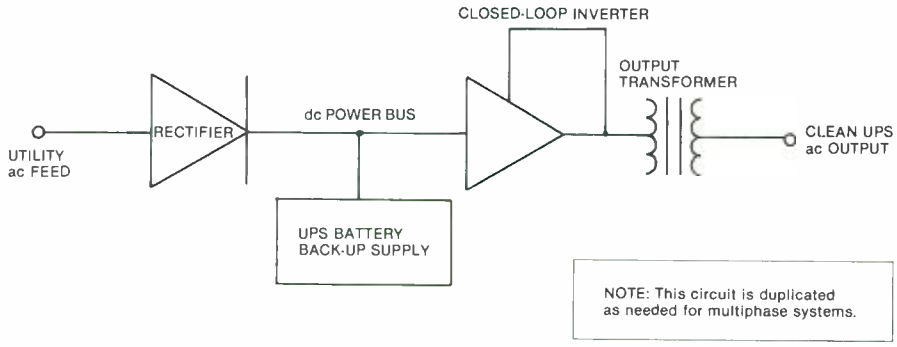


Fig. 11. A block diagram of a typical Uninterruptable Power System using ac rectification to float the battery supply. A closed-loop inverter draws on this supply and delivers clean ac power to the protected load.

Fig. 12. A typical Uninterruptable Power System using externally-located batteries. The control panel on the front of the chassis is used to check the performance of the equipment and to monitor the quality of the incoming ac power. This particular unit is manufactured by the Topaz Electronics Company of San Diego, CA. Units performing similar functions are also made by several other firms.

One application of this technology is shown in Fig. 13, in which transformer noise de-coupling is taken still further by placing the primary *and* secondary windings in their own wrapped foil box shields. The windings are separated physically as much as possible for the particular power rating, and placed between special Faraday shield separator plates. This gives the transformer high noise attenuation from the primary to the secondary, as well as from the secondary to the

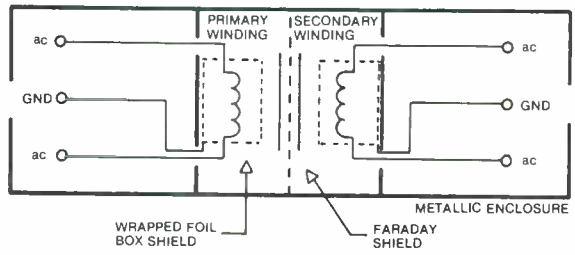


Fig. 13. The shielding arrangement used in a popular high performance isolation transformer. The design goal of this type of unit is high common-mode and transverse-mode noise attentuation.

primary. The interwinding capacitance of a typical transformer using this technology is 0.005 picofarads. Common mode noise attenuation is typically greater than 120dB and transverse mode noise attentuation is typically in excess of 60dB.

STANDBY POWER SYSTEMS

When utility company power problems are discussed, most people immediately think of blackouts. The lights go out and everything stops. Blackouts, however, occur only rarely in most areas of the country and are generally of short duration. Studies have shown that 50% of all blackouts last 6 seconds or less, and another 35% are less than 11 minutes long. These failure rates are not usually cause for concern to commercial users, except where broadcasting is concerned.

A station that is off the air for 11 minutes—or even 5 minutes—will suffer a drastic audience loss that can take hours (or perhaps days) to rebuild. Coupled with this threat is the possibility of extended power service loss due to storm conditions. Many broadcast transmitting sites are located in remote, rural areas, or on mountaintops. Such locations are not well known for their power reliability. It is not uncommon in mountainous areas for utility company service to be out for

days after a major storm. Few broadcasters are willing to take such risks with their air signal, and choose to install standby power systems at appropriate points in the transmission chain.

The cost of standby power for a broadcast facility (particularly high power radio or TV) can be substantial, and an examination of the possible alternatives should be conducted before any decision on equipment is made. Management should clearly define the direct and indirect costs and weigh them appropriately. This cost-versus-risk analysis should include the standby power system equipment purchase and installation price, the exposure of the transmission system to utility company power failure, the alternative transmission methods available to the station and the direct and indirect costs of lost air time due to blackout conditions.

Standby System Options

The classic standby power system using an engine-generator is shown in Fig. 14. An automatic transfer switch monitors the ac voltage coming from the utility company line for any power failure conditions. Upon detection of an outage for a predetermined period of time (generally 1 to 10 seconds), the standby generator is started and once up to speed, the load is transferred from the utility to the local generator. Upon return of the utility feed, the load is switched back and the generator is stopped. This basic type of system is widely used in the broadcast industry and provides economical protection against prolonged power outages (5 minutes or more).

In some areas, usually metropolitan centers, the utility company can bring two power drops into a facility as a means of providing a source of standby power. As shown in Fig. 15, two separate utility company service drops—from separate power distribution systems—are brought into the plant and an automatic transfer switch changes the load to the backup line in the event of a main

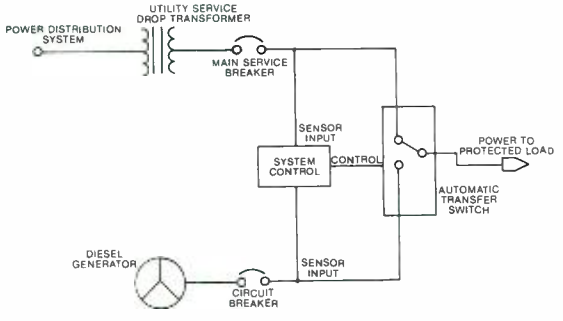


Fig. 14. The classic standby power system using an engine-generator unit. This system protects a facility from prolonged utility company power failures.

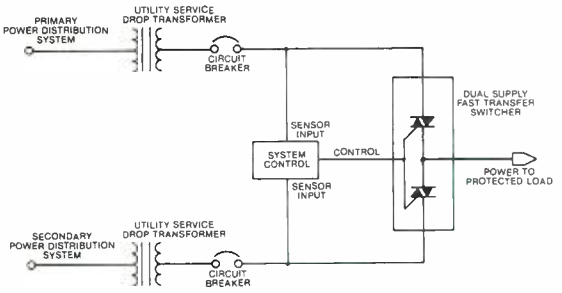


Fig. 15. The dual feeder system of ac power loss protection. An automatic monitoring system switches the load from the main utility line to the standby line in the event of a power disruption.

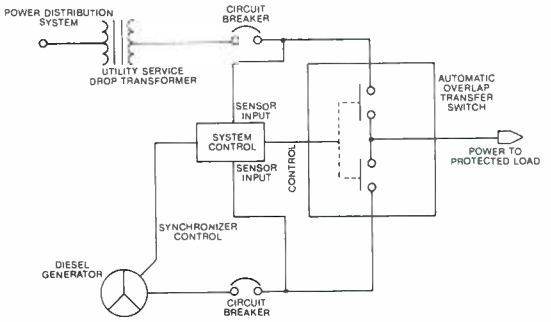


Fig. 16. The use of a diesel generator for emergency power and peak power shaving applications. The automatic overlap transfer switch changes the load from the utility feed to the generator instantly so that no disruption of normal operation is encountered.

line failure. This dual feeder system has an advantage over the auxiliary diesel arrangement shown in Fig. 14 in that the power transfer from main to standby can be made in less than a second. Time delays are involved in the diesel generator system which limit its usefulness to power failures lasting more than several minutes.

The dual feeder system of protection is based on the assumption that each of the service drops brought into the facility is routed via different paths. This being the case, the likelihood of a failure on both power lines simultaneously is very remote. The dual feed system will not, however, protect against area-wide power failures, which can occur from time to time.

The dual feeder system is primarily limited to urban areas. Rural or mountainous regions are not generally equipped for dual redundant utility company operation. Even in urban areas, the cost of bringing a second power line into a broadcast facility can be high, particularly if special lines must be installed for the feed.

Fig. 16 illustrates the use of a backup diesel generator for both emergency power and *peak*

power shaving applications. (See "Peak Demand" discussion on page 7.3-92.) Commercial power customers can often realize substantial savings on utility company bills by reducing their energy demand during certain hours of the day. Fig. 16 shows the use of an automatic overlap transfer switch to change the load from the utility company system to the local diesel generator. This change-over is accomplished by a special transfer system that does not disturb the operation of load equipment. This application of a standby generator can provide financial return to the station regardless of whether the generator is ever needed to carry the load through a commercial power failure.

Advanced System Protection

A more sophisticated power control system is shown in Fig. 17, where a dual feeder supply is used to feed a motor-generator unit (MGU) to provide clean, undisturbed ac power to the load. The MGU will smooth-over the transition from the main utility feed to the standby, often making a commercial power failure unnoticed by station personnel. An MGU will typically give up to 1/2 second of power-fail ride-through, more than enough to accomplish a transfer from one utility feed to the other.

The principle is further refined in the application shown in Fig. 18, where a diesel generator has been added to the ac power supply system. With the automatic overlap transfer switch shown at the generator output, this system can also be used for peak demand power shaving.

The generator rating for a standby power system should be chosen carefully, keeping in mind any anticipated future growth of the broadcast plant. It is good practice to install a standby power system rated for at least 25% greater output than the peak facility load. This headroom gives a margin of safety for the standby equipment and allows future expansion of the facility without worry about overloading of the system.

The type of generator chosen should also be given careful consideration. Generators rated for more than 100 kW power output are almost always diesel-powered. Smaller generators are available that use diesel, gasoline, natural gas or propane as a fuel source. The type of power plant chosen is usually determined primarily by the environment in which the system will be operated.

For example, a standby generator that is located in an urban area office complex may be best suited to the use of an engine powered by natural gas, because of the problems inherent in storing large amounts of fuel. State or local building codes may place expensive restrictions on fuel storage tanks and make the use of a gasoline-or diesel-powered engine impractical. The use of propane is usually restricted to rural areas, and the availability of propane in periods of bad weather (which is when most power failures occur) must also be considered.

Critical System Buss Protection

A station seeking standby power capabilities should consider the possibility of protecting key pieces of equipment at a facility from power

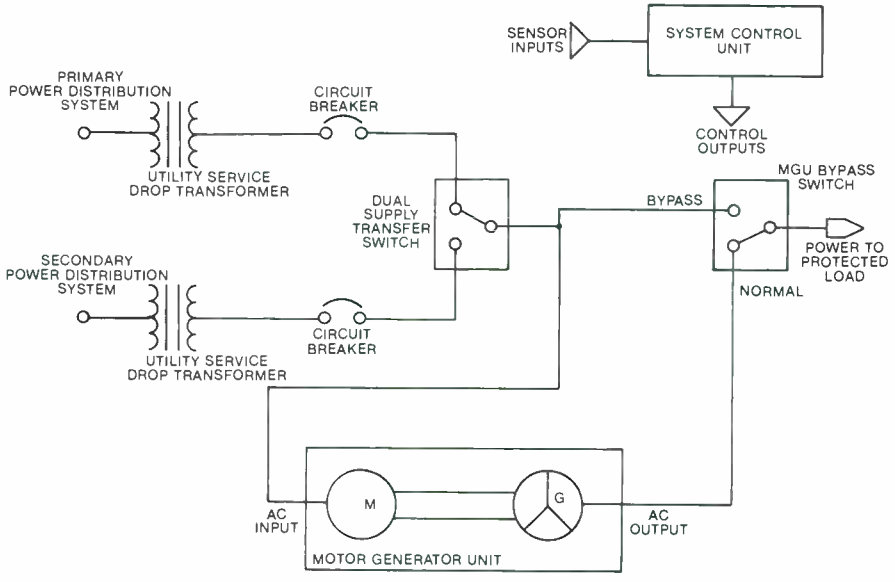


Fig. 17. The dual feeder standby power system using a motor-generator unit to provide power-fail ride-through and transient disturbance protection. Switching circuits allow the MGU to be bypassed, if desired.

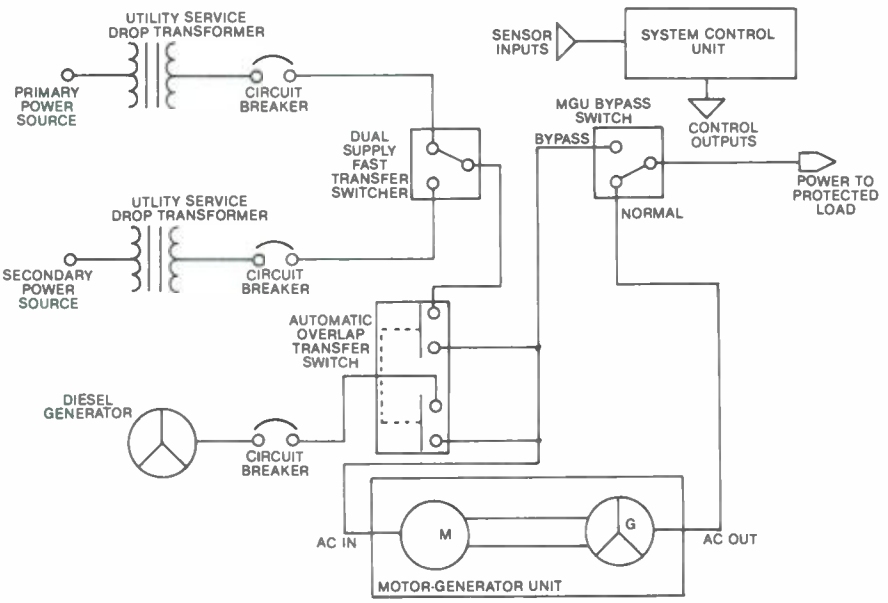


Fig. 18. A premium power supply backup and conditioning system using dual utility company feeds, a diesel generator and a motor-generator unit. An arrangement such as this would be used for critical loads that require a steady supply of clean ac.

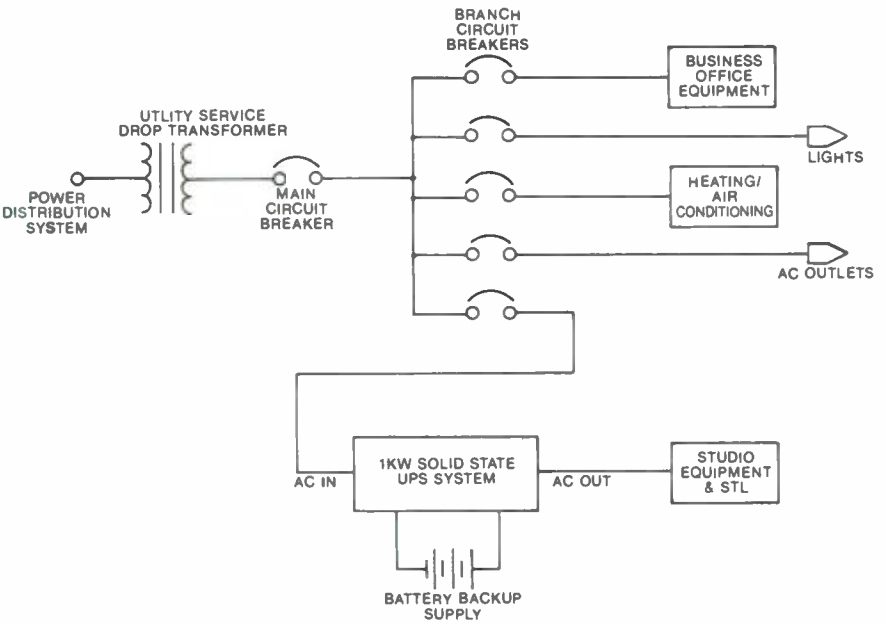


Fig. 19. An application of the critical load power buss concept. In the event of a power failure, all equipment necessary for continued operation is powered by the UPS equipment. Non-critical loads would be dropped until commercial ac returned.

failures with small, dedicated, uninterruptable power systems. Small UPS units are available with built-in battery supplies for microcomputer systems and other hardware used by broadcasters. If cost prohibits the installation of a system-wide standby power supply (using generator or solid-state UPS technology), the engineer should consider establishing a *critical load buss* that is connected to a UPS system or automatic transfer generator unit.

This separate power supply would be used to provide ac to critical loads, thus keeping the protected systems up and running, as illustrated in Fig. 19. Unnecessary loads would be dropped in the event of a power failure. A standby system built on the critical load principal can be a cost-effective answer to the power failure threat.

THE EFFICIENT USE OF ENERGY

Utility company power bills are becoming an increasingly large part of a station's operating budget. In order to reduce the amount of money spent each month on electricity, the broadcaster must understand the billing methods used by the utility. Saving energy is more complicated than simply turning-off unnecessary lights.

The amount of money that can be saved through a well-planned energy conservation effort is often substantial. Reductions of 20% are not uncommon, depending upon the facility layout and extent of energy conservation methods already in use. Regardless of any monetary savings that might be realized from a power-use reduction program, the items discussed here should be considered for any well-run broadcast facility.

Billing Procedures

The rate structures of utility companies vary widely from one area of the country to another. Some generalizations can be made, however, with respect to the basic rate-determining factors.

The four primary parameters used to determine a customer's bill are (1) energy usage, (2) peak demand, (3) load factor and (4) power factor. These items can often be controlled, to one extent or another, by the customer.

Energy Use

The KWH usage can be reduced by turning-off loads such as heating and air conditioning systems, lights and office equipment when they are not needed. The installation of timers, photocells or sophisticated computer-controlled energy management systems can make substantial reductions in a facility's KWH demand each month.

Common sense will dictate the conservation measures applicable to a particular situation. Obvious items include reducing the length of time high power TV studio lights are in operation, setting heating and cooling thermostats for reasonable levels, keeping office equipment turned-off during the night and avoiding excessive amounts of indoor or outdoor lighting.

While energy conservation measures should be taken in every area of broadcast station's operation, the greatest savings can generally be found where the largest energy users are located. Transmitter plants consume a large portion of the monthly power bill, and so particular attention should be given to the equipment, physical layout and system efficiency at the RF facility.

Transmitter room heating should be accomplished with a logic controlled PA exhaust recycling system, and air conditioning equipment should be planned for efficient operation by a knowledgeable consultant in the field. Tower light photocells should be inspected regularly for proper operation, as should antenna element heating control systems. A failure in either of these two circuits can result in a substantial increase in power consumption (if failure latches the system on), or a potentially dangerous condition (if failure latches the system off).

The efficiency of the transmitter itself is an item of critical importance to energy conservation efforts. Most transmitters available today are significantly more efficient than their counterparts of just 10 years ago. In UHF, in particular, major efforts have been made in improving efficiency. Station management can often find economic justification for updating or even replacing an older transmitter on the power company savings alone. Most new transmitters specify a typical ac power consumption figure for the rated RF output, and this point should be seriously considered when the purchase of a unit is planned.

Comparing the efficiency figures of FM transmitters is a straightforward task, since the power consumption does not change with modulation. AM and TV transmitters, however, require further investigation. The overall efficiency figure of an AM or TV transmitter at a carrier-only condition is of little comparison use, since the system is never operated that way. Many manufacturers, though, are now specifying overall ac power consumption at *typical* or 100% modulation for AM transmitters, and *average* or *black picture* in the case of TV equipment. These figures make the comparison process easier and more accurate. Engineers should be somewhat cautious, however, about the typical or average modulation value because of the wide variation that could be expected with respect to what defines *typical* and *average*.

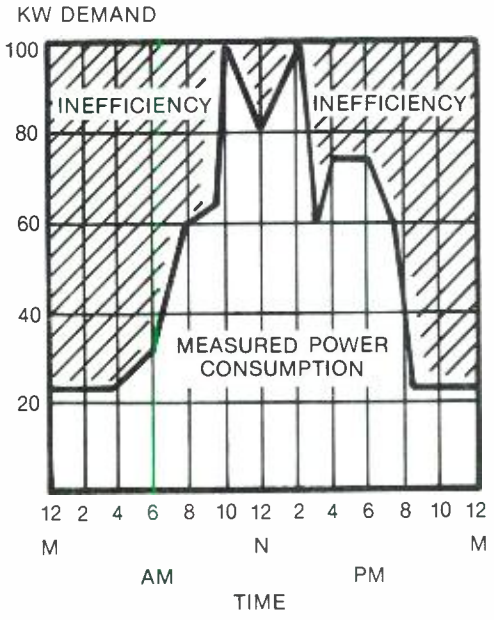


Fig. 20. The charted power consumption of a facility not practicing energy management techniques. Note the inefficiency that the utility company must absorb when faced with a load such as this.

After selecting a transmitter, the final amplifier stage efficiency should be monitored and any necessary tuning adjustments should be made to keep the unit operating at peak efficiency. A final amplifier even slightly out of tune can raise power consumption not only due to inefficient stage operation, but also due to increased air conditioning requirements caused by additional PA stage heat generation.

Significant advancements have been made in recent years that have improved the efficiency of new UHF-TV transmitters. Some manufacturers also offer conversion packages for updating older equipment to the current state-of-the-art.

In virtually any broadcast facility, energy conservation can best be accomplished through careful selection of equipment, thoughtful system design and good maintenance practices.

Peak Demand

Conserving energy is a big part of the power bill reduction equation, however it is not the whole story. The *peak demand* of the customer's load is an important criteria in the utility company's calculation of rate structures.

The peak demand figure is a measure of the maximum load placed on the utility company system by a customer during a predetermined billing cycle. The measured quantities may be kilowatts, kilovolt-amperes, or both. Time intervals used for this measurement range from 15 minutes to 60 minutes. Billing cyles may be annual or semi-annual. Fig. 20 shows an example of varying peak demand.

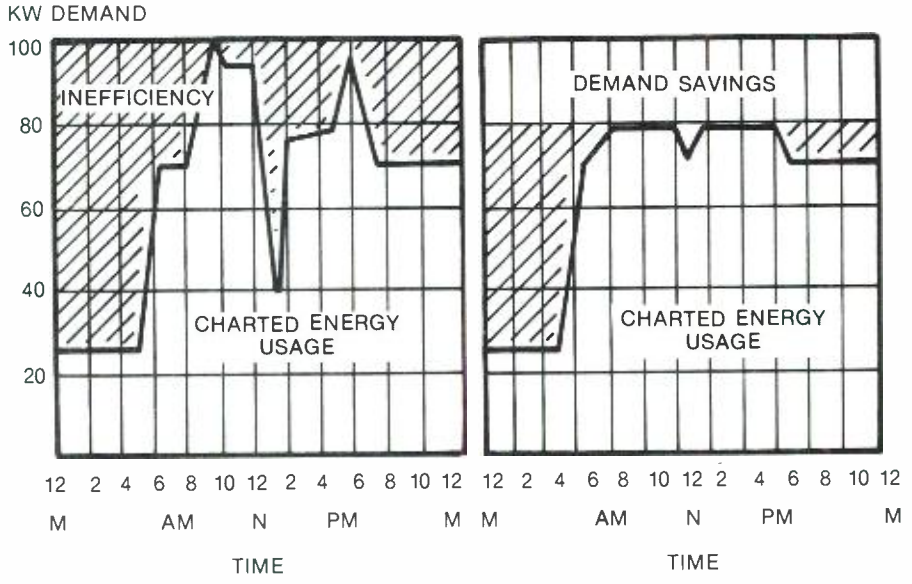


Fig. 21. An example of the successful application of a load shedding program. Energy usage has been spread more evenly throughout the day in the diagram on right resulting in reduced peak demand, and consequently, a better rate from the utility company.

If a facility operated at basically the same power consumption level from one hour to the next and one day to the next, the utility company could accurately predict the demand of the load, and size its equipment (including the allocation of energy reserves) for only the amount of power actually needed.

For the example shown in Fig. 20, however, the utility company must size its equipment (including allocated energy reserves) for the peak demand. The area between the peak demand and the actual usage is the margin of inefficiency that the customer forces upon the utility. The peak demand factor is a method used by utility companies to assess penalties for such operation, thereby encouraging the customer to approach a more efficient (from the utility's viewpoint) state of operation.

Load Shedding is a term used to describe the practice of trimming peak power demand in order to reduce high-demand penalties. The goal of load shedding is to schedule the operation of non-essential equipment so as to provide a uniform power demand from the utility company, and thereby a better KWH rate.

Nearly any operation has certain electrical loads that can be rescheduled on a permanent basis or deferred as power demand increases during the day. Fig. 21 illustrates the results of a load shedding program. This more efficient operation has a lower overall peak demand and a higher average demand.

Peak demand reduction efforts can cover a wide range of possibilities. It would be unwise from an energy standpoint, for example, to test a standby transmitter during the afternoon hours, when air conditioning units may be in full operation. Morning or evening hours would be a better choice, when the air conditioning is off and the demand of office equipment is reduced. For an AM plant, standby transmitter testing should be done during periods of low power operation, further reducing the peak-to-average ratio. Each broadcast operation is unique and requires an individual assessment of the load shedding options.

A very effective method of controlling peak demand is through the use of a computerized power demand controller. A controller can analyze the options available and switch loads as needed to maintain a relatively constant power demand from the utility company. Such systems are programmed to recognize which loads have priority and which loads are non-essential. Power demand is then automatically adjusted by the computer, based upon the rate schedule of the particular utility company.

Many computerized demand control systems will also give the customer a printout of the demand profile of the plant, further helping management analyze and reduce power costs.

Load Factor

The load factor on an electric utility company bill is a product of the peak demand and energy usage. It is usally calculated and applied to the customer's bill each month. Reducing either or both the peak demand or energy usage levels will decrease this added cost factor. Reducing power factor penalties will also help to reduce the load factor charges.

Power Factor

Power Factor (PF) charges are the result of heavy inductive loading of the utility company system. A poor power factor will result in excessive losses along utility company feeder lines because more current is required to supply a particular load with a low power factor than would be demanded if the load had a power factor close to 100%.

The power factor charge is a penalty that customers pay for the extra current needed to magnetize motors and other inductive loads. This magnetizing current does not show up on the service drop wattmeter. It is, instead, measured separately or pro-rated as an additional charge to the customer. The PF penalty charge can sometimes be reduced through the addition of on-site power factor correction capacitors. The capacitors provide a leading power factor to offset the lagging power factor of inductive loads. When a balance is made, the PF is 100%.

Power factor meters are available for measurement of a load's PF performance. It is usually less expensive in the long run, however, to hire a local electrical contractor to conduct the PF survey and recommend possible correction methods.

The use of power factor correction capacitors is usually the simplest and most versatile method of PF improvement. The point of diminishing returns for PF correction is approximately 95%. Loads which exhibit a power factor below 95% can usually benefit economically by the installation of power factor correction components. An experienced electical contractor and the local utility company should be consulted before any attempt is made to change a broadcast facility's power factor situation.

Possible sources of PF problems include transmitters, blowers, air conditioners, heating equipment and fluorescent and high-intensity discharge lighting fixtures ballasts. Most transmitting equipment exhibits fairly good PF performance, with 90-95% being typical. When purchasing a new transmitter, this point should be taken into consideration, due to the increased operating costs that may be incurred from the power company due to PF penalties.

Plant Maintenance

Any serious energy management effort should include an examination of the present circuit layout and maintenance procedures. Power system cables should be heavy enough to carry the full load demanded without heating losses. The system should also be examined for any loose connections, dirty contacts or cable insulation problems. Phase-to-phase load balance likewise should be checked on a regular basis at various points in the ac power distribution system.

BIBLIOGRAPHY

1. *Transient Voltage Suppression,* 4th Edition, General Electricic Company, Auburn, New York.
2. *The Development of a Guide on Surge Voltages in Low-Voltage AC Power Circuits,* By F.D. Martzloff (Fellow, IEEE, General Electric Company, Schenectady, NY), a paper from the 14th Electical/Electronics Insulation Conference, IEEE, Boston, Massachusetts, October 1979.
3. Highnote, Ronnie L., Ph.D,*The IFM Handbook of Practical Energy Management*, Old Saybrook, Connecticut: Institute of Management.
4. Technical report: "The Susceptability of the Open Delta Connection to Third Harmonic Disturbances," Quincy, Illinois: Harris Corporation.
5. Defense Civil Preparedness Agency, *EMP and Electrical Power Systems.* Publication TR-61-D, July 1973.
6. "The Effects of Power Disturbances on Computer Operation," by Thomas Key, *Electrical Construction and Maintenance,* September 1978.

7.4

Translators and Low Power Television Systems

Byron W. St. Clair
President
and
James R. McDonald
Manager, Documentation
Television Technology Corporation
Broomfield, Colorado

REGULATORY FRAMEWORK AND DEFINITIONS

Low Power Television and TV translators are governed by Part 74, Subpart G of the FCC Rules, which define a translator as a device which retransmits a television signal while altering none of its characteristics except frequency and amplitude. An LPTV station is defined as one that may operate as a translator or originate programming and operate as a subscription service. Under Subpart L of Part 74, an FM translator station is defined identically to a TV translator, except that its operating frequency is within the FM broadcast band. Block diagrams and typical installations of these stations appear in Figs. 1 through 6.

MULTIPLE OUTPUTS

The use of more than one output at a translator station may be authorized, if connected to different antennas whose patterns do not overlap and whose different outputs provide signal to different communities or areas. Manufacturers have responded to this provision by designing translators having multiple outputs and translator amplifiers which will accept a single translator output and provide up to four outputs identical to it, thus allowing the translator operator to expand his coverage area in each four different directions. Such a multiple output amplifier is diagrammed in Fig. 4 on page 7.4-98. Although the regulations place no specific upper limit on the number of outputs, more than four of one polarization is usually impractical because of the problem of transmitting antenna pattern overlap.

SITE SELECTION

The selection of a site for a station must satisfy regulatory, engineering and practical requirements. All types of translator and Low Power TV stations are defined by the FCC Rules as providing a secondary service which must not cause interference to any primary broadcast service or to existing land mobile communications services. Additionally, earlier services are protected from later installations of the same type. From a technical viewpoint, the requisite input signal must be available at the site or deliverable to the site by economically feasible means and a clear propagation path from the transmitting antenna to the planned service area is of crucial importance if useful service is to be provided with the relatively low power transmitters ordinarily permitted under Part 74. Practically speaking, the translator site must be accessible under varying weather conditions and not subject to erosion or other damage from wind, snow, heat or water.

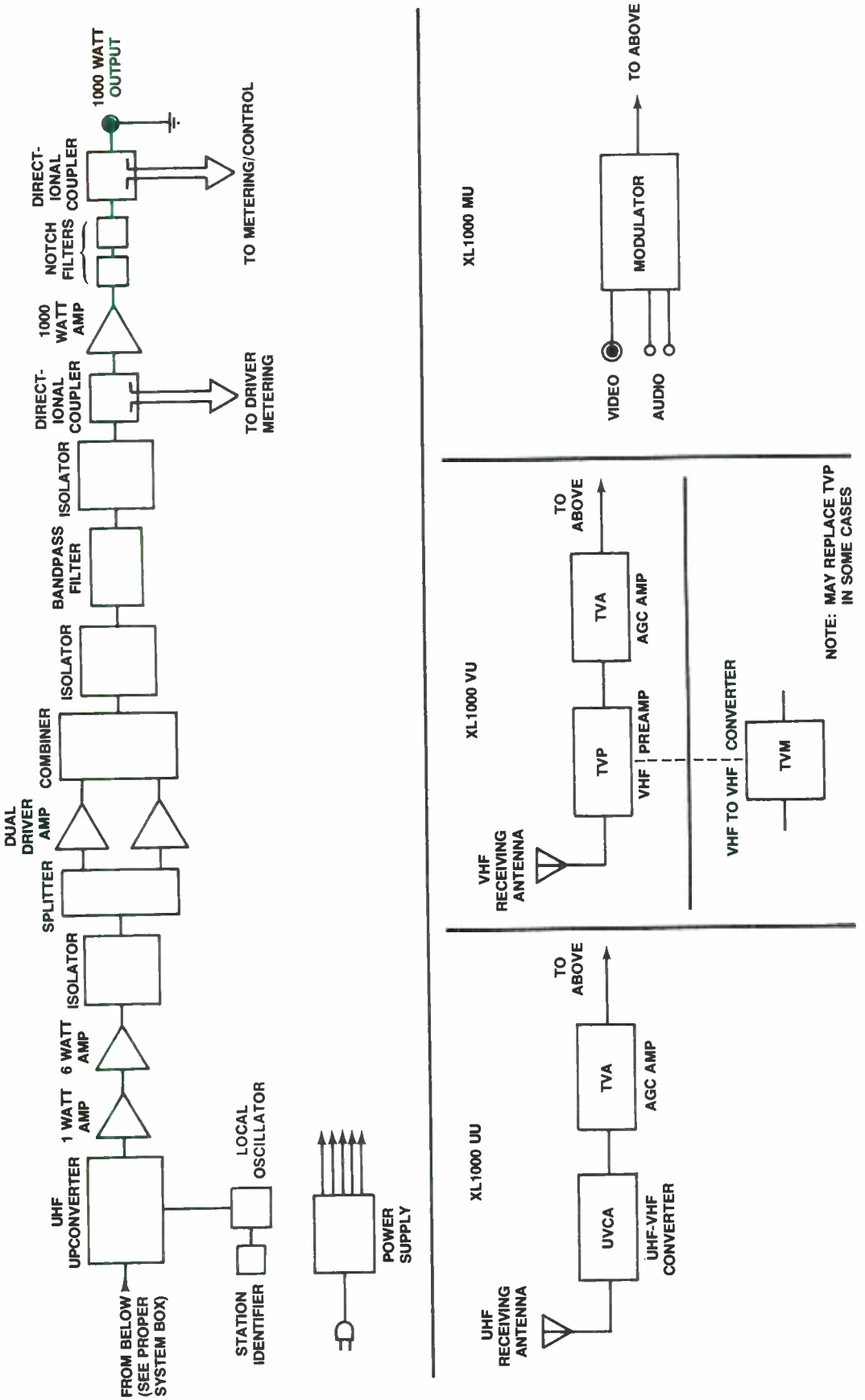


Fig. 1. Block diagram, television technology XL1000U LPTV Transmitter.

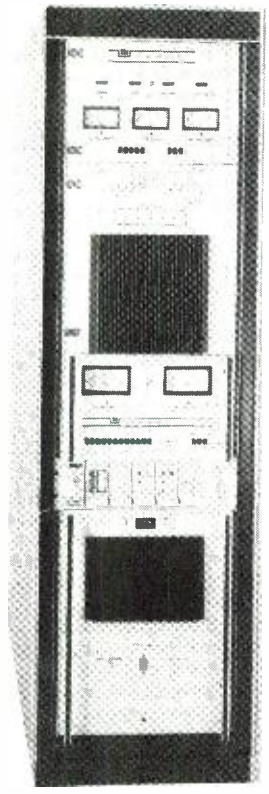


Fig. 2. Television technology XL1000MU LPTV transmitter.

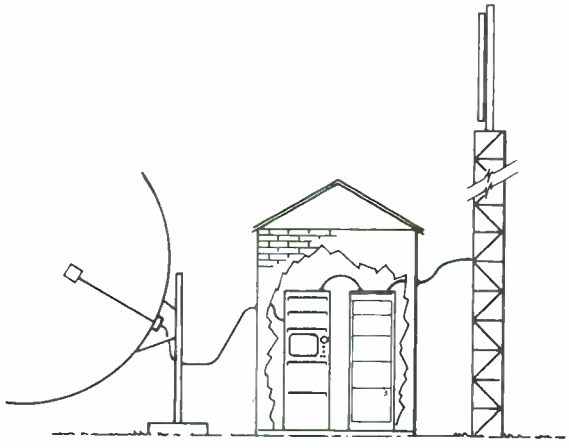


Fig. 3. Satellite fed only LPTV station.

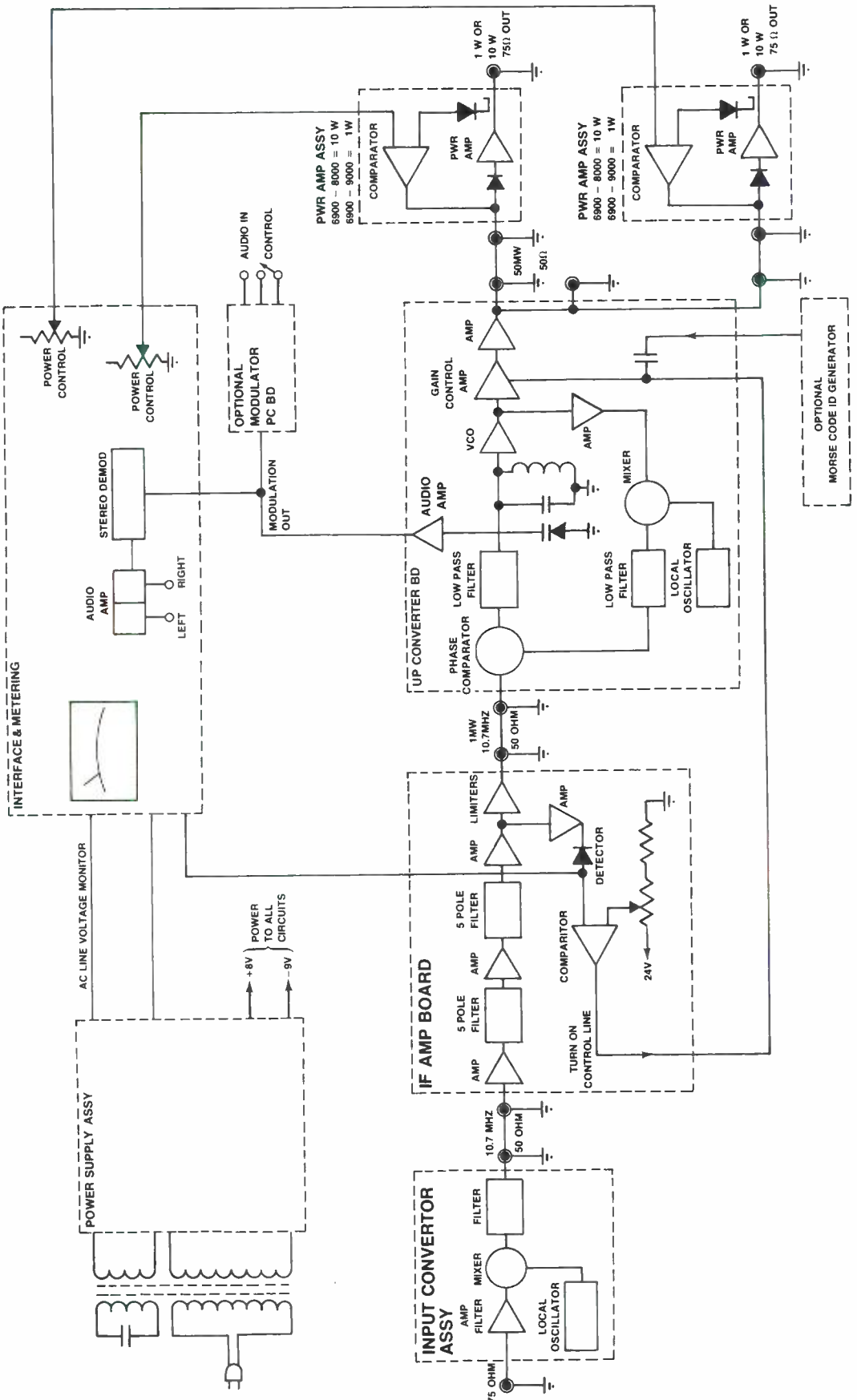


Fig. 4. Block diagram, TTC FM translator.

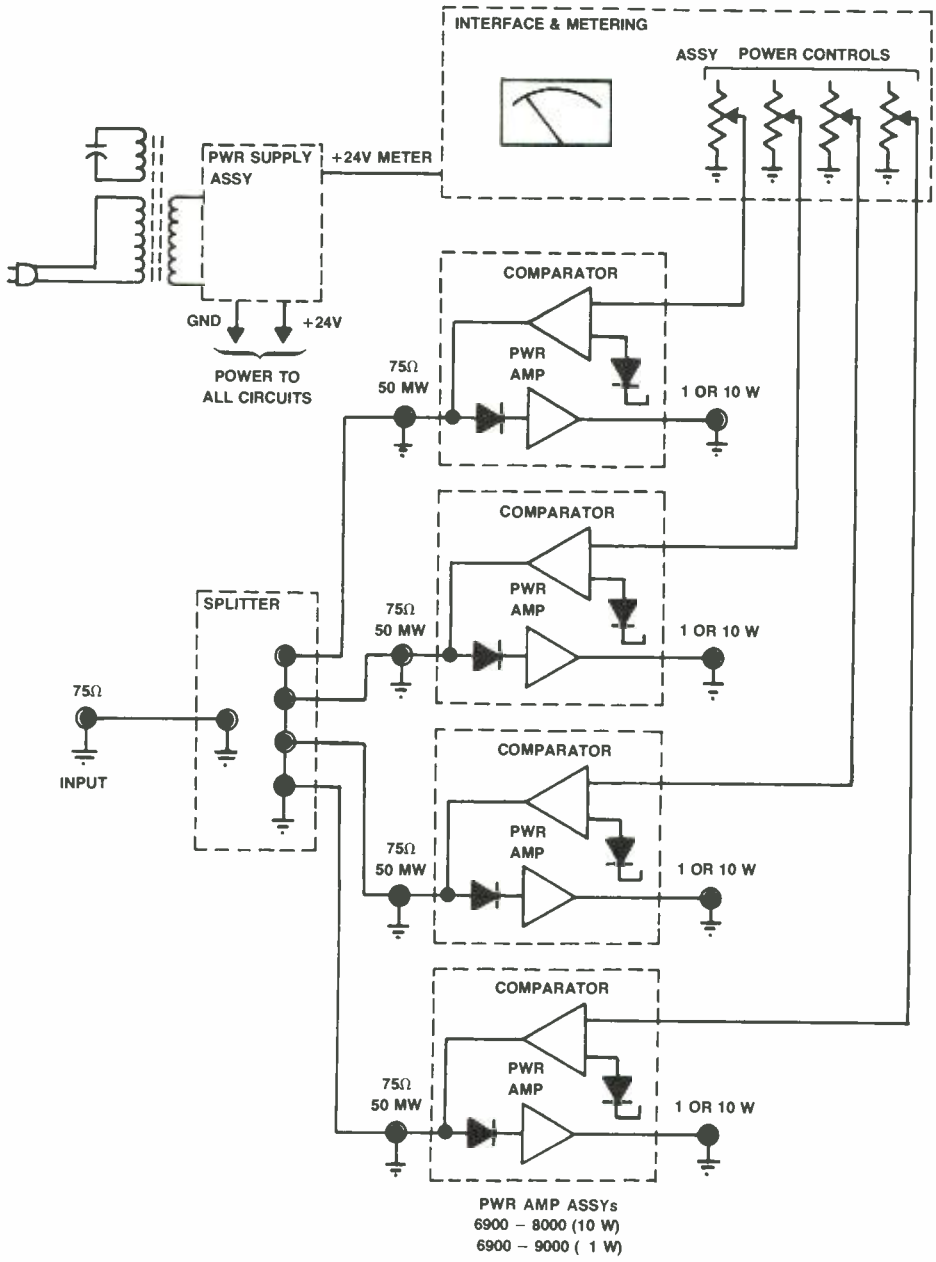


Fig. 5. Block diagram, TTC multiple output FM amplifier.

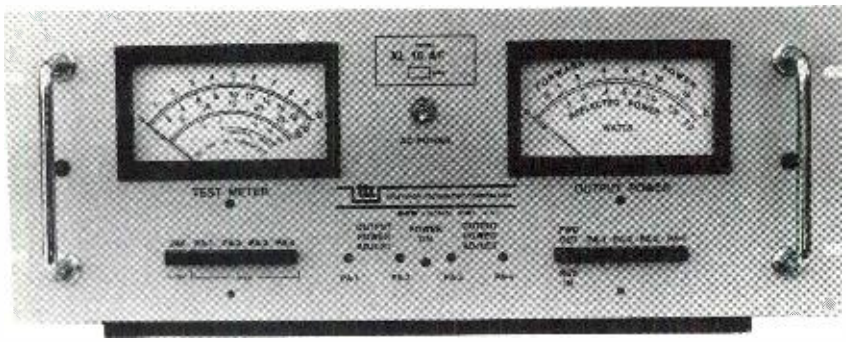


Fig. 6. TTC multiple output FM amplifier.

TABLE 1
Eligibility Requirements and Permissible Program Sources

	Translator	LPTV (Originate)	FM Translator
Who May Operate	Any Financially and Legally Qualified Individual, Group, Broadcast Station or Governmental Body		
What Station May Carry	Rebroadcast of TV Station, LPTV, or Microwave, Satellite, Translator Relay	Same as Translator Plus Local origination, Subscription TV	Full Power FM Except Any Owned by Licensee
Where	See Tables 2 and 3		

TV Regulatory Requirements

Parts 74.705 and 74.707, which outline detailed interference protection standards for LPTV and translator installations, are summarized in Table 2. After establishing a permissible site location, the predicted field strength based upon height above average terrain (HAAT) and effective radiated power (ERP) must not conflict with co-channel and certain other full service stations or existing LPTV stations. Unlike full power TV stations licensed under Part 73, HAAT for Part 74 installations is determined along a radial whose heading is in the direction of concern, rather than averaged over a full 360° circle of radials. Table 3 shows the required field strength ratios.

The restrictions reflected in Tables 2 and 3 apply to operating full-service stations but it is important to take into account the TV Table of Assignments in 73.606 to allow for future TV stations in making channel and site selections.

FM Regulatory Requirements

FM translators rebroadcasting a commercial FM station are authorized to operate on Class A channels, but a channel must be selected which will cause no interference to primary stations or other FM translators. If it is not possible to select a Class A channel and a class B or C channel seems suitable, it is necessary to include with the application a request for waiver of 74.1202 (b) (1) of the Rules. The request must include a detailed engineering showing that no Class A is available in the service area.

Noncommercial FM translators are authorized to operate on FM channels 201 through 220 from the Table of Assignments used by noncommercial FM stations.

FM on-channel boosters have also been used, but may only be licensed to the primary station whose signal the booster will retransmit *within* the station's 1 mV/m field strength contour. There are some severe engineering limitations which confine their use to very special situations. Multipath problems can occur in two ways with on-channel boosters. (1) Any location which will receive signals from both the originating station and the booster will exhibit multipath reception problems, and (2) if the output from the booster contaminates the input with the booster station's own signal, multipath deriving from multiple trips though the booster will degrade the signal.

The transmitted signal from a booster is typically 90 to 110 dB stronger than the desired input signal and if the feedback contamination is to be held to -30 dB as a limiting value, the isolation between receiving and transmitting antennas must be in the 120 to 140 dB range and the circuitry of the booster must be designed to preserve this isolation. Very substantial shielding

TABLE 2
Prohibited LPTV Transmitter Site Locations

PROPOSED LPTV IS:	REGULAR TV		EXISTING LPTV[c]	
	VHF	UHF	VHF	UHF
Co-channel or adjacent channel[a]	within Grade B[b]		within protected contour	
14 or 15 channels above	n/a	within Grade B	n/a	within protected contour
7 channels below	n/a	spaced less than 100 kilometers (62 miles)		
2, 3, 4 or 5 above or below	n/a	spaced less than 32 kilometers (20 miles)	n/a	no restriction

TABLE 3
Interference Protection — Field Strength Ratios

PROPOSED LPTV IS:	REGULAR TV		EXISTING LPTV	
	VHF (protected within Grade B contour)	UHF (protected within Grade B contour)	VHF (within protected contour as defined)[c]	UHF (within protected contour as defined)[c]
Co-channel	−45dB or −28dB with off-set (interference based on F (50,10) chart)			
	Note — all values below based on F (50, 50) chart			
lower adjacent	+ 6dB	+15dB	+ 6dB	+15dB
upper adjacent	+12dB	+15dB	+12dB	+15dB
7 channels below	n/a	n/a	n/a	0dB
14 channels above	n/a	+23dB	n/a	+23dB
15 channels above	n/a	+ 6dB	n/a	+ 6dB

[a]Channels 4 and 5, 6 and 7, and 13 and 14 are not adjacent.
[b]Protected contour is Grade B, defined by the following field strengths; CH 2-6, 47dBu; Ch 7-13, 56dBu; Ch 14-83, 64dBu.
[c]The protected contour for a LPTV station is defined as the following field strengths: Ch 2-6, 62dBu; Ch 7-13, 68dBu; Ch 14-83, 74dBu.
n/a: not applicable

of the receiving antenna by the terrain or a building is necessary and the booster must have detached input circuitry located near the receiving antenna. Additional techniques for achieving sufficient isolation include spacing the input and transmitting antennas at least 300 feet apart, antenna cross-polarization and locating the antennas in one another's null areas.

Generally, the interconnection between the receiving and transmitting halves of the booster will be at an intermediate frequency such as 10.7 MHz and a reference conversion frequency must also be carried between the sections so there is no frequency shift whatever between the input and the output in the process of making two conversions. Finally, the FCC is quite aware of all these problems, so any application for an FM on-channel booster must include a statement concerning the steps which have been taken to prevent signal degradation due to booster operation.

TRANSLATOR AND LPTV COVERAGE

Coverage of full service high power stations is usually determined statistically by the use of the FCC F(50, 50) curves for the appropriate TV channel or for the FM band. These curves are detailed in FCC Regulations section 73.699 for TV and 73.333 for FM. They may be used as a guide for LPTV or translator coverage but it is more desirable to make an estimate of the area to be covered using topographic maps to determine the areas which can be reached with a propagation path having at least 0.6 first Fresnel Zone clearance.

For a signal path whose origin is within about five miles of the translator site, ordinary rectangular graph paper may be used. At greater distances 4/3 earth radius paper should be used which takes into account the earth's curvature and

the slight normal bending of radio waves in the earth's atmosphere. 4/3 graph paper is readily available from most translator or microwave equipment manufacturers as a promotional give-away item. Fig. 7 is an example of this paper.

An assumption must be made about the height of the listener's or viewer's receiving antenna. The FCC assumes 30 feet above ground to be a nominal receiving antenna height for purposes of the 50/50 tables; when dealing with the substantially lower power of LPTV and translator installations, however, a more conservative approach would be to assume the average receiving antenna to be located at 10 feet above ground.

The following formula is provided to locate 0.6 first Fresnel Zone clearance:

$$R = 2280\sqrt{\frac{d_1 d_2}{Fd}}$$

Where:

R = first Fresnel Zone in feet;

d is the distance from transmitter to receiver;

d_1 is the distance from transmitter to the significant obstacle in miles;

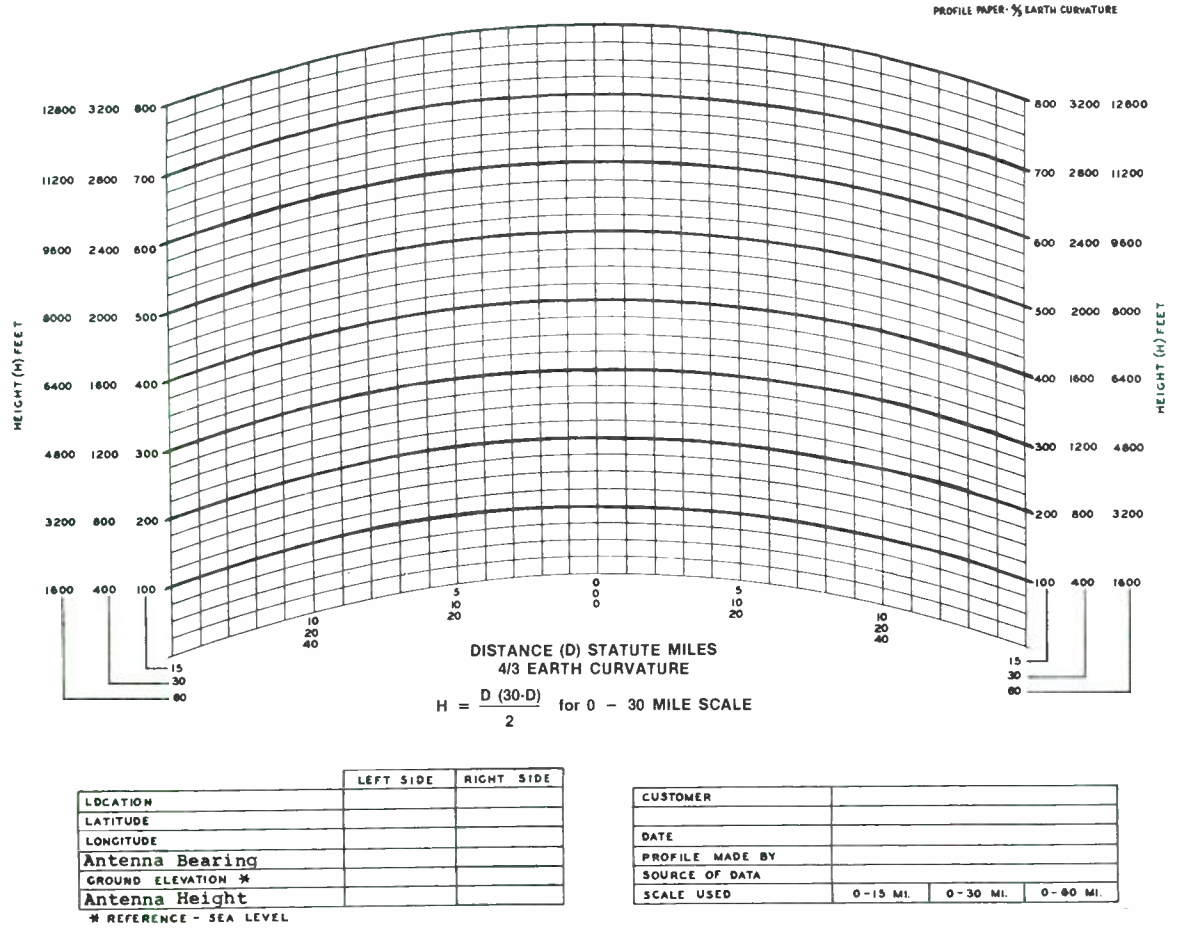
d_2 is the distance from the significant obstacle to the receiver in miles; and

F is the frequency in megahertz of the subject signal.

Clearance is then 0.6 R.

Once the clearance has been determined, add a little headroom to allow for trees, buildings, and other additions to the terrain. Depending on local circumstances, this amount may range from 25 to 60 feet.

The signal strength available to the most distant area of interest must be determined using the above approach and, taking into account the inverse square law which states that a signal will decrease in intensity by a factor of four for every doubling of distance. For example, a coverage rate increase of 3.16 is achieved with an effective radiated power increase of 10 (3.16 is the square root of 10). Such an increase in ERP can be achieved by increasing transmitter power or trans-



	LEFT SIDE	RIGHT SIDE
LOCATION		
LATITUDE		
LONGITUDE		
Antenna Bearing		
GROUND ELEVATION *		
Antenna Height		

* REFERENCE - SEA LEVEL

CUSTOMER			
DATE			
PROFILE MADE BY			
SOURCE OF DATA			
SCALE USED	0-15 MI.	0-30 MI.	0-60 MI.

Fig. 7. 4/3 Earth profile chart.

TABLE 4
Free Space Path, Signal Reception Distance in Miles.

	VHF				UHF					
	10W Lowband Ch 2-6		10W Highband Ch 7-13		100W			1000W		
Horizontal Angle	Omni 20W ERP	90° 80W ERP	Omni 40W ERP	90° 160W ERP	Omni 710W ERP	220° 1000W ERP	80° 2450W ERP	Omni 7100W ERP	220° 10000W ERP	80° 24500W ERP
Rabbit ears or loop indoors	3	6	3.5	7	3	4	5.5	9.5	12.5	17
Small outdoor	12	24	10	21	9	11	16.5	28	35	52
Large outdoor	17	34	15	30	15	18	28	47	56	88
Large outdoor w/preamp	20	40	21	42	30	36	56	95	114	177

Low band in particular and to a lesser extent high band reception may be inhibited by man made noise and long distance co-channel interference.

Heavy foliage will reduce usable distance of UHF signal to about ¼ of above distance. Reception at distances in excess of 40 miles will frequently be limited by earth's curvature.

ERP (Effective Radiated Power) is typical practical value for transmitter power shown. Distances in this chart are based upon *distances* only and assume a "free space" propagation path exists to receiving antenna.

mitting antenna gain. Higher antenna gain is obtained at the expense of narrower beamwidth and increased tower and antenna costs. Thus, antenna gain usually becomes a compromise between the horizontal angle of coverage and the maximum distance required of the signal. High antenna gain through restricted vertical beamwidth requires an antenna array that is large in its vertical aspect. If it is many wavelengths high, it will be difficult to install and costly. Vertical beamwidths of two or three degrees are achievable—particularly at UHF—but such high gain antennas must be installed exactly perpendicular to the horizon within a tolerance of a small fraction of a degree, requiring very precise installation and a tower of sufficient rigidity to maintain the tolerance even in strong winds. Additionally, such high gain antennas often require beam tilt compromises or null fill for satisfactory reception close to the translator. The discussions in Section Two of this book on the subject of full power antennas are applicable to LPTV and translator installations except that the latter more commonly used directional antennas.

A frequent oversight in LPTV and translator planning has been the existence of feedline losses. The chapter on that subject will provide substantial understanding of the phenomenon and how it applies to various types of feedline. LPTV and translator installations, because they are often designed under severe budgetary restraints and operate at relatively low power, frequently use low cost and small diameter coaxial cables. The hardware savings in these cables are achieved at the cost of signal level. Transmitting antenna feedlines are generally low loss and are provided with detailed engineering data which allow the user to accurately calculate and allow for losses.

Not so complete or accurate, however, is the information which accompanies much of the

small diameter 50 or 75 ohm receiving antenna cable used at the input of a translator. Two hundred feet of commonly used RG-59/U cable can cost up to 12 dB of signal at 200 MHz and become virtually useless at UHF. It is therefore important to carefully select the best cable possible for the application.

INPUT SIGNAL CONSIDERATIONS

The delivery of the input signal to the transmitter is an extremely important part of the overall system design, as the quality of that signal may be the limiting factor in the system's overall performance. Previously, the cable degradation of the input signal strength has been discussed but there are other factors which also become important. Virtually every conceivable method of input signal delivery can be found in use and each one has its unique problems and solutions.

All translators were originally confined by regulation to rebroadcasting signals received off the air from primary stations or other translators. Although 1983 saw these restrictions lifted for TV, FM translators are still so confined. Now TV translators may use any technically feasible arrangement. In addition to off the air reception, both AM and FM microwave and satellite fed signals are in common use. A few LPTV stations are fed directly from video tape recorders or by direct connection to an adjacent studio. Microwave, VCR and direct video/audio signal delivery require that a modulator be part of the transmitter; off the air signal delivery requires the use of reception circuitry with a heterodyne mixing system which converts the already modulated input signal to a new channel without demodulation.

Recently, there has been some demand for unattended switching systems that do not merely shut off the translator carrier in the absence of input signal, but rather select another available input signal, usually from a local modulator. This allows local origination in the event of failure of the normal supply signal.

VHF, FM and UHF off the air signals are commonly used in translators and sometimes require extraordinary measures to receive and retransmit cleanly. With respect to management of the input signal, the translator operator is faced with similar technical problems as the cable TV operator, for indeed, if satisfactory reception of the desired signal were easy to achieve, there would be no need for either service. The major problem faced by both is usually a weak signal with poor signal-to-noise ratio. This signal must be pried loose from the noise before it enters the transmitting system as the transmitter will send to the transmitting antenna whatever signal it is provided, noise and all. Thus, a well designed receiving antenna, preamplifier and signal conditioning system must be built into the receiving half of a translator.

Of these, the most important is the receiving antenna and its location. Location, height and cable length have already been discussed so this discussion is limited to the antenna array itself. Numerous techniques have been employed to maximize the performance of receiving antennas. If reliable and noise-free reception can be achieved with a single cut-to-channel yagi on a tower conveniently close to the translator, the operator is fortunate. More often, it will be necessary to increase the antenna gain or narrow the pattern beyond that achievable with such an arrangement.

Sometimes the approximate 30 degree horizontal pattern width of a single receiving antenna allows reception of an interfering signal from a different city. Techniques for solving translator reception problems include antenna-mounted preamplification, signal filtering, and several antenna stacking techniques, both horizontal and vertical.

Briefly, preamplification increases signal level, filtering minimizes out-of band products, stacking increases antenna gain and directivity, and can make positive use of the phase differences at varying angles from the supplying station's or an interfering station's transmitter or those found in certain reflected signals.

Preamplification

Tower-mounted preamplifiers are available from many manufacturers and commonly have gains varying from 10 dB to over 60 dB. Most are powered from a dc voltage impressed on the transmission line between the preamplifier and the translator, thus making use of the translator's available power. Translators not equipped with dc power diplexers for this purpose may ordinarily be so equipped upon inquiry to the manufacturer of the translator or the preamplifier. Preamplifiers are mounted as close to the antenna as possible because the received signal is subject to further losses and increased noise as it travels down the cable to the translator. This occurs due to cable capacitance, impedance variations arising from kinks, bends, and connectors, and losses resulting from line resistance.

Ideally, a well-selected preamplifier will have no effect on the received signal except to augment its amplitude sufficient to overcome all system and cable losses and render the signal useful. A preamplifier having 45 dB gain does not necessarily perform better than a unit whose gain is 20 dB. High-gain preamps are more prone

to overload with increased signal input. Each preamplifier must be carefully selected to match the installation and its input signal requirements must not be exceeded. An overloaded input stage will produce a severely distorted signal that can never be "cleaned up" by any subsequent stage. Further, if a preamplifier sees at its input a poor signal-to-noise ratio, the same—or slightly worse —signal-to-noise ratio will show up at its output.

Filtering

This technique may be used in any of several ways. A translator's input amplifier is typically tuned to the frequency of use, providing substantial attenuation of out-of-band products. Particularly in early gain stages of translator equipment, tuning is not particularly sharp as increasing sharpness of input tuning tends to make this system noise figure rise. Individual cimcumstances may dictate that this phenomenon be accepted, thanks to a strong first or second adjacent signal which might either take a "free ride" into the translator or, more commonly, overload the input.

Bandpass filters or traps may be used at the input to the equipment or on the tower to solve special reception problems. A bandpass filter normally attenuates all but the desired signal and a trap is selected to attenuate a specific interfering signal. Use of either equipment is subject to the attendant increase in system noise figure because of their insertion losses, which may range from 0.5 to 6 dB.

Antenna Stacking

Properly used, this technique will deliver the cleanest signal to the translator. Antenna stacking can become critical and expensive for the same reasons that numerous transmitting antenna elements become so. See the section on translator and LPTV coverage earlier in this chapter for the discussion of that subject. The one major difference is that the supply signal comes from one point and thus reception from any but the exact desired direction is unwanted. Antennas may be stacked in the horizontal plane and in the vertical plane. Additionally, they may be offset to solve a particular reception problem.

Horizontal stacking: This technique is used to narrow the beamwidth from side to side of the array and to add 3 dB to the antenna gain for each doubling of the antenna stack if the antennas are connected together in phase. A single yagi antenna has a horizontal angle of acceptance that is about 30 degrees wide between the 3 dB down points off its front. Utilizing horizontal stacking, the horizontal beam width can be substantially reduced and specific off-axis signals can be greatly attenuated. This technique does not alter the vertical beam width of the array.

Vertical Stacking: This method affects the vertical beam width and is useful to enhance the gain of the array.

Stacking Variations: Normally used to solve particular reception and interference problems, antenna stacking may be varied in several ways. One of them is offset antenna arrangements, allowing phase reinforcement off the front of the array and phase cancellation off the rear of the array. Here is how it is done: Vertically stack the antennas, with one antenna forward of the other by exactly 1/4 wavelength at the center frequency of the channel to be rejected. That distance in inches is provided by the formula:

$$d(\text{inches}) = \frac{2951}{\text{Frequency of undesired signal (MHz)}}$$

Connect the rearmost antenna to the common junction with a short length of feedline, and connect the forward antenna to the common junction with a feedline whose length is the result of the above formula multiplied by the velocity of propagation of the cable used, plus the amount of cable used for the rear antenna. This is required because signals travel faster in free space than in cable. The velocity of propagation of a cable will normally be expressed in percent. Therefore, if 1/4 wavelength is 15.1 inches and the cable has a velocity of propagation of 68% and the rear antenna requires 8 inches of cable to arrive at the common connection, the forward antenna will require 68% of 15.1 plus 8, or 18.268 inches of cable running to the common connection. At the subject frequency this will cause the antennas to add when reception is off the front and cancel the signal received off the rear.

In another arrangement, the spacing from one antenna boom to the other can be set so that cancellation of an unwanted signal arriving from a particular forward direction can be achieved. The antennas are installed with the center of each spaced such that the undesired signal is out of phase at the connection between the two antennas, so that the interfering signals cancel one another at the combined output, while the desired station received along the aiming axis appear in phase.

TRANSMITTING SYSTEMS

The FCC technical standards for TV translator and LPTV transmitting systems are in Part 74.750 and those for FM translators are contained in 74.1250 of the FCC Rules. Although transmitting equipment and linear amplifiers such as

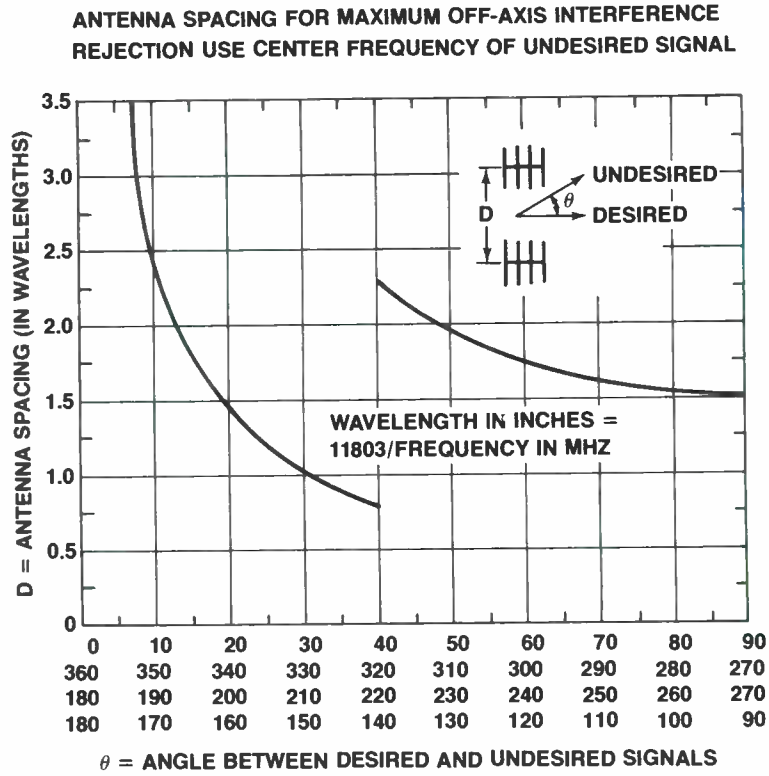


Fig. 8. Antenna spacing chart.

multiple output amplifiers must be type-accepted by the FCC, no such requirements exist for antennas or auxiliary equipment.

Antennas

With respect to transmitting antennas, there are several types available. For omnidirectional use at UHF, slot antennas have found wide use. The radiating elements of these antennas are "windows" in a metal tube, whose size is a function of the channel or channels used. Some of these antennas are broadband allowing the use of a single antenna for several diplexed transmitters. For omnidirectional FM use, low-power versions of the standard FM transmitting antennas are used and can be provided in horizontally and elliptically polarized models. Additionally, FM turnstile antennas are available. Directional antennas for all transmitting purposes within the translator and LPTV industry often resemble heavy-duty versions of their receiving counterparts. FM and VHF-TV antennas, commonly rated in power to 100 watts are often Yagi, log-periodic or folded dipoles with a single reflector and may be stacked to provide higher antenna gain. UHF directional antennas may take the form of dipole/reflector arrays resembling receiving antennas or may take the form of panel antennas. A panel antenna consists of a group of driven dipoles and matching electronics all mounted on a panel and covered by a radome. Virtually all transmitting and receiving antennas are available in 50 or 75 ohm models.

For a particular installation, the terrain studies covered earlier in this chapter will have already determined that the antenna selection will be a general type. By this time, the operator will know the necessary gain, height, and directivity pattern required of the installation. However, several other considerations peculiar to antennas will still be open to discussion. One of the most important is the relationship between the tower and the radiating elements.

Not only must the tower be capable of withstanding the wind loading presented by the antenna, it must not substantially alter the antenna's directivity pattern after installation. Mounting must be made to minimize the tower's electrical effect on antenna performance. In any antenna selection, the antenna and tower manufacturers selected must be consulted about all phases of these possible problem areas.

Transmission Lines

Cautions about the low-cost small diameter coaxial cable used in some receiving antenna installations or between components within equipment have been outlined earlier in this chapter

and installation considerations are located toward the end of the chapter. Losses in this or any transmission cable must be taken into account when planning the installation. For LPTV and translator use, transmitting feedlines normally are available in two configurations.

Foam Dielectric:

This cable is flexible and does not require pressurization. It also exhibits comparatively high losses in use. Prolonged exposure to high temperatures have sometimes caused center conductors to migrate and exhibit subsequent variations of impedance along the cable. If its losses are acceptable within the limits set by the transmitting antenna gain and transmitter output power capabilities and it is installed carefully with no kinks or sharp bends, it may prove to be an economical alternative to air-dielectric transmission line.

Air Dielectric:

This transmission line is manufactured with a spiral-wound spacer along its length which holds the center conductor in position. It is much stiffer in use than foam cable and is thus more difficult to handle and install properly. Its diameter ranges in size from 1/2″ to 5″ but the most commonly used sizes in translator and LPTV applications are 7/8″ and 1-5/8″. By comparison to foam cable, losses are lower but it requires pressurization, usually supplied by a nitrogen bottle and regulator situated near the transmitter and connected to a pneumatic joint on a cable connector.

Towers

The tower supporting any broadcasting antenna is an extremely important item in the overall installation. Towers are costly, have great impact on the surrounding environment, and are potentially dangerous. The loss of a tower in an LPTV installation can cost more time off the air than the loss of virtually any other major component and can cause severe damage. Therefore, the initial cost of the best grade tower for the purpose will not equal the cost of two towers plus whatever other damage might be done in the event of failure.

The FCC may require with the application an environmental impact statement if erection of the tower is in certain areas or is 300 feet or more in height. Section 1.1305 of the FCC Rules is the source of the correct and current information. If an installation meets the test of a "major action" under this rule, the application may be subject to delays or rejection and a second choice tower location may be indicated. Additionally, the FAA has a great interest in radio and television towers. Part 17 of the FCC Rules deals with the subject of marking, lighting, and maintenance of antenna structures.

Standing Wave Ratio, Combiners, Isolators and Systems Considerations

The combination of installed feedline and antenna represent the load into which the transmitter will be expected to operate. In the ideal case, the system would represent a lossless system having a standing wave ratio of 1:1. In practicality, a completed antenna system installation will show a higher VSWR . . . typically, up to 1.4:1 upon initial measurement. If it runs higher than that, there may be some problem with the installation. Adverse moisture conditions and aging of the transmission line will usually make the VSWR rise over time; thus, it is most important to get it as low as possible during initial system installation. Particularly at UHF, isolators are frequently used to absorb reflections in the transmission system as well as to protect the transmitter.

The Television Technology XL1000U transmitter, diagrammed in Fig. 1, incorporates a circuit which turns the output power level of the unit down as VSWR rises, thus protecting the equipment and allowing the signal to remain on the air.

Translator installations, thanks to their normally unattended operation, are likely candidates for such protection as the VSWR is not monitored on a frequent basis. It is important that some form of protection, whether an isolator or a power reduction circuit, be used in unattended applications.

There are several other factors to be considered in the overall transmitting system. The combination of a transmitter and receiving elements on the same site implies some possible problems of signal feedback and noise. With most translator frequency selections, signal feedback does not cause the same "multiple trips through the equipment" problems inherent in FM boosters, but does cause an increase in system noise. Selection of an output channel widely spaced from the frequency of the input channel and physical separation of the receiving and transmitting antenna elements will improve this situation. If the assigned channels are close-spaced, the input tuning of the translator can, if necessary, be tuned more sharply and signal filters, as discussed previously, may be used.

Careful antenna placement is normally the best overall engineering approach to feedback reduction. Each antenna is normally provided with horizontal and vertical polar patterns which show the antenna's null areas. If the antennas are located within one another's null areas, the distance requirement between them may not be

so great. Although the horizontal null areas are the most frequently considered, high gain antennas in particular also allow beneficial use of the vertical pattern of each antenna. If the antennas can be practically mounted at different heights so that they are in one another's horizontal and vertical null areas, a substantial amount of possible signal feedback will be reduced. Other techniques include shielding by means of natural topographical features or buildings.

System Noise—TV

The noise figure in the specifications of a translator can become an important factor in the overall system performance. In a properly installed system whose input signal is of sufficient level (usually 750–1,500 microvolts) and having a good S/N ratio, the translator will provide a clean and relatively noise-free signal to its viewers. There are, however many cases in which the signal is very weak or the noise level is high and noise becomes one of the most critical issues in an installation. In a multihop translator system, the signal to noise ratio deteriorates with each hop. If, in addition to that noise increase, the signal is weak, evaluations must be made of each component in the system.

To evaluate an overall planned translator system, some data and requirements must be known. Measurement of the available input signal, study of the manufacturer's translator equipment specifications, and knowledge of the FCC Rules together provide the fundamental information for system planning. The noise factor of a typical installed translator system is determined by the following equation:

$$F_{abc} = F_a + \frac{F_b\text{-}1}{G_a} + \frac{F_c\text{-}1}{G_aG_b} \qquad [1]$$

Where:

F_a = Antenna-mounted preamp noise factor
F_b = line noise factor
F_c = Translator (input amplifier) noise factor
G_a = Preamp gain
G_b = Line loss

To convert noise factor to noise figure (stated in dB), use:

Noise Figure (dB) = 10 $\log_{10}$ Noise Factor

To determine the noise power at the input, use:

$$\text{Noise} = kTB \qquad [2]$$

Where:

k = Boltzmann's constant ($= 1.38 \times 10^{-23}$ joules/Kelvin)
T = Temperature Kelvin (nominally 289.9 degrees in temperate zones)
B = Bandwidth in Hertz

Using the above formulas and information and knowing (1) the available signal level, (2) the noise figure/factor of the translator, and, (3) the required 55 dB S/N ratio at the translator's output, it should not be difficult to plan a properly designed translator installation.

FM Noise Considerations

The TV system noise information is partially applicable to FM translators. Noise not transmitted by the FM translator will normally be removed by the limiter in the listener's FM radio, assuming his received signal level is high enough to achieve full limiting action. FM receivers are typically about 10 dB more sensitive than TV receivers and the bandwidth of an FM channel is 200 kHz rather than the TV channel bandwidth of 6 MHz, so there is less opportunity for the intrusion of atmospheric noise.

A TYPICAL UHF TRANSLATOR

UHF Input

Fig. 9 is a block diagram of a basic UHF translator. A UHF signal at the input enters the UHF-VHF input converter module where it is amplified, and mixed down to a VHF channel. The converter has a UHF stripline filter at the input followed by a broadband UHF preamplifier. A double balanced mixer is employed to maximize dynamic range. The local oscillator is a crystal oscillator followed by two to three stages of multiplication, depending upon the frequency of use. The input converter has a gain of about 20 dB.

VHF Input

If the translator is a VHF input model, the signal enters a VHF preamplifier, which typically contains a two-pole bandpass filter followed by a two-stage broadband preamp. The gain of the VHF preamp is variable and is normally factory set for the specific application. With some VHF input frequencies, the VHF input channel is converted to another VHF channel by a converter module. This additional conversion is necessary as direct conversion of some input channels to the UHF output channel will result

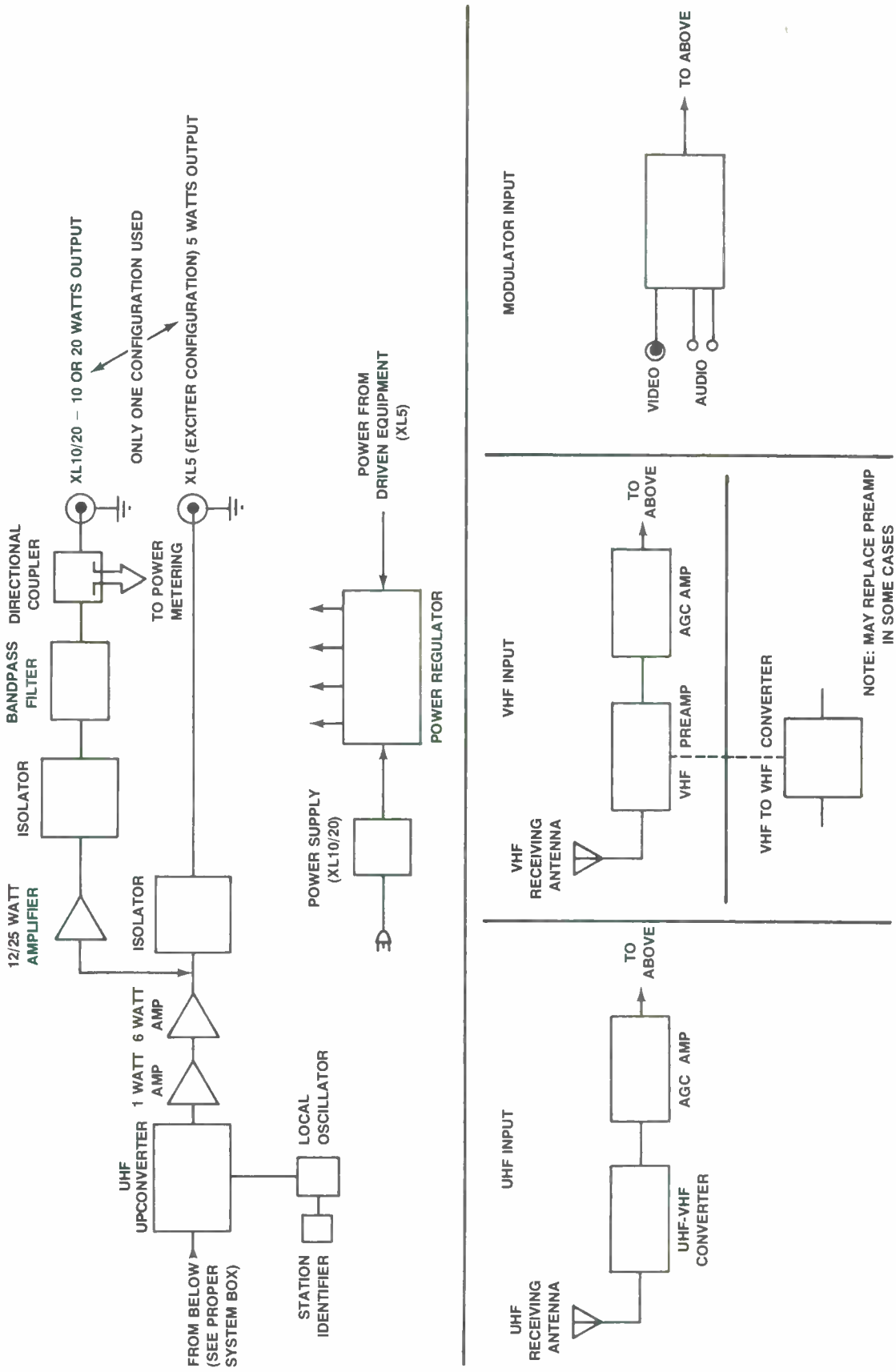


Fig. 9. TTC XL5-10-20U block diagram.

in spurious products that fall inside or close to the output frequency. This converter contains an input preamplifier feeding a double balanced mixer and post amplifier. The local oscillator is generated by a crystal oscillator feeding a multiplier stage (L.O. frequency times 1, 2 or 3). If the VHF input converter is required, it is set to have the same gain as the preamplifier it replaces, thus in either case leaving the balance of the translator identical.

From the input preamplifier or converter the input signal is fed to an AGC amplifier. This module contains most of the gain and filtering required in the translator and provides the necessary AGC. The unit illustrated contains two gain controlled stages separated by a four-pole bandpass filter. From the output of the second stage the signal travels through a variable aural trap circuit which can correct the visual/aural ratio if necessary. The trap is followed by a buffer amplifier. The output of the buffer stage is filtered by a two-pole filter before being amplified by a broadband high power hybrid amplifier. The output of the hybrid amplifier is tapped by a directional coupler before it appears at the AGC amplifier output. The sample of the output thus derived is detected and sent to processing circuitry which monitors both the visual and aural levels and sends corrective signals to the appropriate sections. The illustrated AGC amplifier has a maximum gain of 60 dB and its output level is set to 1.2 volts.

LPTV Application

If the equipment is an LPTV transmitter, the preceding modules are, of course not used. Instead, the RF output from the modulator is fed directly to the UHF upconverter.

The Mixing Process

The output of the translator's AGC amplifier or the transmitter's modulator is connected to a UHF upconverter module, or mixer. This module converts the VHF channel at its input to the assigned UHF output channel. To do this, it requires a local oscillator signal developed, in this instance, by a separate local oscillator module. The mixer's VHF input signal first goes through a variable attenuator after entering the UHF upconverter. This attenuator uses PIN diodes and is controlled by the power output control on the front panel. From the PIN attenuator, the signal is upconverted by a balanced mixer, then amplified to an approximate 50–100 mW level by a two-stage amplifier. The maximum overall gain of the upconverter is more than 12 dB. It requires a nominal 50 mW of drive from the local oscillator.

The local oscillator develops the necessary signal with a synthesizer which uses an 8 MHz crystal oscillator as its reference, followed by a two stage buffer-amplifier between the synthesizer and the output to obtain 50 mW for the upconverter.

Amplifier Stages

The output of the mixer is amplified by a one watt power amplifier which, in this instance, is biased for class A operation and typically has 9 dB gain. The output of this amplifier is between 1/2 and 1 watt depending on the output power required of the translator. The output of the one watt amplifier is supplied to the 5 watt amplifier, which is a Class AB amplifier having a gain of about 7.5 dB. The output of this amplifier enters the final amplifier module. This module is either a 12 watt or a 25 watt amplifier, depending on the output required of the translator. Class A amplifiers have higher power requirements as there is constant output current flow. These three amplifiers run off a 24 volt supply separate from the rest of the translator. This supply, called the 24 volt PA, is switched on from the "turn on" circuitry on the metering interface board.

Output Circuitry

The output of the final amplifier passes through an isolator followed by a bandpass filter before appearing at the output connector. The filter attenuates the intercarrier beat products and any spurious products occurring at the output of the upconverter. The isolator allows the final amplifier to see a constant 50 ohm load regardless of output VSWR or filter tuning. A directional coupler at the output connector monitors both the forward and reverse power and its tap outputs run to the power metering board, which contains the detectors and metering circuitry to measure forward, reverse and aural power. It also contains a splitter that routes a portion of the forward power to a front panel connector for connection of external equipment.

Additional Features

The metering and interface board contains all the metering for the modules within the translator. With the exception of the three UHF output modules, all the subassemblies within the translator plug into this board.

The board also contains a video presence detector that monitors a detected video output of the AGC amplifier and turns on and off the power supply which powers the amplifiers and meets FCC requirements for automatic unattended power shutdown.

There is an automatic Morse code keyer for station identification required on some installations. This keyer is adjustable to several time cycles and programmable to provide automatic frequency shifts to the local oscillator's output frequency.

LPTV Transmitter and Translator Specifications

These products are required to be type accepted by the FCC before they are sold. The Commission's "Radio Equipment List" is a published directory of such equipment. If there is a question regarding type acceptance, the manufacturer can provide the FCC file number of any piece of his type accepted equipment. Many of the specifications of LPTV transmitters and translators are self explanatory, but there are a few which justify explanation here. More detailed explanations of transmission standards can be found earlier in the *Handbook*.

Linear waveform distortion, often listed in specification sheets as "2T K" factor, is a measure of distortion of a picture's fine detail. The 2T sine-squared pulse and the 2T bar are used to define the K factor, which is the actual distortion. LPTV standards are met when the K factor is less than 3%.

Differential gain is the variation in gain of the translator of LPTV system for a small, high frequency signal (chrominance) at two specified levels of a low frequency signal (luminance) upon which the high frequency signal is superimposed. At an average picture level ranging from 10% to 90% the differential gain must not exceed 10%.

Differential phase is the variation in output phase of a signal like that used in differential gain measurements. It should not exceed 7 degrees over the range of blanking to white.

Envelope Delay is the delay within the system of the modulation envelope. It is typically a function of frequency, with higher frequencies having shorter delays. For transmitters, the standard is built on a baseline of the delay within the equipment found between .05 and .2 MHz. Up to 3 MHz that delay is to be maintained. Beyond 3 MHz the delay is to linearly decrease up to 4.18 MHz so that the delay is -170 nanoseconds with respect to the baseline at 3.58 MHz.

For translators, envelope delay should be flat. That is, the translator should not alter the delay relationships of the incoming signal.

TRANSLATOR/LPTV INSTALLATION CONSIDERATIONS

There are several considerations regarding the installation of an LPTV system. The instruction manual accompanying the transmitter or translator should be followed carefully. The requirements for the equipment's safe installation and operation are generally covered within the manual. Some of the more important considerations are discussed below.

Power

Although small transmitters often come equipped with power cords and plugs, the ac input of larger models should be hard-wired. Larger models may require three phase power. Three-phase transmitters are not to be connected to open delta primary power. Such a supply is subject to voltage fluctuations which could damage the equipment.

Special consideration should be given to lightning protection of all systems in view of the vulnerability of most translator or transmitter sites to lightning. Lightning arrestors should be installed in the service entrance. Ground runs of all types should be straight and short, and the electrical service itself well-grounded. For further information on lightning protection, see that chapter in Section 2.

Power circuits within a shelter should be branched. Each translator or transmitter is best connected to its own circuit breaker so a failure in one does not shut off the whole mountaintop. Breakers should be thermal type, capable for handling an inrush current of up to 1650 Amps for 1,000 watt translators. An ample supply of separately protected outlets should be available at the workbench and anywhere test equipment or tools may be needed.

About the Shelter

The quality of the shelter is of great importance for long life, serviceability and accessibility of the transmitter. The building must be kept dry, temperature controlled, clean and secure. The floor space should allow adequate space for each item of equipment, arranged so that all equipment doors can be opened and test equipment moved about. Space for tools, ladders, storage, emergency equipment, first-aid kit, and other required items must be planned.

The shelter should be well-roofed with good material. The cooling load will be lowered with reflective or light-colored roofing material. A sloping roof will tend to develop leaks less rapidly.

Buildings adjacent to towers in locations where icing occurs should be protected or have sufficient roof strength to prevent damage from falling ice.

Many small translators and transmitters are designed to be cooled convectively. This method

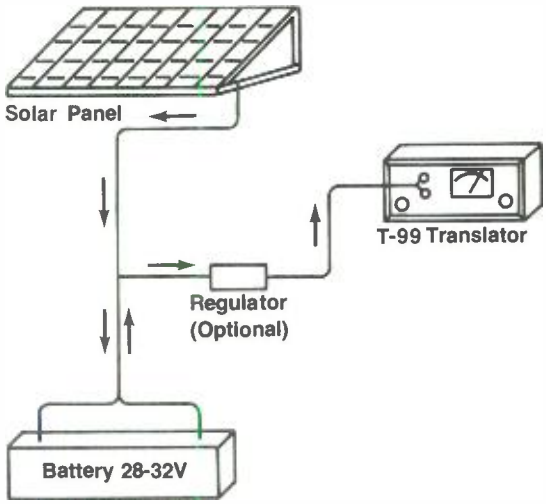


Fig. 10. Solar powered translator—power diagram.

requires substantially less attention to the maintenance of the translator. Convective cooling merely requires that the unit be free of any obstructions to the convection, which generally means that the surfaces and heat sinks of the unit be clear of any extraneous material and that there be some space between the unit and other heat producing units. Additionally, the ambient air temperature must be maintained at a level tolerable to the equipment.

In translators over 100 watts a cooling fan is usually employed. If so, access to the inlet and outlet from the unit's internal airflow must not be restricted. Again, the ambient air temperature must be maintained at a tolerable level.

In both cases, the manufacturer's instructions must be followed for adequate life from the equipment and the building must be temperature controlled if the temperature rise in the building cannot be controlled convectively or through ventilation. The building air intake should be filtered and must have capacity for all airflow in the building plus about 20%. A 1,000 watt transmitter internally exchanges approximately 350 cubic feet of air per minute. Building air intake should be below the roof and away from exhaust to avoid preheated air, but the intake and exhaust must be on the same side of the building to avoid the pressure differential that occurs during windy conditions.

In the event the outside temperature often runs over 90 degrees Fahrenheit, air conditioning may well be required. If so, discuss the situation with a qualified HVAC technician. The sun's heat load requires one ton—or 12,000 BTUs—to cool about 500 empty square feet to a comfortable level. For transmitter buildings, add all the electrical power figures used by all equipment in normal operation and subtract the total combined RF output power. Multiply this number by 3.4 to find the necessary additional BTUs required for the equipment load.

Security

The FCC requires that the transmitter be secure from entry or control by unauthorized persons, and that any hazardous voltages or other dangers (including many tower bases) be protected with fences as necessary to protect personnel and prevent unauthorized operation or tampering. Additionally, the building should be secure from the local wildlife. Other aspects of security for a translator shelter may include its location with respect to the prevailing wind, weather and erosion conditions.

Emergency Situations and Fire Protection

Weather changes, transportation failures or injuries may require an operator to extend his stay at a remote translator site. Prudence indicates the site be equipped with basic survival items to include food, water and related items. Fire is a possibility with unattended operating electrical equipment. If the site is sufficiently extensive as to require automatic fire protection, Halon or CO_2 systems will not destroy equipment as will traditional dry chemical "ABC"-type fire extinguishers, which contain ammonium chloride and will corrode electronic equipment after their use.

Power For the Translator

Power lines in rural areas are subject to interruption and voltage variation to a greater degree than in urban areas. With regard to variations, line regulating transformers are available in all sizes to accommodate transmitting equipment. If the variations are wide, component aging will increase and there will be a point at which the cost curves of protective transformers and of parts replacement will intersect. It is not unwise to so protect the installation.

Automatic utility load control is becoming more commonplace in rural electric power distribution. Such load control allows the utility company to turn off sections of the power distribution grid which may supply power to high capacity pumps or heavy loads. If the translator is connected informally to power available nearby in a farm field, the utility company may unknowingly take it off the air.

Alternate Power Sources

Small translators have often been powered by banks of solar cells. The equipment in such installations is often modified to minimize power requirements. When this is done, metering func-

tions are reduced or made temporarily connectable, pilot lamps are removed, and accessory features may be disconnected. These changes in the equipment must not interfere with its being operated in accordance with the regulations, but are helpful in preserving storage cell life and output power. A solar powered translator is diagrammed in Fig. 10.

Solar power is of varying practicality with location. Particularly in northern areas of the United States, the wintertime output of solar panels may be reduced below a useful level because of the lower angle of the sun. Areas with protracted periods of cloudiness or precipitation may allow discharge of the storage batteries before the solar panels can recharge them. Additionally in solar-powered installations, storage batteries must be kept well-charged to prevent freezing damage. Location limitations of this sort also affect wind generator powered systems. Many areas of the world are subject to almost constant prevailing winds which make the idea of wind generators attractive. The high plains in the central United States is one such area. Conversely, there are many protected areas which do not lend themselves to practical use of wind generators.

Gasoline powered engine driven generators have occasionally been used in translator installations. Their most common application is in the 300 to 3,000 watt range; they require substantial amounts of fuel for extended operation and are not maintenance free. Models are available for gasoline, diesel fuel and propane.

Another type of power supply used occasionally is the thermoelectric generator. These units are most practically applicable to requirements in the 10 to 300 watt range. They provide dc, usually at 12 to 48 volts and catalytically burn propane, butane or natural gas at a low temperature during operation. Their operation is based on the principle that there is electron flow between two dissimilar metals bonded together when one of the metals is heated. They are relatively maintenance free but require about 500 pounds of propane or butane fuel per hundred watts output per month during continuous operation.

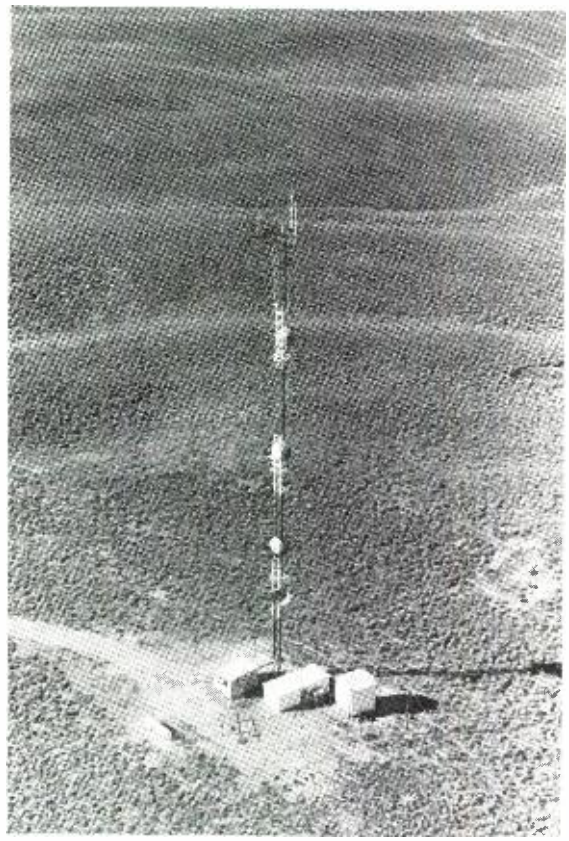


Fig. 11. Translator installation, Colorado.

PROGRESS INTO THE FUTURE

Stereo TV

Developments in full power television have had their impact on LPTV and translator technology. LPTV stations which originate programming are now confronted with multichannel sound and stereo television. In March, 1984, the FCC adopted a policy on the subject of subcarriers in the aural baseband. The policy does not require a single standard but does require protection of the system which was recommended by the Broadcast Television Systems Committee of the EIA. The FCC requires protection of the BTSC pilot frequency of 15,734 Hz unless the station is transmitting with that system. Therefore, other systems may be used which do not interfere with BTSC system use. As most LPTV transmitters are internally diplexed, all additional signal components—whether stereo or independent subcarrier—will be within the passband of the transmitter. The aural section of the modulator will, however, have to accomodate a wider baseband and be capable of deviation up to ± 73 kHz. Objectionable incidental phase modulation of the additional information by the video sync pulses may occur in transmitters not specifically designed for this more demanding requirement.

SAW Filters

A technology dating back to 1966, Surface Acoustic Wave (SAW) filters are now enjoying increasing use in the LPTV industry. This is expected to grow as their manufacturing cost is now dropping sharply. Computer-driven planar processing techniques used on the ST quartz substrate normally used for filters in the TV range have assured manufacturing repeatability and decreas-

ing costs. For the bandwidth requirements of television broadcasting, SAW filters more closely approximate the ideal rectangular model filter than other designs. Quartz versions of this filter, in particular, have insertion losses averaging around 20 dB and often require buffer amplifiers on either end of the filter. Phase shift within these filters ranges from 2 to 6 degrees.

Offset Operation

As the number of LPTV and translator stations grows, so does the problem of interference. Offset operation has been employed to allow this growth while minimizing the attendant interference by allowing or even requiring a new LPTV applicant to operate at the particular channel with a frequency assignment offset of +10 kHz or −10 kHz from the channel's normal visual and aural carrier frequencies.

The benefit thus achieved is that a new station's signal, when offset, need only be 28 dB below the existing co-channel station's at the existing station's protected contour rather than −45 dB if the offset were not employed. This allows the LPTV applicant a 17 dB benefit when using this approach. The price of this approach is much tighter frequency control. Stations licensed without offset are required to maintain their frequency tolerance to within .02% of the assigned frequency if up to 100 watts and .002% if a transmitter of over 100 watts is used. With offset operation, the station carrier frequency must be maintained to within 1,000 Hz of the carrier frequency regardless of the channel frequency. In a translator so licensed, this is maintained by an AFC system which will hold the output within 1 kHz despite variations in the incoming frequency. In all cases, the relationship between visual and aural carrier frequency remains the same at 4.5 MHz ±1 kHz.

Therefore, to a station licensed at UHF channel 49 (visual carrier 681.25 MHz) operation at 100 watts or less means frequency variation of 136.25 kHz is allowable; operation over 100 watts requires maintenance of a ±13.625 kHz variation but offset operation at any power requires maintenance of the carrier frequency within 1 kHz. Thus, the equipment for offset operation is slightly more expensive, but allows licensing of stations otherwise not possible. Its inclusion in a look at LPTV's future is due to the increasing necessity for its use.

7.5

Instructional Television Fixed Service (ITFS) and Multipoint Distribution Service (MDS)

Robert M. Unetich
President
Information Transmission Systems Corporation
McMurray, Pennsylvania

INTRODUCTION

Instructional Television Fixed Service (ITFS) and Multipoint Distribution Service (MDS) are television transmission systems authorized by the FCC. ITFS was first authorized in 1963 for educational television. Use of ITFS has grown slowly but steadily and to date there are approximately 250 operating channels. MDS is relatively new. It was first proposed as a two channel service in the early 1970's. It is a "common carrier" service and has been used primarily for the distribution of "pay television" programming. Recently the FCC approved a multiple channel version of this service known as Multi-channel MDS (MMDS), allocating it two groups of four channels of the ITFS band. Additionally, the FCC authorized ITFS licensees to lease excess capacity to operators providing service similar to MMDS.

The technical characteristics of these two services are similar to each other and to broadcast television transmission. In the FCC Rules and Regulations, ITFS is defined in Part 74, Subpart I and MDS is defined in Part 21, Subpart K. The ITFS service originally occupied the 2.5 to 2.686 GHz band. MDS occupied 2.150 to 2.160 GHz, which was later extended to 2.162 GHz. The ITFS band was divided into 32 6 MHz channels and further divided into 8 groups of 4 alternately spaced channels. These 8 groups were identified as A through H. ITFS operators were permitted to operate on an entire group of four channels. The highest frequency channel, H4, was reserved for voice and/or data response communication. Subsequently, H1 through H3 were assigned to Operational Fixed Service (OFS) for the distribution of closed circuit programming.

The original MDS band was divided into 3 channels: Channel 1, which covered 2.150 to 2.156 GHz; Channel 2A, which covered 2.156 through 2.160 GHz; and Channel 2 which covered 2.156 through 2.162 GHz. Channel 2 was assigned only to the top 50 markets. Channel 2A was permitted to handle narrow band television without an aural carrier or other restricted bandwidth transmissions.

In 1983 the FCC allocated E and F groups of the ITFS band to MDS. The FCC is currently considering proposals for the technical standards of this new service and is expected to begin processing applications for construction permits in the near future.

TECHNICAL SYSTEM CONSIDERATIONS

RF System

Currently ITFS and MDS utilize transmitter output powers of 100 W or less per Channel, resulting in relatively low field intensities compared to full service broadcast. Additionally, the

use of frequencies above 2,000 MHz requires greater consideration of signal path clearances. These factors tend to make these services primarily dependent upon radio line-of-sight coverage. This imposes upon the receiving system a requirement to have a reasonably high gain antenna and a low noise figure downconverter. The downconverters normally heterodyne convert a block of the ITFS/MDS band to a VHF frequency band, often utilizing standard television channels such as 7, 9, 11 and 13. Paths from transmitter sites to receive sites are often partially obstructed by trees, buildings and terrain. In those cases, received levels cannot easily be predicted without considering the index of refraction, the reflectivity of obstructing surfaces and the amount of defraction occurring near the receive site.

Additional problems the RF System faces are adjacent and co-channel interference. With the ITFS/MDS spectrum becoming more crowded, there is an increasing probability of interference. Adjacent channel systems are being planned in numerous cities, and several field tests of alternately polarized adjacent channel systems, have already taken place. Co-channel interference has been a problem in several Channel 1 MDS systems. It is expected that ITFS will experience this problem to a significant degree as that band becomes more occupied. General engineering principals applicable to VHF and UHF broadcast will often be beneficial to the resolution of these problems. In adjacent channel systems, the suppression of out-of-band products is vital. Older transmission systems often exhibit high degrees of lower side band re-insertion and out-of-band product generation. The use of wave guide filters and externally diplexed linear transmitters can effectively reduce these products to a level that allows operation with undesired adjacent channel levels comparable to the desired channel level. The technology of offset frequency operation can be employed with moderately high levels of co-channel interference. Utilization of this technology will require careful coordination of channel offsets and modification of existing transmitters. Frequency control will be more difficult in these services than in standard television broadcast because the percentage frequency error allowed will be smaller at the 2 to 3 GHz range than it was in the VHF and UHF bands.

The area of best signal coverage will be in the range known as radio line-of-site. This extends beyond visible line-of-sight because of the refraction of electromagnetic waves in the atmosphere. On the average, this produces a signal path range that can be approximated by using a profile of the earth with an increased radius, usually 1⅓ times the true radius. See Fig. 1 for a typical ⅘ earth profile chart.

To avoid diffraction loss due to path obstructions, a path clearance of 0.6 Fresnel Zone is desirable. To determine the Fresnel clearance on a particular path, the following formula can be used:

$$R = ((\text{wavelength} \times d_1 \times d_2)/(d_1 + d_2))^{1/2}$$

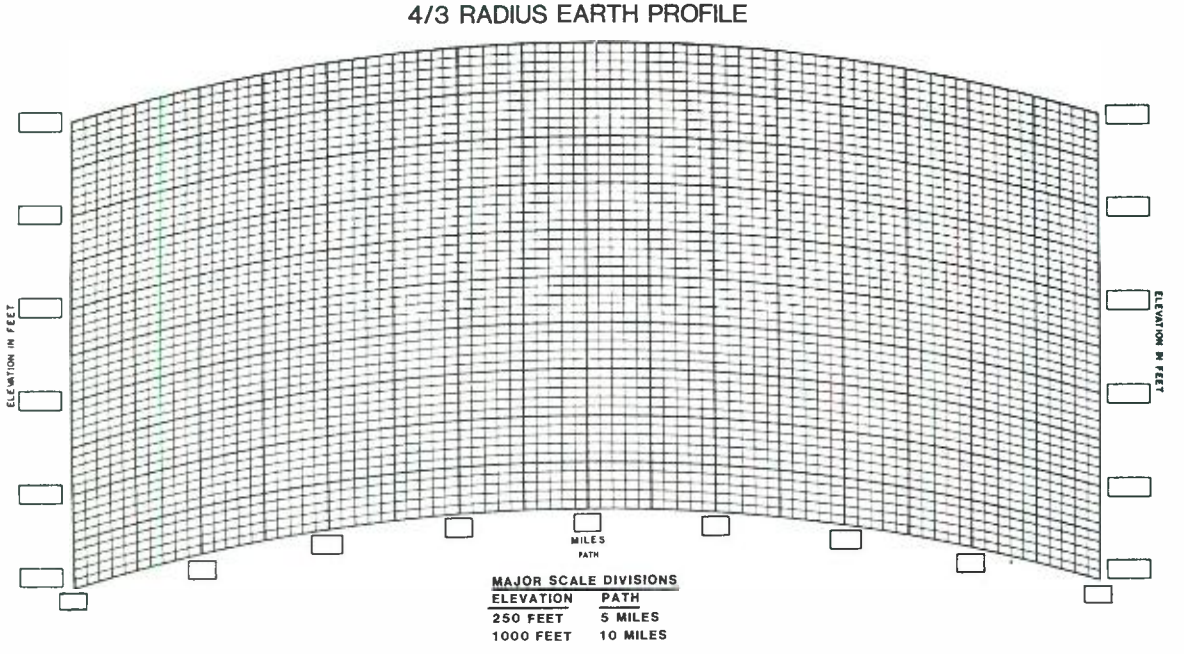


Fig. 1. Path profile chart.

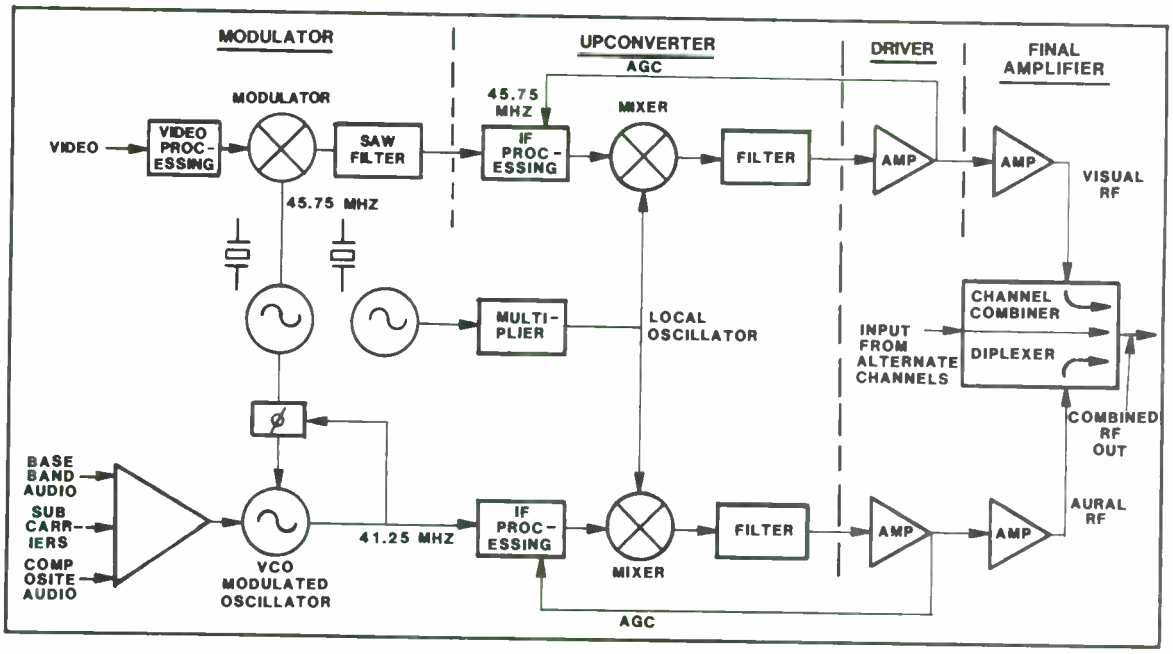


Fig. 2. ITFS/MDS transmitter block diagram.

Where:

d_1 = the distance from the transmitter to the obstruction

d_2 = the distance from the obstruction to the receiver

To determine signal levels in the diffraction region, refer to diffraction loss curves such as those found in *Bell Systems Journal*, Volume XXXVI, No. 3. Path clearances in excess of 1.3 Fresnel Zones can result in multipath propagation, producing nulls in received levels and/or picture ghosts in received pictures. Often it is possible to minimize these problems by moving the receiving antenna slightly to avoid such reflections. Receive levels can also be significantly affected by seasonal foliage, which should be considered in antenna installations.

Transmitters

Transmitters for ITFS and MDS have generally been rated at 10 watts to 100 watts visual power, with 10% aural capability. In the last few years the 10 watt transmitter has become fully transistorized. Amplifiers using triode vacuum tubes are available to reach 50 to 100 watts in both the 2.160 and 2.600 GHz bands. The aural output stages of these transmitters are solid state and operate with up to 10 watts of output power.

Both internally and externally diplexed transmitters are in widespread use. In uncongested areas where adjacent channel difficulties are not likely to occur, low level internally diplexed systems offer a high degree of simplicity and economy. Modern linear amplifier design, coupled with amplitude and phase pre-correction techniques, provides high quality signal performance. In repeater service this avoids the need to perform de-modulation and re-modulation. Externally diplexed transmitters offer higher rejection of products caused by the intermodulation of visual and aural carriers. An additional benefit of externally diplexed systems is the reduction of cross-modulation of video sync components onto the aural carrier. With the advent of multichannel sound and pay television encoding and decoding, aural carrier signal integrity can become an important factor in system performance. One disadvantage of a high level diplexed system is that it can introduce video frequency response errors, group delay variations, and aural bandwith reduction. In lower power ITFS transmitters, the diplexer can be a simple hybrid coupler. Notch diplexers are universally used in higher power versions of the transmitters to avoid the loss incurred in hybrid couplers. Refer to the block diagram (Fig. 2) for the following description of the functions incorporated in a typical ITFS/MDS transmitter.

Transmitters are typically built as combinations of functional trays. These trays, usually 19-inch rack-mount assemblies can be installed in cabinets supplied by the manufacturer or can go directly into the user's cabinet. The trays normally separate the video modulation, upconversion, and amplification functions into separate trays. This provides ease of alignment and shielding through physical separation. The following describes a

tray layout for a typical 10 Watt ITFS/MDS transmitter.

Input baseband video and audio are sent to the modulator tray. This tray performs video and audio signal processing and the basic function of modulation. The video signal is back-porch clamped, and group delay pre-corrected. It then modulates a 45.75 MHz crystal oscillator signal to form the double sideband amplitude modulated television waveform. This IF signal is then vestigial sideband filtered in a surface accoustic wave device (SAW) to produce a precise frequency response.

The audio circuitry allows for three different types of inputs: a 600 ohm balanced standard audio base band program channel; a 75 ohm composite audio system comprised of L+R base band, L−R stereo, and second audio program (SAP) input; and a separate 75 ohm high frequency subcarrier input for data or voice communication purposes.

These signals are mixed and used to modulate a wideband aural voltage controlled oscillator (VCO), operating directly at the intermediate frequency of 41.25 MHz. This modulator has wide deviation capability and low harmonic distortion, allowing multi-channel sound operation. The center frequency of this modulated oscillator is phase locked to the 45.75 MHz IF visual oscillator. These two modulated signals are buffered and sent to the upconverter trays for further processing and heterodyne frequency conversion.

The visual upconverter tray provides Automatic Level Control (ALC) of the IF signal (including motorized remote control interface), IF linearity correction, and ICPM correction before upconversion. Additionally, it includes Automatic Gain Control (AGC) from the output of the correctors to the output of a higher power 2GHz RF amplifier stage. This feature insures that gain of the system from the correctors to the RF amplifier stages is held constant, so that the pre-set amounts of amplitude and phase pre-correction remain as correct values under conditions of temperature change. The amplitude pre-correction circuitry provides for correction of differential gain and sync compression occurring in the last amplifier stage in the system. Since the circuit is adjustable, it can be used to correct the changing characteristics as these output tubes age. This is also true of the ICPM corrector. Its purpose is to provide a compliment of the amplitude vs. phase characteristic of the output amplifier stage. These two pre-correctors insure optimum video characteristics of the output signal. This enables multi-channel television sound signals to be transmitted by the aural section without interfering sync buzz or buzz-beat caused by output amplifier ICPM errors. This is especially necessary for high power tube amplifiers that have ICPM errors near white and sync tip. The upconverter tray also includes an oven control crystal oscillator and multiplier chain.

The IF and LO signals are mixed, filtered, and amplified to about the l0 MW level and then sent to the driver amplifier tray for further amplification.

The aural upconverter operates in much the same manner as the visual upconverter, but without the presence of amplitude or phase correctors. The output amplifiers in the aural upconverter tray are similiar to those in the visual driver tray and provide up to 5W of aural output power to the diplexer.

The output of the visual driver tray drives a 10W solid state amplifier, which includes eight transistors operating in parallel. Each device is provided with a video compensated constant current bias source. This amplifier utilizes microstrip transmission line techniques on teflon circuit board and is cooled by forced air.

In the metering/control panel, the output and driver powers are metered and diplayed. The panel also distributes AC and control signals to each tray. The control logic is CMOS for high noise immunity. A "D" connector interface is provided for a remote control system interface.

The visual and aural output signals are diplexed and combined with the ITFS/MDS channels in a three input, one output wave guide channel combiner-diplexer. This device integrates the function of diplexing and channel combining into one assembly and eliminates the jumper losses normally incurred while connecting diplexers to separate channel combiners. Additionally, because it is built entirely of wave-guide, inherent losses are low, especially in the through line waveguide. This results in an essentially lossless channel combining technique that can be cascaded with other alternately spaced ITFS channels. Because the wave-guide cut off frequency is below 2 GHz, this main line wave-guide can also multiplex Channel 1 or Channel 2 MDS systems onto the same line. Using this device, it is possible to combine up to 17 ITFS/MDS channels on a single wave-guide in a relatively low loss manner. The diplexer sections of these devices utilize directional filter techniques and result in very high isolation from channel to channel and from visual to aural carriers. Since the loss of these filter sections is compensated for in the output amplifier stages, the transmitter can provide a full 10 watts of visual power at the output of the channel combiner. Recent versions of this device incorporate temperature-stabilized specialty steels to provide maximum temperature stability. Refer to Fig. 3 for a photo of a wave-guide diplexer/channel combiner. Other versions of this device have been developed for channel combining internally diplexed repeaters.

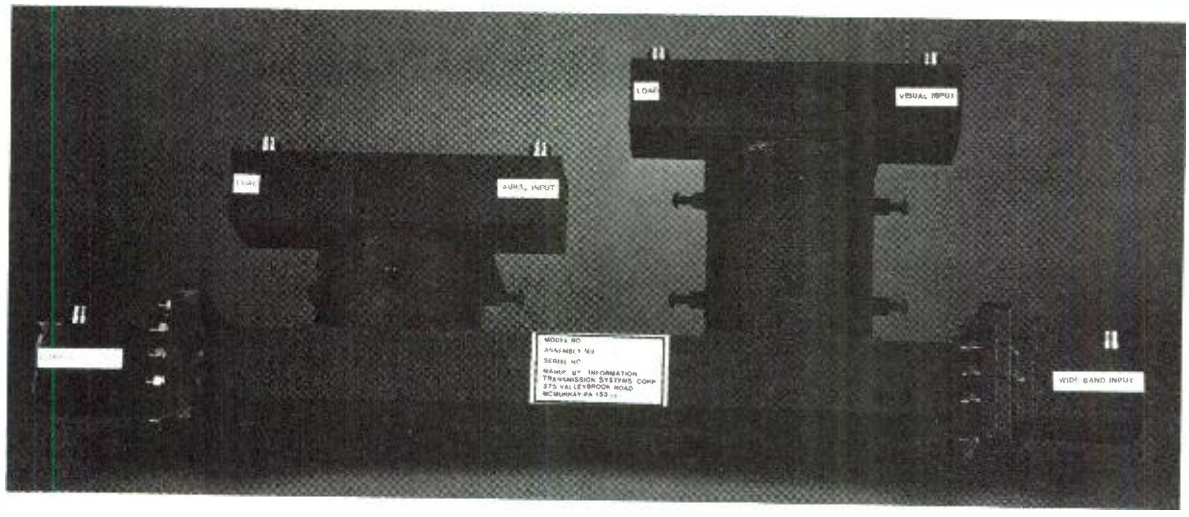


Fig. 3. Diplexer/channel combiner.

Repeaters

ITFS repeaters are usually comprised of ITFS transmitters driven by receivers instead of modulators. In a typical system design an ITFS downconverter "block converts" an entire ITFS group to a VHF band of frequencies. A wide-band splitter then splits this signal to drive the required number of repeaters. Each individual repeater employs a VHF receiver tray to convert the appropriate VHF channel to standard IF. Referring to Fig. 4, a typical downconverter utilizes a remote preamplifier section that is located near the receive antenna. The preamplifier stage is powered from dc supplied by the output co-axial feed line. This pre-amplifying preserves input signal-to-noise ratio and allows the downconverter to be placed in a controlled environment to enhance frequency stability and reliability. The downconverter is a 19 inch rack mount tray that contains an input filter for the desired group, another low noise amplifier stage, a local oscillator, a mixer assembly, and a wide band VHF output amplifier. Since this amplifier stage must handle relatively high level multiple channel signals, it must be designed to produce a minimum of cross-modulation and inter-modulation distortion. The ITS-640 accomplishes this with a wide-band CATV amplifier device. Frequency generation is accomplished by an oven controlled crystal oscillator and multiplier chain, similiar to that in the ITFS upconverter tray.

The receiver tray converts the VHF input channel to the standard IF of 41 to 47 MHz. Another oven controlled oscillator is used for frequency control and a single channel input filter is used to provide selectivity. In the IF strip, the selectivity is further enchanced by a SAW device that provides 60 dB of rejection of adjacent channel signals. This high selectivity insures that other VHF channels are not hetrodyne converted into a desired ITFS output channel. This receiver tray

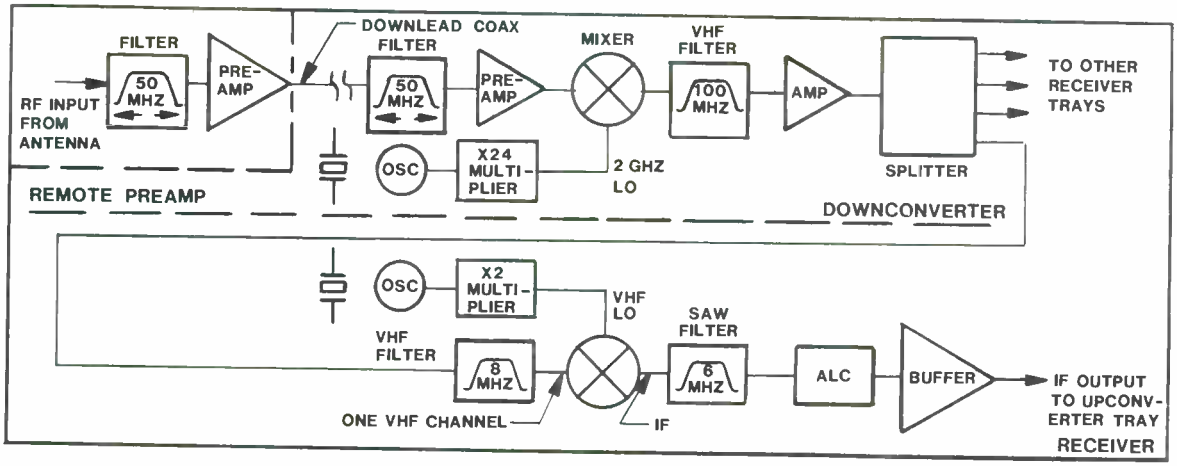


Fig. 4. Downconverter/receiver block diagram.

also includes Automatic Level Control (ALC), and carrier detection circuitry to initiate operation of the output upconverter. There is also a video detection circuit that is utilized to prevent radiation of an unmodulated output signal.

A repeater must be designed to operate with the full range of input signal levels expected. These typically range from −30 to −60 dBm. The input signal handling capability and the system noise figure must be carefully set to handle this wide input dynamic range. Repeaters can be cascaded to more than one hop. Careful consideration must be given to system signal-to-noise ratio, frequency stability and total system distortion since these errors are additive. Channel selection should be done to avoid alternate or adjacent channel operation, if possible. Typical channel selection often reuses the originating channels in the output of a multiple hop system.

Amplifiers

High power amplifiers for MDS and ITFS are available at the 50 watt to 100 watt visual power levels. Higher power level systems are being considered. The present hardware used to produce these power levels is single or parallel planer triode amplifiers. A typical amplifier is shown in Fig. 5. In this unit a Siemens YD1380 triode is operated as a Class AB linear amplifier. The amplifier circuit is a ¾ wavelength output coaxial cavity. It is single tuned for a bandwidth of about 10 MHz at 1 dB. In the ITFS band, this unit provides about 13 dB of gain and in excess of 50 watts of visual or visual plus aural power. This stage produces distortion products that are approximately 50 dB down from the peak visual output power in the internally diplexed mode. This level is easily corrected to more than 56 dB down with the use of the IF correctors previously described. The linearity characteristics of this stage age slowly and require only an occasional (2 to 3 times yearly) pre-correction. Additionally, as the tubes near end-of-life, pre-correction can be employed to effectively extend the tube's operating life. Although this is a relatively low power vacuum tube stage, the delicate nature of this tube's grid structure requires that quick acting protection circuits are included. In this model, optically coupled isolators are used in all of the tube element lines for fault detection. This provides rapid protection in case of a fault. CMOS control logic provides proper delay in application of voltages and automatic re-cycling under fault conditions. Two of these amplifiers can be combined for 100 watt operation.

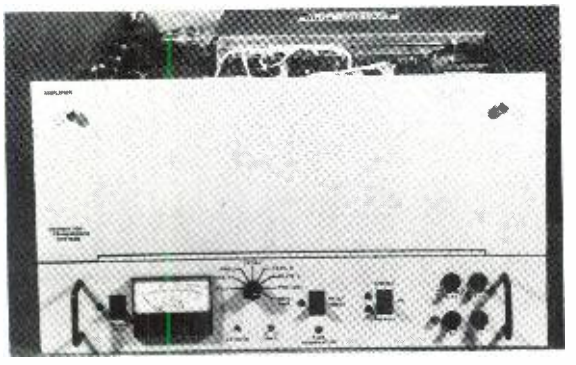


Fig. 5. 50 watt amplifier.

Antennas

The output of the channel combiner feeds a coaxial line or elliptical wave-guide. Normally, this transmission line is pressurized and feeds a pressurized antenna. Transmission line losses can be a significant factor in reducing radiated power. Coaxial transmission lines can only be as large as 1⅝ inch in diameter to avoid mode problems. This size corrugated line has about 1.5 dB per 100 feet of loss in this band. Another common line, ⅞ inch in diameter, has a loss greater than 2 dB per 100 feet. For this reason, elliptical waveguide such as Andrew EW20 is often used. EW20 has less than 0.5 dB of loss per 100 feet. These losses exclude connector transistions and jumper cable losses. Flexible cable as small as ½ inch in diameter is often used for these jumpers, even though this cable has 0.4 dB of loss per 10 foot length. For this reason, jumper cable length should be minimized.

Transmitting antennas are available in both vertical and horizontal polarization, with azimuth patterns of omni or cardioid shapes. Gains range from below 10 dBi to more than 18 dBi. Vertical beam widths range from 13 degrees to less than 3 degrees. These antennas are usually top mounted for the omni pattern case and side mounted for the cardioid pattern, although omni pattern antennas are occasionaly side mounted with some resultant pattern deformation. (See Fig. 6)

Receiving antennas range from small 12 dB gain dipole reflector combinations to large dishes. A very common receive antenna is the disk rod array, which has about 18 dB of gain. For more distant receive points, a 4 ft. dish is often employed with a nominal gain of 28 dB. Some antennas are built directly onto the case of the downconverter to minimize costs and eliminate jumper cable losses. In other cases the downconverter is mounted close to the receive antenna and a short length of flexible coaxial cable interconnects the assemblies.

Downconverters

Receiving converters normally include an RF pre-amplifier stage to preserve signal-to-noise

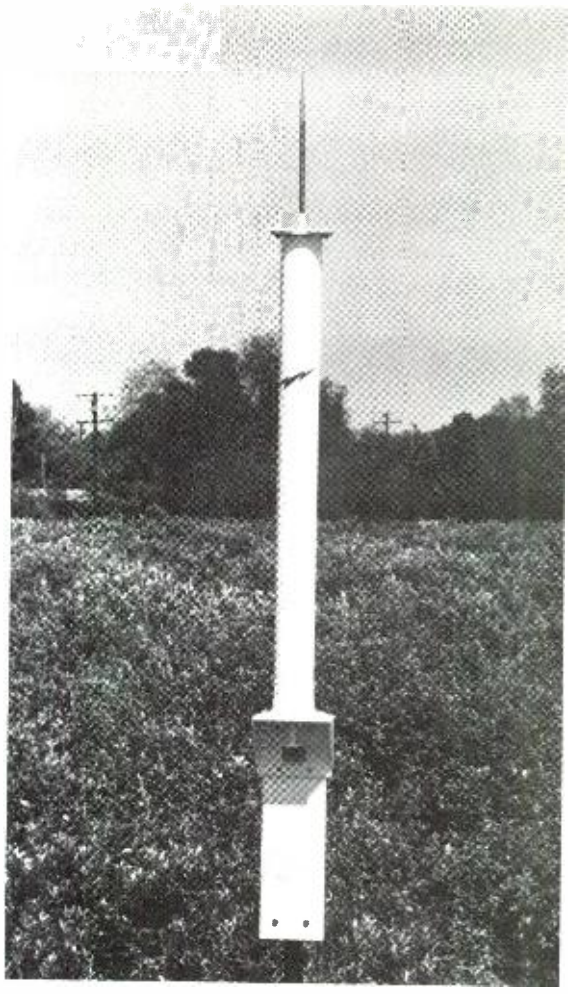


Fig. 6. ITFS/MDS antenna.
(Courtesy of Andrew Corporation).

ratio and a single balanced mixer for frequency conversion. The local oscillator signal is generally derived from a crystal oscillator and multiplier. The VHF output amplifier is usually of discreet component design and often the entire assembly is designed as one printed glass epoxy circuit board to minimize manufacturing costs. Because of the low Q nature of this di-electric material and because of the small physical separation between functions, those devices occasionally have undesired spurious outputs. In multiple channel systems, the single handling capability of the transistor output stage becomes a determining factor is the amount of output signal cross-modulation distortion. In a carefully designed downconverter, input noise figures below 6 dB can be achieved and out-of-band spurious signals can be held 50 dB below typical output levels. When additional input selectivity is required, pre-selector filters are sometimes used before the downconverter section. Since the output of the downconverter often interconnects with other television signal distribution equipment, consideration should be given to the fact that crystal oscillator products and various input signal mixing products may appear on the output, often at levels well above the noise floor. Since the downconverter has a wideband VHF amplifier in its output section, it will produce a broadband noise spectrum independently of the downconverter's oscillator or input signal. Success in interfacing a downconverter in a television signal distribution system may require that VHF filtering be done after the downconverter's output. A typical converter is shown in Fig. 7.

RESPONSE CHANNELS

The ITFS rules also allocate a set of frequencies for voice and/or data transmission. This has most often been used for a return link from a classroom to the main television transmission point. The response channels occupy part of ITFS Channel H4, with each ITFS television channel having an assigned response channel. These response channels are 125 kHz in width and can be used for amplitude or frequency modulation transmissions. Usually, 25 kHz deviation FM is

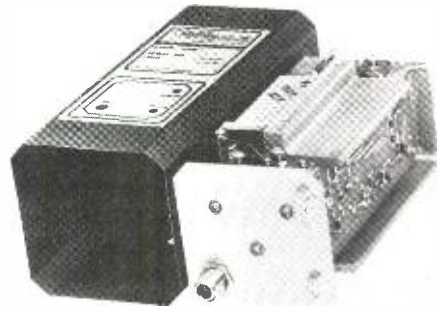


Fig. 7. ITFS down converter.
(Courtesy of MICRO-NOW, Inc.).

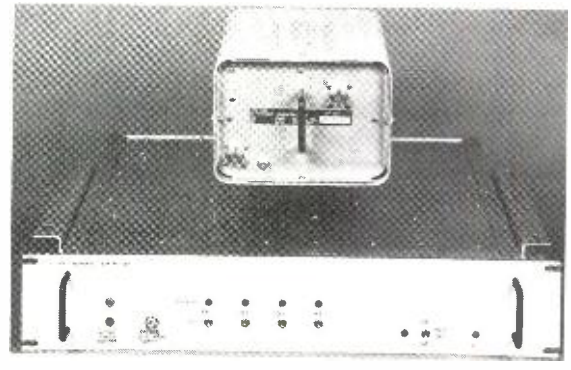


Fig. 8. ITFS response transmitter.

employed. Transmitter output power is normally limited to 0.25 watts. Transmitter power of 2 watts may be permitted, if a need can be shown.

A typical response transmitter is shown in Fig. 8. In this system, a "base unit" consisting of audio processing circuitry, control logic and a frequency modulated crystal oscillator, operating at ¼ of final output frequency, drives a "mast unit" that is located near the transmitting antenna. The "mast unit" performs the functions of frequency multiplication, amplification and power level control. At the receiving point, a standard downconverter is used to heterodyne convert the response frequency to a suitable VHF frequency to drive an FM receiver. The FM receiver is normally a crystal controlled unit with squelch. This unit drives an audio amplifier and speaker. In the case of data transmission, it may drive a suitable modem for interfacing with a computer. Preceeding the base unit at the transmitter site is a microphone mixing network and/or modem that originates the input signal. Because of the channel bandwidth limitations, the audio or data bandwidth is usually restricted to less than 15 kHz. Data transmission rates of 300 to 4800 baud have been achieved.

7.6

Broadcast Newsroom Computer Systems

Kenneth R. MacBride
Manager—News Computer Operations
National Broadcasting Company
New York City, New York

INTRODUCTION

Computer systems are replacing typewriters increasingly in broadcast newsrooms. These systems enable a station to manage the complex processes involved in broadcast journalism with increased efficiency and speed. The technology of "Electronic News Gathering", the "Global Immediacy" provided by satellite sound and picture transmission, and the competitive pressures of broadcasting demand "state-of-the-art" command and control of the broadcast journalism activity.

Broadcast newsrooms in the 1980s and beyond can benefit from computer-assisted activities in areas such as newsgathering, story development, resource allocation (crews and equipment), on-air broadcast schedules, support functions, and business affairs. This part describes newsroom computer technology and presents a plan for moving a station's news operation into the computer age.

BASIC PRINCIPLES

Newsroom computer systems typically include: one or more computers; *software* (programs) which cause the computers to perform useful tasks; terminals such as VDTs (Video Display Terminals), printers, and prompters which permit people to interact with information in the computer system; data communications which provides access to the newsroom computer from remote locations; newswire services (AP, UPI, Reuters, etc.); and some means to interconnect all the parts.

The Computer(s)

Broadcasters have been using computers for years. Computers control our audio and video editing equipment, pre-roll and switch our on-air program material, monitor and log our RF (radio frequency) emmissions, bill our clients, and even produce our paychecks. The application of computers in broadcast newsrooms is merely another use of an already familiar technology.

Computers come in many shapes and sizes, ranging from shirt-pocket size to large *mainframes* which may occupy thousands of square-feet of floorspace. Newsroom computer equipment tends to be small and flexible. See Figs. 1 through 4.

From the tiniest to the largest, computers share similar architectural elements. See Fig. 5.

The *ALU* (Arithmetic/Logic Unit) is a circuit which performs basic arithmetic and logical operations (typically addition, subtraction, and logical comparisons) on binary numbers represented by the presence or absence of current at designated points in the circuit.

ALUs are characterized by the number of *bits* (binary digits) they process at a time. Typical newsroom computer ALUs process eight or six-

Fig. 1. A battery operated pocket-sized computer which can store a reporter's notes or script. (Courtesy of Sharp Electronics Corporation)

Fig. 2. A battery operated lap-portable computer with built-in software which handles word-processing, contact lists, and a reporter's assignments. The unit includes an internal modem which permits the user to send and/or receive information by telephone dial-in to the main newsroom computer system.

Fig. 3. A desk-top computer system with internal floppy disk and hard disk storage exceeding ten million BYTES. With newswire service input, this system can give a single user most of the functions of a multi-terminal newsroom computer system. Connected to a data communications network, it can perform as a full-featured newsroom workstation. (Courtesy of Basys, Inc.)

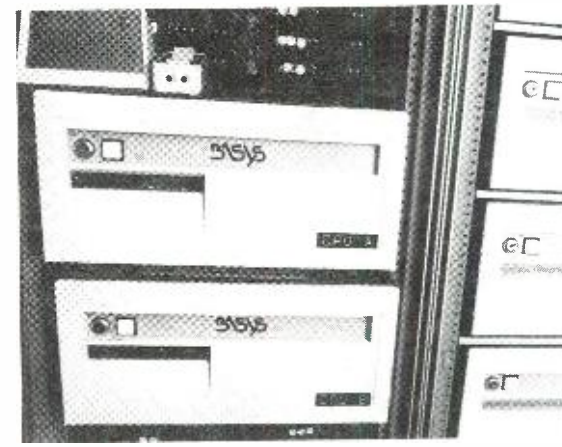


Fig. 4. A mini-computer system with dual CPUs and over eighty million BYTEs of storage. The two CPUs are "tightly linked" and each maintains its own full copy of the database. If either CPU fails, the other can survive with its separate database. The system shown can support up to eighty terminals, printers, dial-ins, and/or newswire feeds when both CPUs are operational; up to forty devices when only one CPU is on-line. (Courtesy of Basys, Inc.)

teen bits at a time. Large mainframes may process 32, 36, or even 64 bits in a single ALU step.

Two concepts: *bus* and *bit-width* apply to many newsroom computer ALUs. The "bus" structure defines the signals—data and control—which pass between the ALU and other internal parts of the computer. "Bit-width" describes the number of bits the bus can pass at a time. A given ALU circuit may be able to process 16 bits at a time internally, but may be constrained by the bus structure to only an 8 bit path through the bus to other internal parts of the computer.

Computer *memory* circuits can store and retrieve binary numbers which represent program instructions and/or data. Program instructions typically cause the ALU to execute a command. Data stored in the computer memory might be tonight's six-o'clock newscast script, a newswire story, or tomorrow's camera crew schedule.

Memories are characterized by the number of *BYTEs* (eight bits of storage) or *WORDs* they can store. A WORD is a measure of the number of bits the ALU processes at a time; an "eight-bit machine" has a word-length of one BYTE (eight bits); a "sixteen-bit machine" has a word-length of two BYTEs (sixteen bits); and a "thirty-two- bit machine" has a word-length of four BYTEs (thirty-two bits).

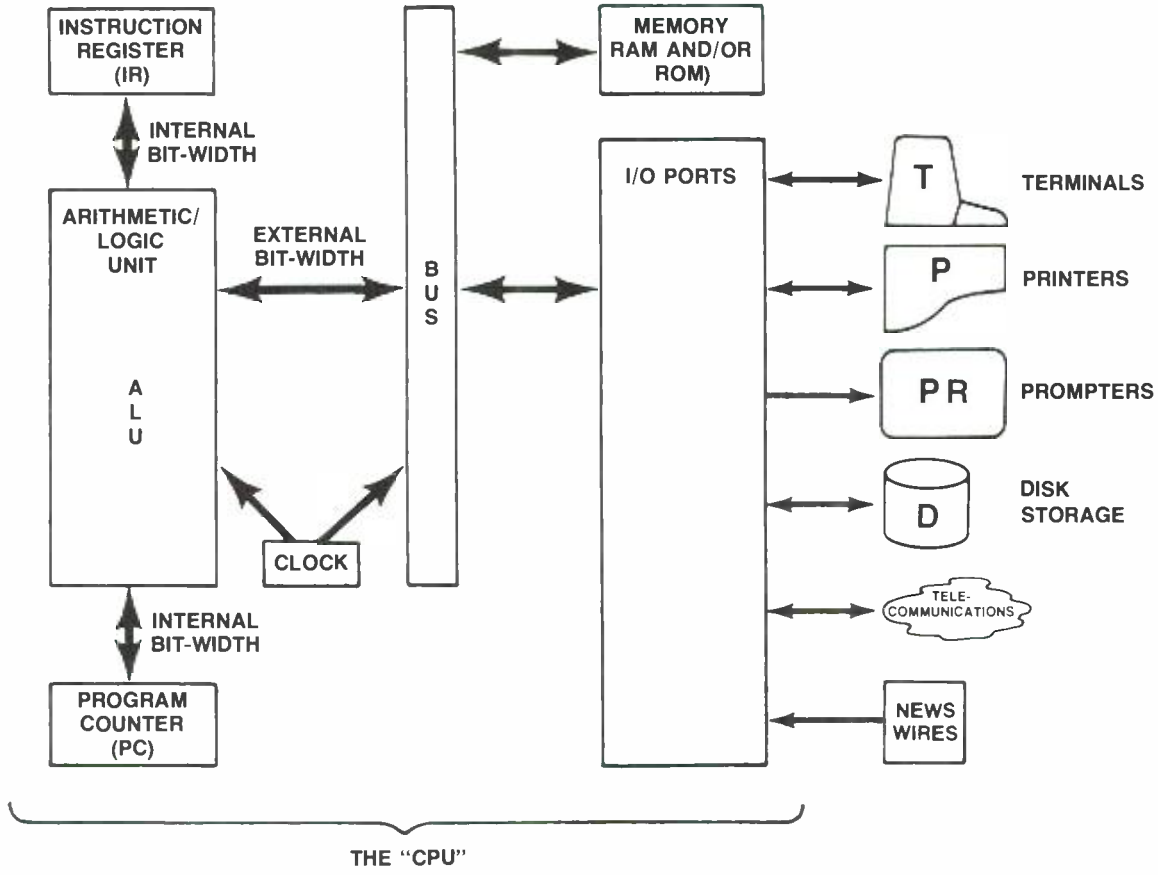


Fig. 5. Conceptual computer.

A BYTE can represent any of 256 (2^8) binary values. Half of these have been assigned standard alphabetic, numeric, punctuation, and "control" designations under the *ASCII* convention. See Appendix A. The remaining binary values are used by some newsroom computer systems for special purposes.

The PC (Program Counter) contains the *address* in memory of the next instruction to be executed by the ALU. An address is a binary number which specifies the location of a program instruction or data item in a computer's memory. See Fig. 6.

The IR (Instruction Register) temporarily holds a binary number which represents an instruction, or command, to be executed by the ALU. Typical instructions are "add a number in memory to the accumulator", "increment the accumulator by 1", "zero the accumulator", "XOR (logical exclusive OR) a number in memory with the accumulator", etc. The binary number in the IR is *decoded* by control circuitry and sent as a command to the ALU which performs the operation.

The I/O (Input/Output) section permits data to be sent to and received from external equipment. This information, typically in ASCII format, might be characters sent to a printer or video display, the "keystrokes" of a video terminal user, the text of a newswire story, or a request for a crew's next assignment from a user in the field. Computers have I/O *ports* which permit the transfer of data to and from external devices such as VDTs, printers, newswires, etc.

The clock controls the transfer of data among the internal parts of the computer. Clock pulses of several "phases" are used to initiate the transfer of an instruction into the IR from memory, to cause the instruction to be decoded and passed to the ALU, to cause the ALU to execute the instruction, and often to store the result of the activity back into memory. The execution of an instruction by the ALU may require one or many of these step-by-step clock pulses.

Newsroom computer equipment is usually based on the technology described above. Newsroom computer *systems*, however, use the technology to support the special purpose tasks news people need to perform.

Commercially available newsroom computer systems fall into two categories:

1. Those which are based on "off-the-shelf" computer *hardware*, typically manufactured by another company; and

2. Those which are based on special purpose computer hardware, usually made by the company selling a newsroom package.

The off-the-shelf approach normally is based on a major computer manufacturer's equipment. This offers well proven hardware, readily available field maintenance and support, and often a range of compatible equipment options from which to choose. The disadvantage in this approach is that off-the-shelf equipment is general-purpose in nature; no use is made of hardware optimized for the newsroom *application*.

In contrast, special purpose newsroom computer equipment is designed specifically for the application. This can lead to a more efficient hardware/software combination which often handles tasks with higher apparent speed than a general purpose system. The disadvantages in special purpose newsroom computer systems stem from their uniqueness. Replacements, *enhancements*, and additions to a special purpose system must usually be done through the system vendor. The local computer store will not be able to supply special purpose system hardware or software off-the-shelf. Another problem is that special purpose equipment which relies on *PROMs* (Programable Read-Only Memory) to store software for each terminal may prove cumbersome when it is time to install a new *software release* (in some cases, every terminal and the central equipment will need PROM chips replaced).

The Software

Software, or programs (lists of commands to be executed by the ALU), give a computer system a kind of "personality". This can be characterized as "user-friendly", "austere", "cumbersome", "fast", "slow", "chaotic", "user-surly", etc.

Typical newsroom software uses features such as "menus", "prompts", "function keys", "cursors", "status messages", and others to guide the user through his or her task.

A menu is a list of items displayed on the user's terminal. The menu may show the set of commands available to the user or a list of newswire story *slugs* or a list of *data files*. The user is expected to choose one of the menu items in order to proceed with his or her work. The software waits for the user to indicate a selection through the terminal's keyboard. Once the selection has been made, the software takes appropriate action.

Some newsroom software "prompts" the user with a message indicating what the user should enter next. Some examples are:

PLEASE ENTER FILE NAME >

PLEASE ENTER DATE >

STRIKE "HELP" KEY FOR MORE INFORMATION

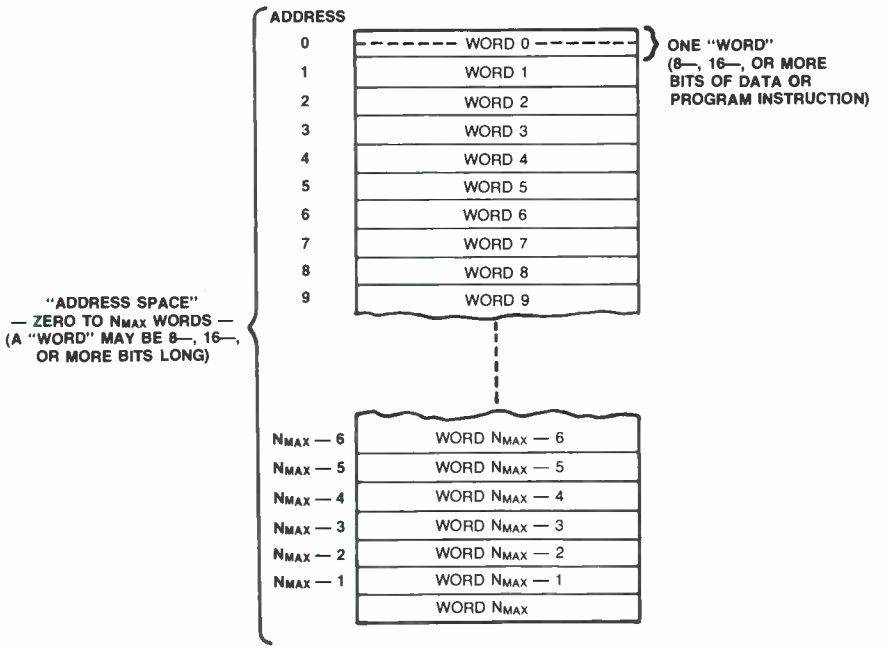


Fig. 6. Memory addresses.

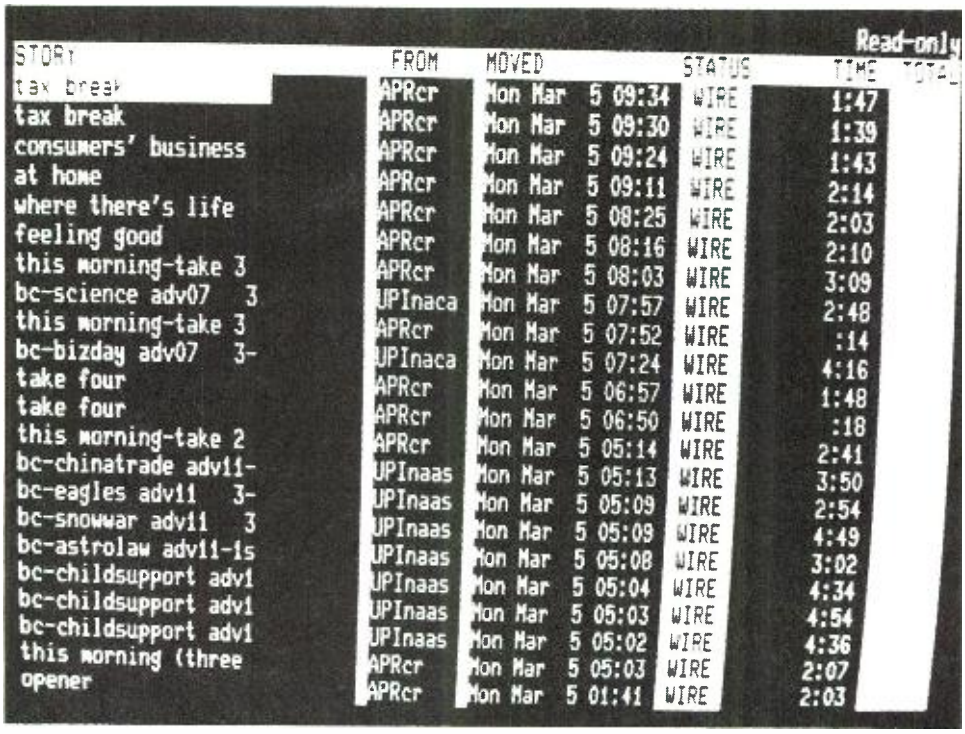


Fig. 7. A menu display presenting a list of newswire stories. The top story in the list, "tax break", has been selected (indicated by the black-on-white story name). To see the full text of the selected story, the user strikes a function key. (Courtesy of Basys, Inc.)

Prompts can also be simply one character such as the greater-than sign (>) or an asterisk (*). These typically appear at the left side of the terminal screen when the user is expected to enter a line of text.

"Function keys" are additions to some terminal keyboards beyond the alphabetic, numeric, and punctuation keys found on a typewriter. In some systems, the function keys have fixed labels such as "PRINT" or "ERASE". In others, they may be labeled as "f5" for function key five. In the latter case, the software can change the function of the function keys to match the user's task. For example, "f3" might mean "PRINT STORY" when the user is reading through the wires, and mean "DELETE SENTENCE" when the user is writing a script. Some software causes the changing meanings of function keys to be displayed as video labels at the bottom of the terminal's screen.

Most newsroom software uses a *cursor* on the video terminal screen to indicate the position of the next character the user enters or one of the items in a menu. Cursors may be a rectangular block of one character size, an underline, or a screen position in reverse video. Often cursors are caused to blink on and off to attract the user's eye. The software usually permits the user to move the cursor around the screen by striking function keys. This gives the user a means of selecting a menu item and is useful when editing text.

"Status messages" are guides and advisories which software displays on the user's screen. In some systems, a section of the screen is reserved for these messages. In others, the messages are displayed as needed. Message content might be a warning that some part of the hardware or software has failed, an indication that a newswire Urgent or Bulletin has been received, or a message from a co-worker at another terminal.

Newsroom software controls the video terminal's *display attributes*. The attributes may apply to single characters, groups of characters, sections of the screen, and the entire screen. Typical attributes controlled by software include "reverse video", "half-intensity video", "high intensity video", "underlining", "blinking", "alternate character fonts", "color displays", and "graphics". These features, when used by a given vendor's software, can give the user a visual indication of what the system is doing and what is next to be done.

Newsroom software is written in one or more computer "languages". Examples are: Pascal, C, FORTRAN, PL1, Assembler, and COBOL. A computer language allows a human computer programmer to write a list of instructions for the computer using human-readable symbols instead of the binary numbers the computer uses. A com-

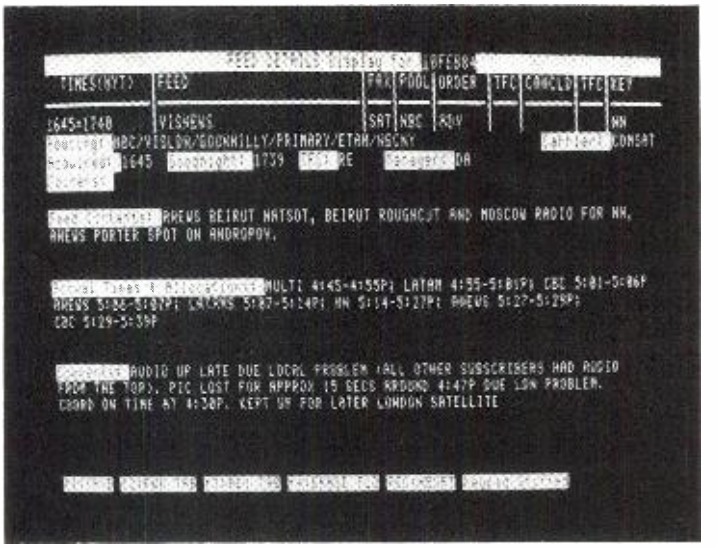
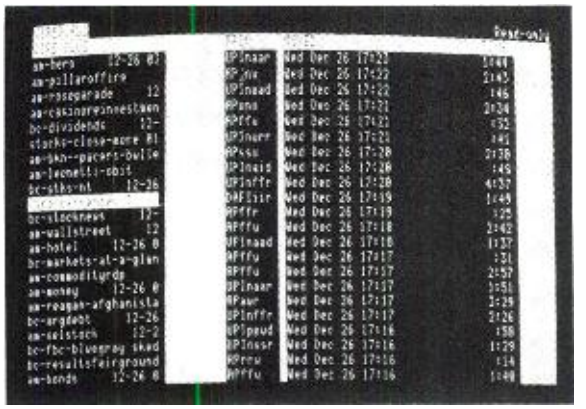
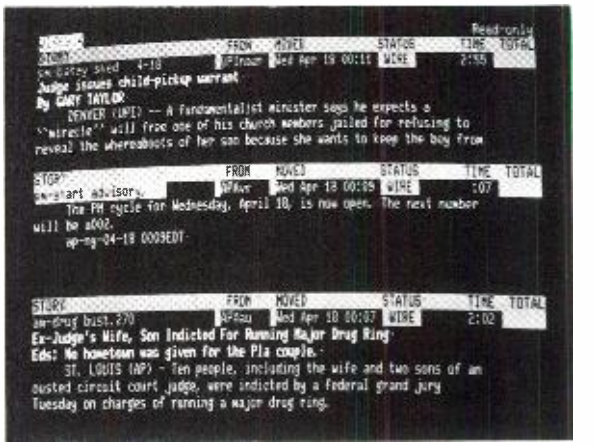


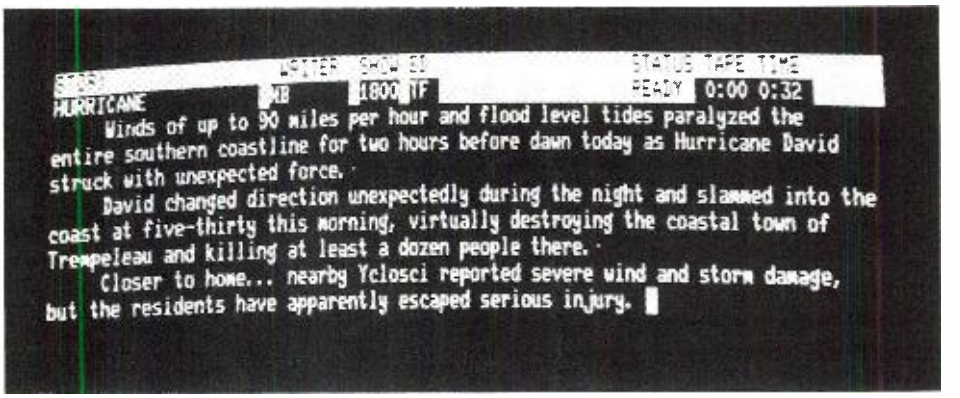
Fig. 8. A video screen showing function key labels on the bottom line. The user selects an action by striking the appropriate key.



(a)

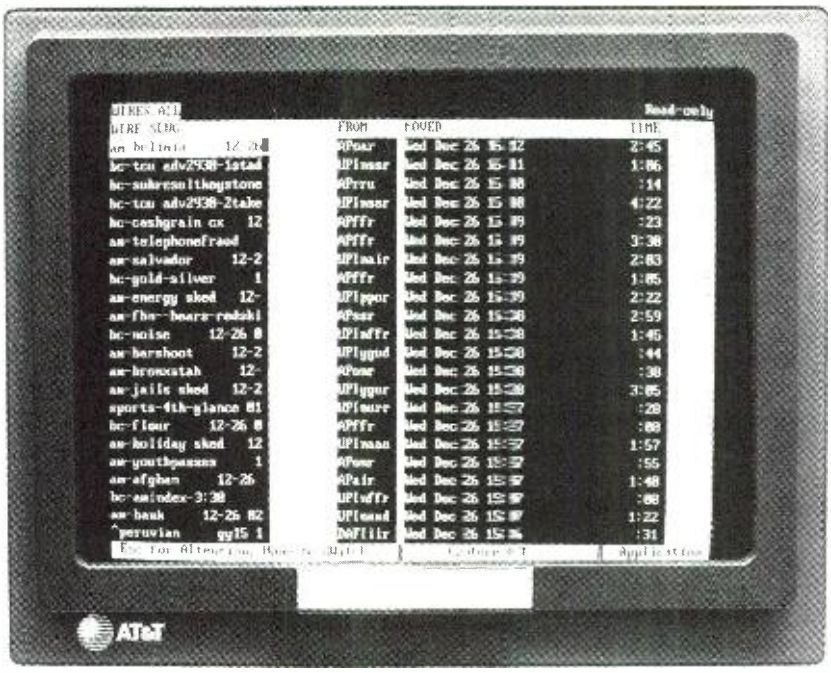


(b)

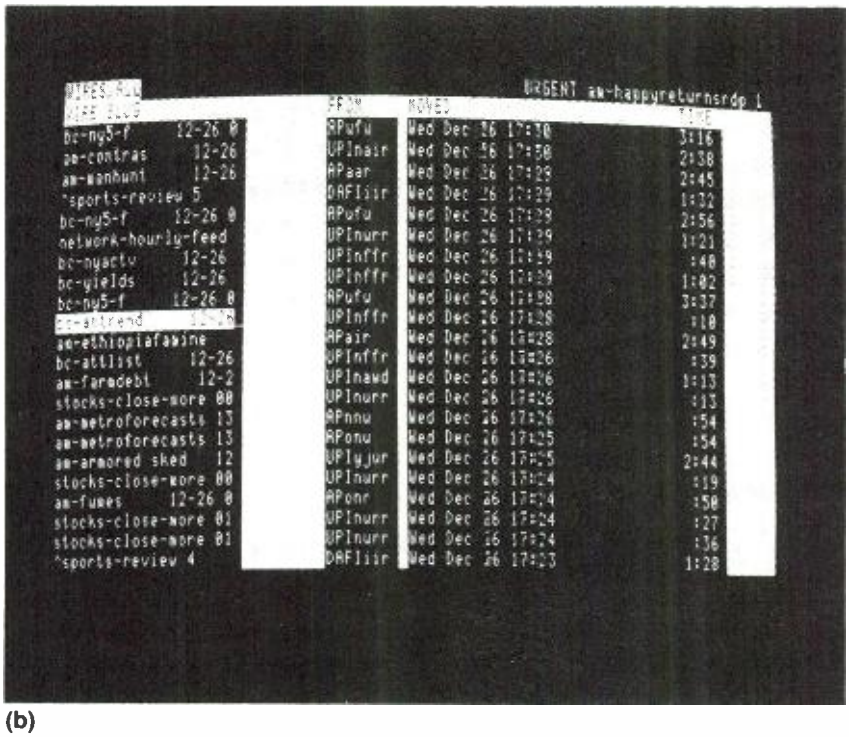


(c)

Fig. 9. Examples of the use of cursors: (a) shows a newswire menu with a "wide-cursor" selecting the "sports-review 3" story; (b) shows a "three-cell" display which presents the first several lines of three stories — the cursor is positioned on the middle story, "pm-start advisory"; (c) shows a "block cursor" which is often used in text entry (the white rectangular block at the end of the story). (Photos courtesy of Basys, Inc.)

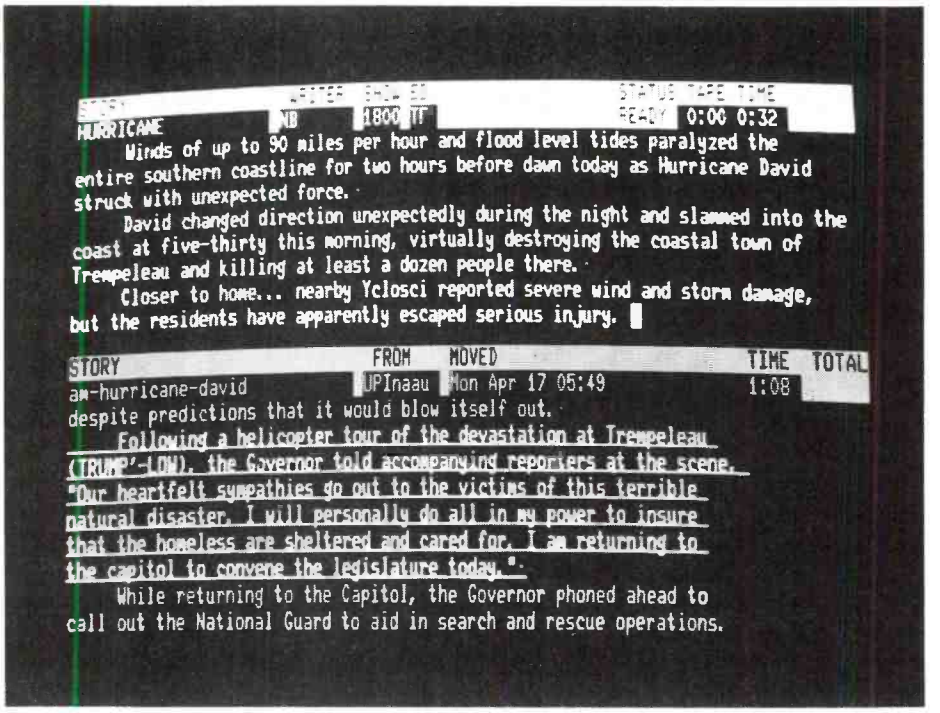


(a)

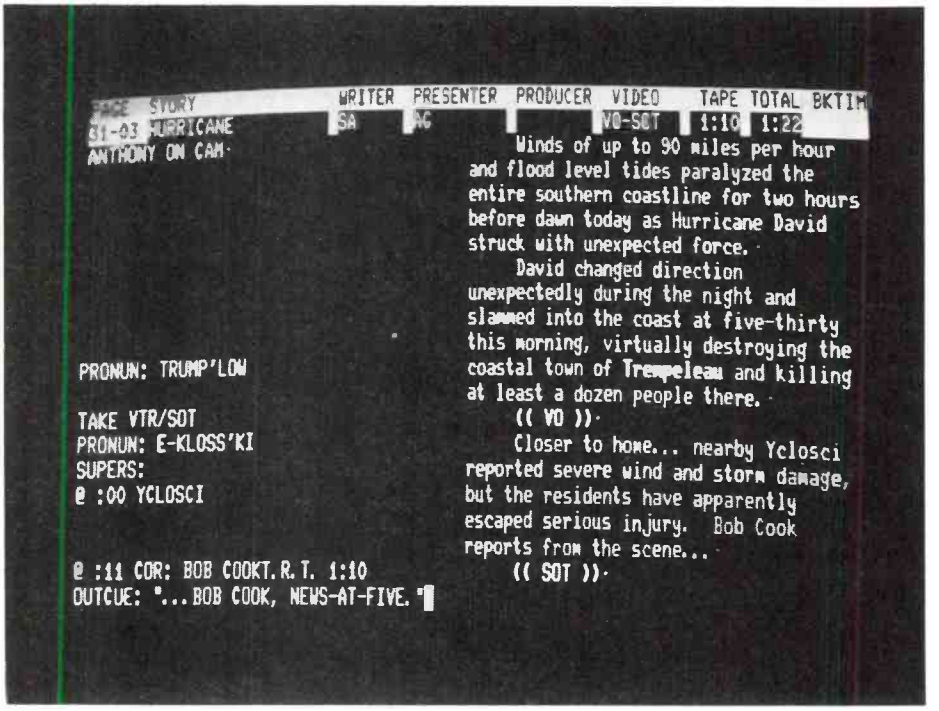


(b)

Fig. 10. Examples of the use of status messages: (a) shows the file label (WIRES.ALL) and the file status (Read-only) on the top line, and on the bottom line, several optional commands which the user can invoke; (b) shows, in the top line at the right, an URGENT story status message which indicates that one of the newswire services has transmitted an urgent story.

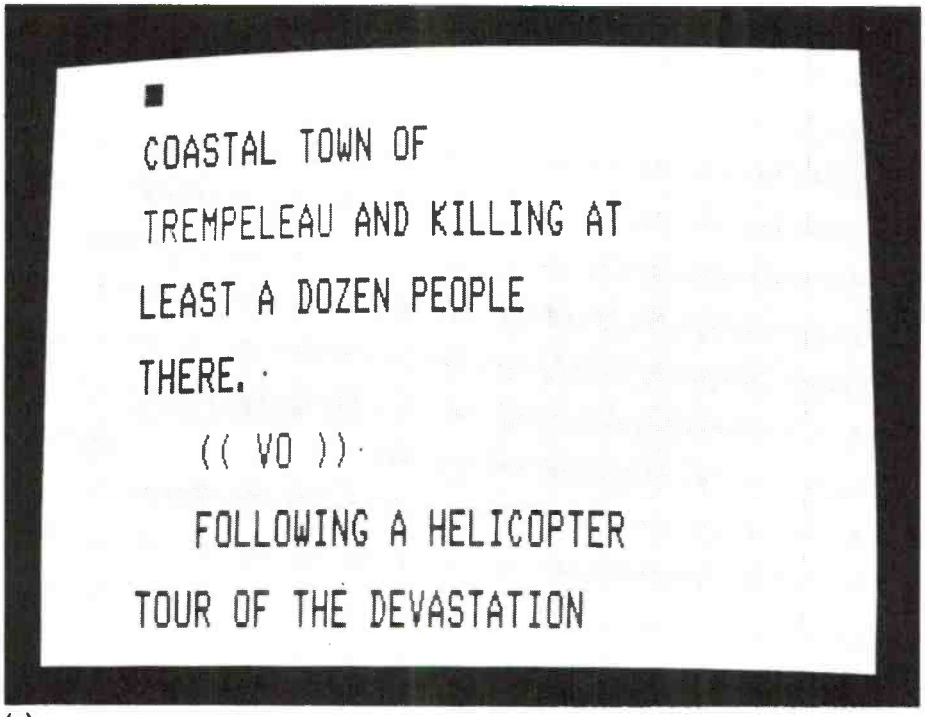


(a)

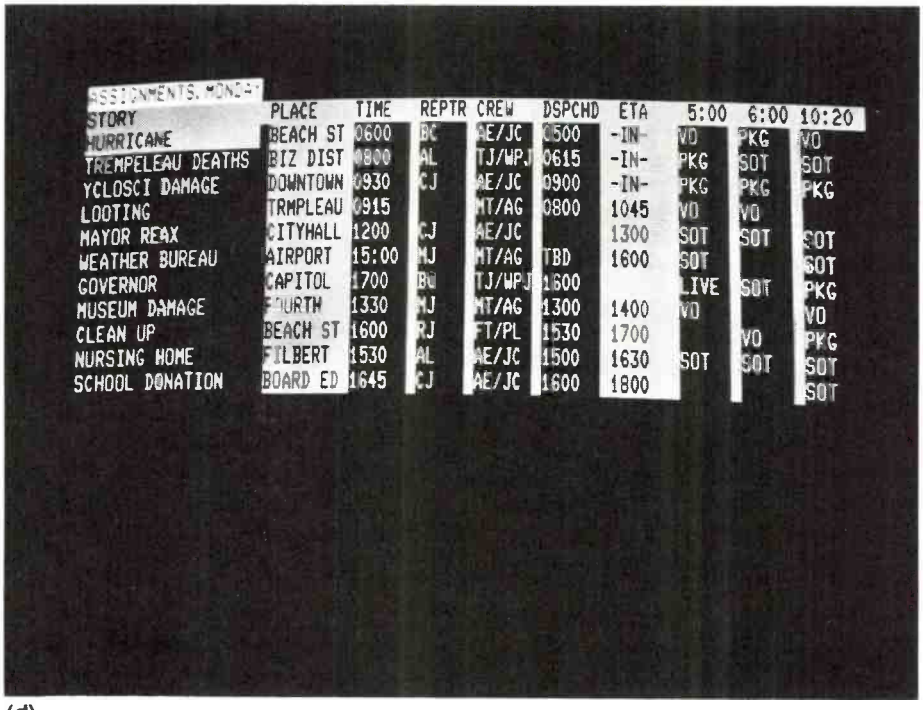


(b)

Fig. 11. Examples of the use of display attributes: (a) shows a mixture of reverse-video, low-intensity video, and underlining; (b) shows a television newscast script display which uses high-intensity video for emphasis;



(c)



(d)

(c) shows an alternate character font in use to simulate a prompter display; (d) shows an assignment menu which uses normal, reverse, and high-intensity reverse video attributes. (Photos courtesy of Basys, Inc.)

puter is then used to translate the human symbols into binary numbers which computers can later use to do the tasks the programmer intended.

The instructions the human programmer writes are called *source code*. The computer translates the source code in a process called *compilation* into binary numbers termed the *object code*.

The object code normally represents only a portion of the newsroom software: an example is the section which prints a selected newswire story. Modern software is written in *modules* which are compiled separately into object code modules. These modules are then *linked* by another computer program to form what is termed the *absolute code* or *executable code*. The absolute code contains all the binary instructions the computer needs to behave as a newsroom computer.

Most newsroom systems based on general purpose hardware and some of those based on special purpose equipment rely on an *operating system*. Operating systems, also known as *system software*, are computer programs supplied with the newsroom computer hardware to handle such tasks as moving data from memory to *disk storage*, moving data from disk storage to memory, controlling the execution of the newsroom software, providing *backup* or *mirror* copies of newsroom data, maintaining *directories* which permit newsroom software to locate stored information, interpreting user requests, etc. A computer's operating system interacts with both the user (processing his or her commands) and with the newsroom vendor's software (to control the flow of information between the computer and the terminal equipment connected to it). Operating systems are normally the product of a company specializing in this type of software. Newsroom computer system vendors typically acquire an operating system for their customers through a licensing agreement with such a company. License costs are passed on to the customer.

The Terminals

The primary, fixed-site, terminals for a newsroom computer system are normally supplied by the newsroom system vendor. These include the VDTs, printers, and possibly the prompters. Field terminals, such as pocket-sized, "lap-portables", and "carry-ons" are infrequently offered by the vendors; a station is expected to acquire them from the local computer store.

Many computer terminals are controlled by their own internal microcomputers. Most fixed-site newsroom terminals of this type contain a microprocessor which is controlled by a software program stored in ROM (Read-Only Memory). The microprocessor also has access to RAM (Random Access read/write Memory) which holds the data to be displayed on the terminal's video screen and which stores any video attributes or dynamic terminal parameters.

Video terminals typically have a video display unit, a control unit, a keyboard, and I/O port(s). The control unit and I/O ports are often housed in the same enclosure as the video display unit. Keyboards are normally separate, connected to the control unit by a cable. Fig. 13 shows several types of fixed-site newsroom computer terminals.

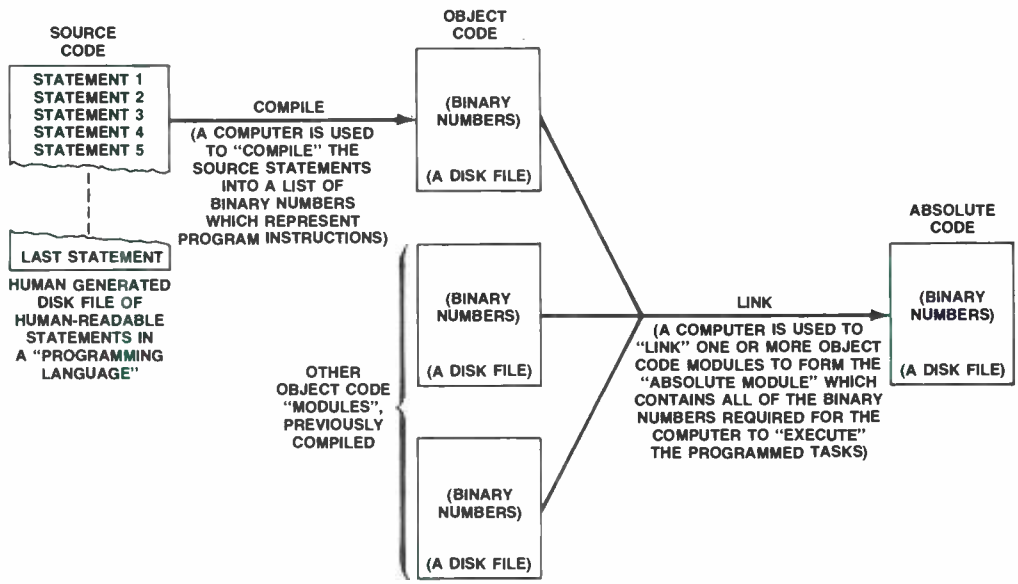


Fig. 12. Source, object, and absolute code.

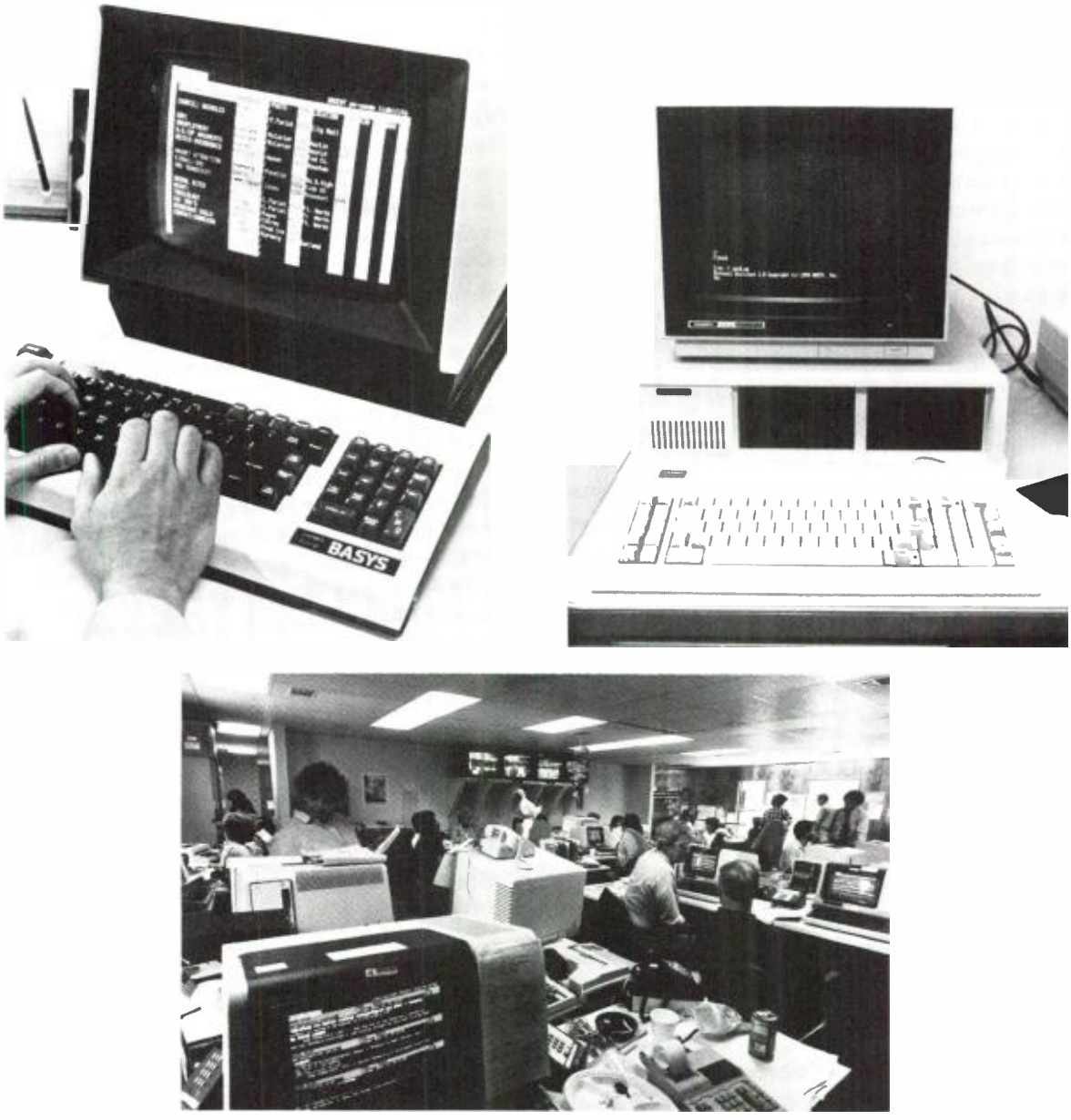


Fig. 13. Typical newsroom computer terminals. (Courtesy of Basys, Inc.)

Fig. 14 shows the relationship between the video display unit (VDU), the terminal control unit (TCU), the keyboard (KBD), the character generator (CG), and the input/output (I/O) ports of a typical newsroom video data terminal.

The VDU is similar to a high quality studio video monitor. Monochrome VDUs can display twenty-five or more eighty-character lines of data. This requires a minimum monitor bandwidth in the 15 to 20 MHz range for acceptable display resolution. Color VDUs either meet such bandwidth/resolution requirements or display fewer characters and/or lines per screen. The high-resolution color VDUs require individual RGB (Red, Green, Blue) video signals since NTSC (National Television Standards Committee) composite video only provides for a bandwidth of about 4.2 MHz.

The TCU controls the flow of data between the keyboard, the display, and the I/O ports. Most newsroom terminal TCUs include a microprocessor, ROM which holds the microprocessor's program instructions, and RAM which stores the VDU's screen contents and video attributes.

There are two types of CGs used in newsroom video terminals. One is a "preset font" type which can display one or more character fonts

which are pre-programmed into the CG's ROM when it is manufactured. The other type offers a "user-programmable font" feature which is used to permit the TCU's software to control the appearance of characters and graphics displayed on the terminal's screen. The latter type gives the software vendor more flexibility in designing displays and has been used to simulate prompter-like displays by at least one newsroom system vendor.

Newsroom terminals must have at least one I/O port to permit them to communicate with other devices in the newsroom system. It is desirable to have two or more. The primary I/O port is used to send and receive newsroom system data. The second port is often connected to a nearby printer which can make paper copies of information displayed on the video screen. Additional ports beyond the first two are sometimes used with alternate communications backup circuits, additional printers, prompters, video monitors, etc. Three types of I/O ports are popular—the *serial* I/O port, which sends and/or receives one data bit (binary digit) at a time —the *parallel* I/O port, which sends and/or receives eight bits at a time—and the LAN (Local Area Network) I/O port, which sends and receives serial data through a coaxial cable at more than one-million bits per second. Different newsroom system designs may use one or more types of I/O ports.

Standard electrical specifications exist for several types of I/O ports; these are discussed in the sections on "Data Communications" and "Interconnection" below.

Data Communications

"Data Communications" (here meaning the movement of information among the various parts of a newsroom computer system) is a specialized technology which has evolved from roots in the technologies of computer systems, electrical transmission, and telephony, and the science of information theory.

Practical applications of data communications in newsroom computer systems include: *hard-wired* connections between a newsroom terminal and the nearest computer system port, *modem* (modulator-demodulator) connections between either terminals or *concentrators* and the nearest computer system port, *dial-in* connections, *private-line* connections, and miscellaneous connections. Fig. 15 shows some typical data communications configurations which apply to broadcast newsrooms.

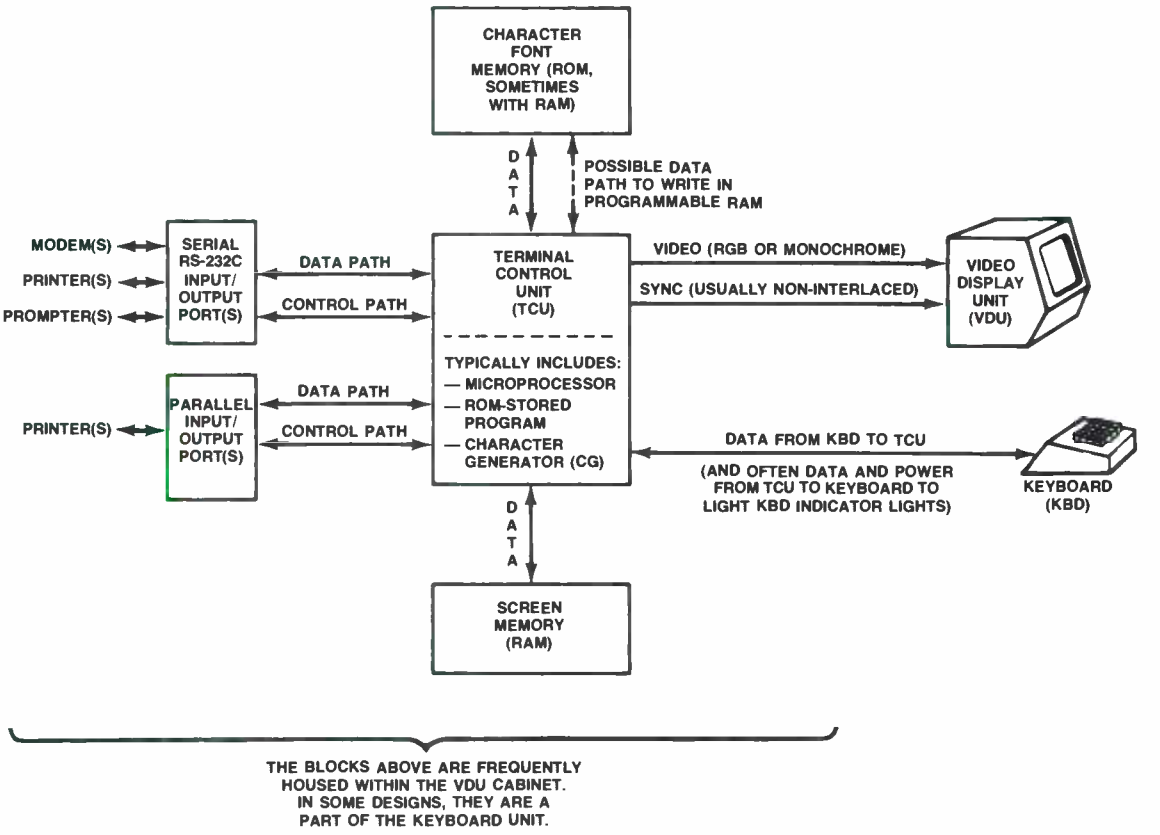


Fig. 14. VDT block diagram.

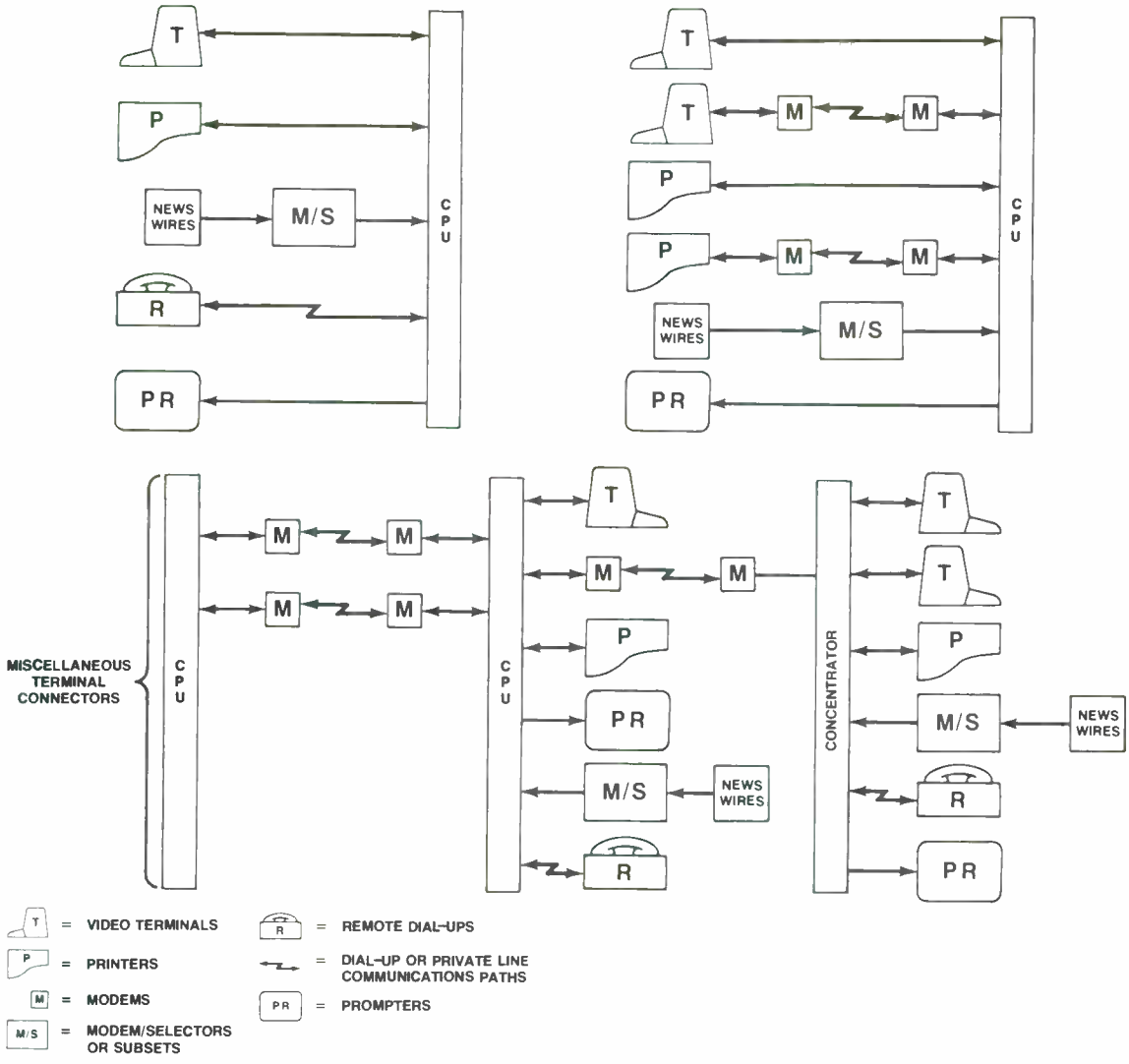


Fig. 15. Typical data communications applications.

Hard-wired connections between terminals and a computer system are employed when the terminals and the system are located within a given number of "cable-feet" between each other. Many newsroom computer systems use the EIA (Electronic Industries Association) standard known as "RS-232C" (see Appendix B) to specify the electrical and physical parameters of such interconnections. Some newsroom computer systems use coaxial cable for hard-wired interconnection. RS-232C interconnection, using special low-capacitance shielded cable, can be used to interconnect terminals and computers up to 500 cable-feet apart. Coaxial cable interconnection schemes often can be used in systems which have terminals 1000 cable-feet or more away from the computer. The choice between RS-232C and coaxial cable is determined by the vendors' newsroom system architectures.

When the distance limits of hard-wired interconnection can not be met (for example, the case of a remote bureau terminal located many miles away from the computer), modem equipment is used. Data communications modems convert digital signals sent from a computer or terminal into an analog audio signal which can be transmitted over telephone lines. Modems also can receive analog signals from a distant modem and convert them into digital signals which are presented to the local terminal or computer port for interpretation. Thus, an analog communications circuit with a modem at each end can interconnect digital devices (computers, terminals, printers, etc.) over longer distances than would be possible with hard-wired connections.

Two types of analog communications paths exist: a "dedicated path" and a "dial-up path."

Dedicated analog paths are *point-to-point* con-

nections which include a transmission mechanism (telephone circuit, satellite circuit, optical fiber circuit, radio circuit, infra-red circuit, etc.) and an "interface" at each end to make the analog signals available to modem equipment for conversion to the digital signals used by the computer or terminal. Dedicated paths are either available on a permanent basis or on a pre-planned schedule of usage.

A dial-up path uses the telephone network to establish a connection between a terminal and a computer system on an ad-lib basis. An example would be the dial-up call a correspondent in the field makes from his portable terminal to the station's computer system to file a script or read the newswire services. Dial-up paths can also be used to replace, temporarily, a failed dedicated path.

In addition to analog paths, some communications common carriers offer end-to-end digital services. These digital paths provide a relatively error-free transmission medium between terminals and computer equipment. (Analog transmission paths are subject to incremental degradation due to various factors; while digital technology permits re-generation of the original signal at intermediate points and at the far end of the path.) However, all "end-to-end digital" services are not the same.

Some carriers claim to offer "end-to-end digital" service, but use an analog circuit between the "digital" modems they supply. There is a difference. For true digital transmission, there should be no "analog sections" in the transmission path.

Two types of serial data communications transmission are widely employed—"synchronous transmission" and "asynchronous transmission". Each uses a different scheme to maintain synchronization between the data transmitter and a receiver at the far end of the circuit. Synchronous transmission passes both data signals and a "clock" signal. The clock signal is used by the receiver to determine when to check the data signal for the next bit. Asynchronous transmission passes only a data signal and relies on "start" and "stop" bits to maintain synchronization between the data transmitter and the far-end receiver. Equipment at both ends of an asynchronous data path must be set to the same number of bits-per-second and the same number of bits per character. The receiver waits for a start bit from the incoming path and then counts the data bits as they arrive. When the pre-set number of data bits per character has been received, the receiver awaits a stop bit which causes the character to be processed. The receiver then waits for the start bit of the next character, etc.

Multiplexers, devices which permit several terminals to share a data communications path between a remote location and a computer system, are used in newsroom computer systems to reduce the cost of such communications and, in some cases, to ensure error-free transmission of digital data between the locations.

Multiplexers are installed between a modem and the terminals. The MUX (multiplexer) has "ports" for each of the terminals it serves and gives each terminal access to the communications line through a *protocol* (a set of conventions which determines when and how the terminal can communicate through the MUX to the far end of the path). A multiplexer's purpose is to permit more than one terminal to share a single modem line to a remote computer system. See Fig. 16.

Two schemes for multiplexing several digital devices onto a single line are popular. One is *time-division multiplexing* (TDM) and the other is *statistical multiplexing* (STATMUX).

Time-division multiplexing divides the communications line's data transmission into a number of "time-slots" which are assigned to specific multiplexer ports. An eight-port TDM MUX, for example, would have eight time-slots, one for each port. In rotation, each port is given a chance to transmit and/or recieve data during its assigned time-slot. The data communications path between the TDM MUXs carries a composite signal which includes data from each of the eight ports. The path passes data at a given number of "bits-per-second" (see glossary). In a typical case, a path might be capable of sending and receiving at 9600 BPS (bits-per-second) and be connected to eight-port TDM MUXs at each end. If the eight time-slots were divided equally, each device could pass data at one-eighth of the 9600 BPS rate, or 1200 BPS each. In practical applications, however, time-slots are frequently divided unequally in order to accomodate a mixture of speeds among the MUX ports. Typical examples appear below.

Port #	Example A Bits/sec.	Example B Bits/sec.	Example C Bits/sec.
1	4800	2400	1200
2	2400	2400	1200
3	1200	1200	1200
4	300	1200	1200
5	300	1200	1200
6	300	1200	1200
7	150	—	1200
8	150	—	1200
Totals:	9600	9600	9600

In Example A, half of the data communications path's 9600 BPS transmission rate is assigned to port 1, with the remainder divided among ports 2 through 8. Example B shows an

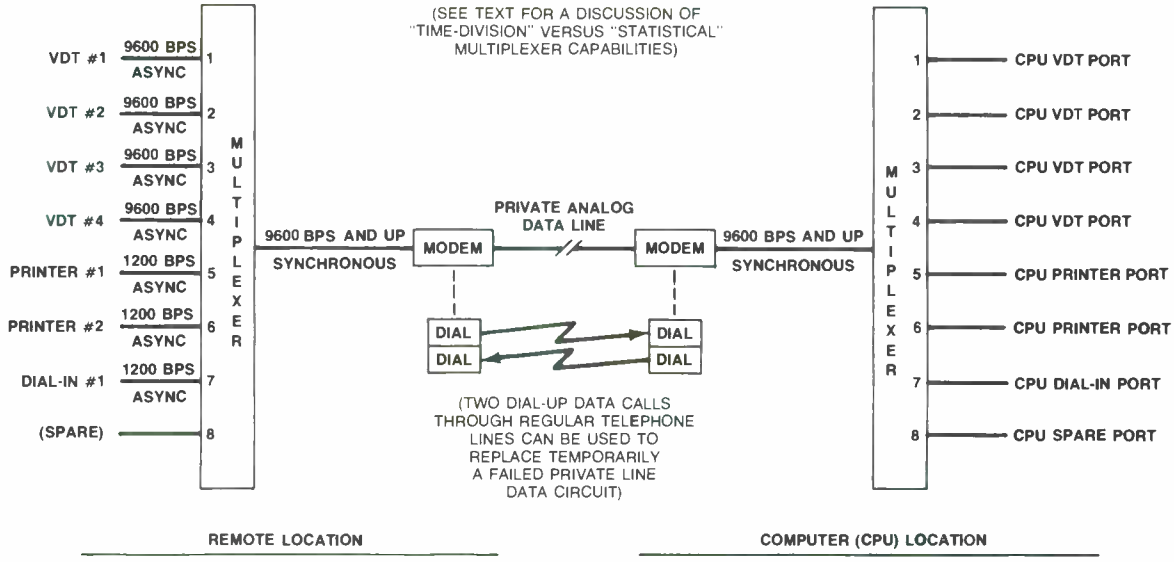


Fig. 16. Conceptual multiplexer application.

eight-port TDM MUX configuration using fewer than eight ports but using the full 9600 BPS capability of the data path. Example C has each of the eight ports using one-eighth of the path's transmission rate. TDM technology permits a maximum combination of port speeds up to the bit-rate at which the data path between the MUXs operates.

Statistical multiplexers, in contrast, offer an apparent data *thruput* (see Glossary) higher than that which would be expected from a data path of a given BPS speed. STATMUXs allocate the data communications path's transmission capacity dynamically. Terminal or computer ports with "nothing to send" are not given a portion of the path between MUXs. If one terminal user is "scratching his or her head" to decide what the next step is and another is actively entering data from the keyboard, the active user's keystrokes will be transmitted over the path normally; the user "looking up the next step" will not be allocated "space" on the communications path until he or she returns to active use of the terminal. Depending on terminal usage patterns, STATMUXs can provide an apparent thruput of two or more times that of a TDM MUX system.

Newswire Services

Most newsroom computer systems permit the various newswire services such as AP, UPI, and Reuters to be "read" and stored in the computer's memory. The newswire stories are then available on video terminals throughout the computer system. Users can "scan" the wires on their screens, print a paper-copy of an interesting story, re-write a wire story to add a local slant, etc.

The more sophisticated newsroom computer systems offer features which can significantly add to productivity in a station's news operation. For example: bulletins, urgents, and flashes from a wire service can cause terminals to "beep" and display the "slug line" of the priority story (interested users may then request a full display of the newswire story). Some systems can interpret the *ANPA* header information sent by most wire services and divide the stories into directories of categories such as "Foreign", "National", "State", "Regional", "Business", "Weather", etc. This permits the user to scan only the stories which interest him or her. In some systems, users can create personal directories of stories which contain specified "key-words". A writer working on a gun-control story might create a personal directory with a key-word of "gun". From then on, all wire stories which contain the word "gun" would be listed in the user's personal directory.

Newswires are delivered to a station through dedicated telephone circuits or satellite receive dishes. Depending on the type of service ordered, the incoming newswire signals may be processed by modems, *selectors*, and/or *subsets* located at the broadcast station. Fig. 17 shows some typical newswire connections.

The modems, normally supplied by the newswire agency, are similar to those discussed under "Data Communications" above. They convert analog audio signals from the wire service into digital signals which can drive a printer and/or be connected to a computer system for processing.

Selectors are often supplied to "filter-out" newswire stories which do not apply to a station's

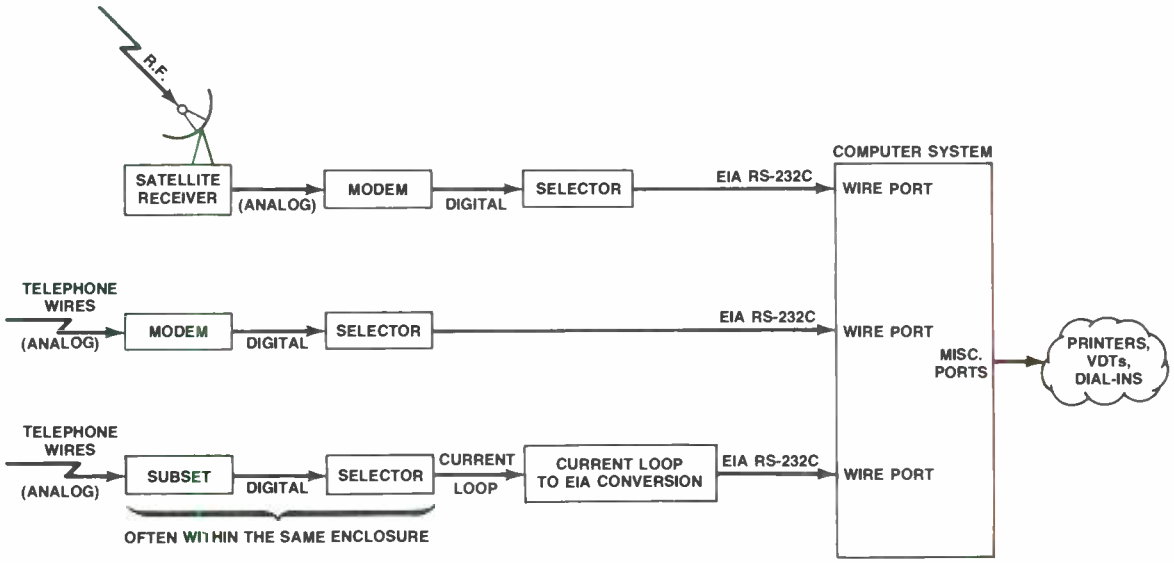


Fig. 17. Typical newswire connections.

coverage area, or information services to which the station has not subscribed. The selector unit is pre-programmed at the time of installation to pass certain classes of stories—based on the AN-PA or special wire service headers—to the station's printer or computer. Other stories on the wire are rejected by the selector.

Subsets are typically supplied with low-speed (below 110 BPS) newswire services. These units supply a "current loop interface" to printers and computer systems. Most newsroom computer systems use a conversion device to convert the current loop signals into RS-232C compatible signals before they enter the system.

Interconnection

Cables, wires, modems, multiplexers, subsets, and other facilities are required to interconnect the various parts of a newsroom computer system. Some of these are normally supplied by the newsroom computer system vendor; others are the responsibility of the station.

Typically, a station should expect to supply the following interconnection facilities when converting to a newsroom computer system.

- Cables: either RS-232C or coaxial, to connect to local terminal equipment (VDTs and Printers)
- "Taps" or "drops" of newswire feeds (often a joint venture between the station and the vendor)
- "Dialtone" lines from the local telephone company if dial-in access is required
- Data lines from remote locations, if required

The cables between terminals and the computer system are normally installed by the station, either using station personnel or an outside contractor. The computer system vendor will frequently work with station people in the planning and specification phases of the cable installation. RS-232C cables should have an overall shield wrap with a *drain-wire*, grounded only at the computer end. Cable routes should be planned to minimize the possibility of "noise crossover": keep computer cables away from low-level audio circuits and away from high-level radio frequency equipment where possible.

Two methods of interconnecting newswire feeds to a newsroom computer system are commonly used. The *tap* method assumes that the newsroom has an existing newswire service connected to a printer which will remain in service after computerization. This method uses a *Y-cable* or adaptor to split the newswire feed into two outputs, one for the printer and one for the computer. The splitter is normally supplied by the newsroom computer vendor. The other method uses a separate *drop*, supplied by the newswire service. The dedicated "computer drop" has its own modem, selector, and/or subset. The printer supplied by the newswire service remains on a separate drop which can be continued or disconnected. Since printers are normally supplied with a newsroom computer system, many stations elect to discontinue the newswire printers. Some stations install a transfer switch which permits the newswire to be printed directly on a computer system printer if the computer is not working.

"Dialtone" lines from the local telephone company, to permit field and remote bureau people to dial in to the computer system, are delivered on an "interface unit" supplied by the phone company. An *auto-answer* modem interconnects the dialtone line with the computer system. The newsroom computer system vendor should specify the type of modem needed. In some cases, the vendor supplies modems as part of the newsroom system; in others, the station is expected to acquire the modems.

"Data lines" are used to interconnect relatively permanent remote locations such as bureaus to the newsroom computer. Such lines are special point-to-point circuits which are *conditioned* for data transmission and are available twenty-four hours per day. Modems—and multiplexers, if more than one remote terminal is needed—are installed at both ends of the circuit. Stations use data lines instead of dial-ins when the amount of traffic between a remote point and the computer justifies the cost or when the higher thruput of a data line is needed.

NEWSROOM COMPUTER SYSTEM ARCHITECTURE

The *architecture* of a newsroom computer system describes the way the system's hardware, software, and communications "building blocks" have been assembled to form a useful structure. Several basic structures are presented below; practical system architectures depend on a station's requirements, the newsroom computer vendor's system design, and cost factors. Fig. 18 shows the basic "centralized", "distributed", and "hybrid" architectures.

Centralized Systems

Centralized newsroom computer systems have at least one "computer room" which houses CPU, communications, and frequently test and monitoring equipment. A *computer room* may be anything from a previously unused closet to a large new space with special air-conditioning, power supply, and raised *computer-floor*. The

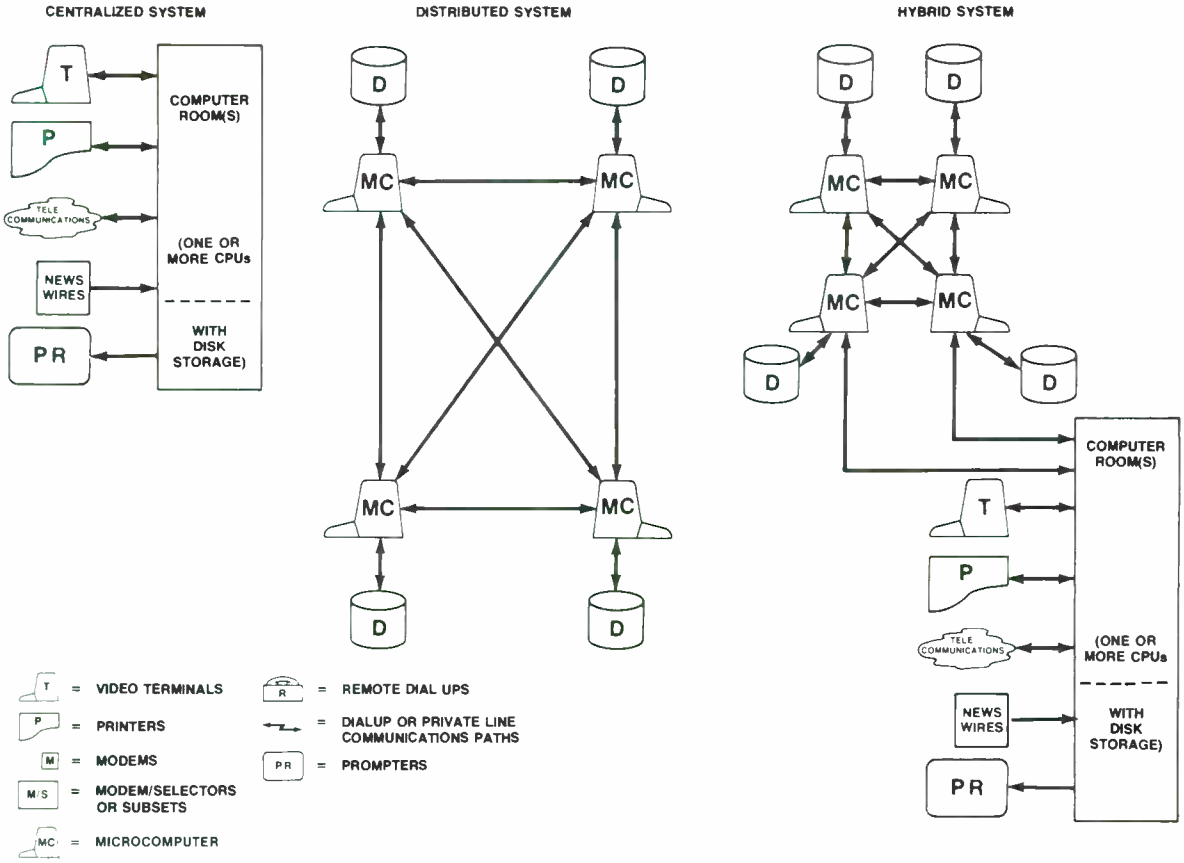


Fig. 18. Newsroom system architectures.

size and requirements of the newsroom system determine what is needed in the centralized site(s).

In centralized newsroom systems, all information flows through the computer room. The terminals, printers, dial-in lines, data lines, and newswire services connect directly to computer equipment in this room. The system's data files reside on magnetic disk or tape devices in this room. The *system console(s)* which permit a *system manager* to control the flow of work through the computer system and to reconfigure the system's hardware or software are located in this room.

The advantages and disadvantages of a centralized computer system architecture stem from centralization.

On the advantage side, centralized systems offer direct control of all system operations from a single location. In the central computer room, an operator can "tune" the system's workflow, make safety copies of the system's data files, install new software, resolve hardware or software or communications problems, monitor system security, etc.

Disadvantages in a centralized system architecture are centered around the "one point of failure" issue. Anything which adversely affects the central computer system can cause problems which may affect some or all terminals connected to the system. The computer room air-conditioning might fail, causing the equipment to overheat and stall; a disk drive which has tonight's newscast script on it might *crash* during the broadcast; the local electric service might go into a "brownout" or "blackout" which could cause a central computer system to lose some or all of its data files; the "cleaning person" might unplug the computer to get an outlet for a vacuum cleaner; or a fire caused by a faulty piece of equipment in the central room might damage the equipment around it.

Distributed Systems

The distributed newsroom computer system architecture places a small computer at each terminal location. The combination of a VDT, a computer, magnetic data storage equipment (usually floppy disks), and possibly a printer is termed a "workstation." At a workstation, the user interacts with his or her own dedicated computer to write scripts, read the newswires, assign crews to stories, or whatever the person's tasks are. Each workstation is a complete computer system, usually serving only one user at a time. Workstations can also be used as terminals for dial-up access to other computer systems.

The workstations, distributed where needed throughout a newsroom system, require some means of inter-communication to permit electronic transfer of one user's information to other users. This need can be satisfied by data lines, a *Local Area Network* (LAN), or a combination of the two. A writer may want to send a copy of a finished script to his or her editor's workstation for review; the news program producer may want to advise the staff of a revised running order for the broadcast; a user may want to send an advisory note to another user; and certainly, the newswire services must be sent to most (if not all) workstations in the system. Distributed architecture links individual *stand-alone* workstations into a *network* which forms the newsroom computer system.

The advantages and disadvantages of a distributed computer system architecture stem from the overall distribution of system resources.

Primary advantages of a distributed architecture include minimal susceptibility to the "single-point-of-failure" syndrome, the capability for each user to maintain direct control of his or her information, and a minimal need for human intervention to keep the system running. Since each user in a distributed system has a dedicated one-user computer system, other parts of the system can fail without having a major effect on the user's capability to perform his or her tasks at the workstation. User tasks which depend on information from other workstations or the newswires may be affected in some types of failures. The typical magnetic storage medium, floppy disks (and sometimes tape cartridges), gives the user direct physical control of his or her information; magnetic storage media can be considered as "portable file-cabinets" which the user is free to lock in a desk or carry along. In contrast to a centralized system, a distributed system normally has no central control console to be staffed (actually, each workstation gives its user the control console functions which apply to his or her own set of tasks).

Disadvantages of a distributed system architecture include lack of centralized control of the *database*, user functions, and data communications; logistical problems in propagating improvements or "bug-fixes" throughout the system; and frequently, higher cost than with other architectures. The lack of centralized control puts the burden of "system-management" on newsroom system users, some of whom will have no interest in or aptitude for such tasks. News writers want to write their scripts; the news program producer wants to control the program's running order; the technicians want to know what items to playback when; etc. Under the pressures of the broadcast news environment, these people may not be willing or able to make "backup-disk copies", to "restart" a neighboring terminal which has stopped communicating with its user or the rest of the network, to "re-boot" their own

dedicated computer system, or to "challenge" an outside person attempting to access the system by dial-in telephone line.

Inevitable modifications to the system, whether to fix problems or to make improvements, are frequently difficult to achieve within a distributed system. Systems which use PROM (Programable Read-Only Memory) or ROM (Read-Only Memory) chips to store the newsroom system software will require a technician to change chips at each workstation whenever software upgrades are required. Some upgrades require all system units to be modified at the same time. In such a case, installation of the upgrade may require more than one technician, major pre-planning, and some *downtime* for the overall system.

Costs for a distributed newsroom system are typically higher on a per-workstation basis than with other architectures. Since each workstation contains its own one-user computer system and often a separate micro-computer-based communications processor, there is more hardware (and cost) associated with a distributed system workstation than with a terminal or printer connected to a central computer. However, cost-factor comparisons between a distributed system and other system architectures should include the "effective-cost-per-workstation" (divide the total system cost by the number of users who can be supported simultaneously).

Hybrid Systems

Hybrid newsroom computer system architectures attempt to combine the best features of both the centralized and distributed approaches. They have one or more central computer locations, terminals and communications connected to the central location(s), and workstations which connect to the central site(s) (which also may process newswires, dial-in lines, LAN communications with other distributed workstations, etc.).

Two types of hybrid newsroom computer systems are defined below; additional hybrid architectures can be expected in the future.

The first hybrid architecture combines *dumb terminals* and *intelligent workstations* into a newsroom computer network. The dumb terminals connect directly to a central computer system and can do nothing without the central computer services. The intelligent workstations also connect directly to the central newsroom computer network, but can operate in the stand-alone mode if connection to the central system is broken.

The second hybrid architecture places a portion of the computer "intelligence" in a central location and the remainder in the individual terminals connected to the central location. Each terminal normally relies on the central computer system to handle user functions, but if connection to the central equipment is interrupted, these "semi-intelligent" terminals can continue to handle a limited set of the users' tasks.

PLANNING A NEWSROOM COMPUTER SYSTEM

Like other technical projects, the installation of a newsroom computer system requires planning. The better the plan, the better are chances for successful project completion. This section addresses planning issues associated with the installation of a broadcast newsroom computer system.

Define Objectives

The first step in planning a newsroom computer system is to define the objectives of the change to a computerized news operation. This includes descriptions of current (probably manual) means of handling news information, of the proposed computerized means (possibly in several stages over time), of the anticipated benefits through computerization, and of the estimated effect on the station's business.

The definition of objectives should include both quantitative and qualitative factors. A quantitative example would be a station which currently processes fifty news stories a day through manual means and needs to process eighty stories per day to compete effectively in its market. Qualitative factors which tend to improve the newscast product include more rapid distribution of story and news program development information throughout the news operation, greater efficiency for writers and editors through automated *word-processing* features, and with these a productivity increase which can provide the newsroom staff more time to concentrate on broadcast journalism rather than the "mechanics" of getting a story on the air.

A useful tool in this stage of planning is the *work-flow diagram*. One should be done to show how information flows through the current newsroom; another should depict the flow after computerization. These diagrams should include items such as how the newswire stories are sorted and distributed, how crews and correspondents get their assignments, how the content and running order of news programs are created, how contact information is maintained, etc. The resulting drawings may be as simple or complex as the scope of a news operation warrants. They are useful in discussions with computer system vendors, station management, and the news operation staff.

Determine Workstation Requirements

The number of workstations, printers, and other devices to be connected to the newsroom computer system should be determined through careful analysis of the work-flow diagrams. Generate a list of functions and allocate the appropriate equipment to each function. An example is presented below.

TV News Workstation Requirements

Function	VDTs	Printers	Misc.
Assignment Desk	2	1	2 modems
Editor's Desk	1		
Writers	3	1	
Producer's Desk	1		
Anchorperson Office	1		
Studio A Control Room	1	1	
Studio A Anchorperson Set	1		3 prompters
Tape Room	2	1	1 label printer
Tape Library	1	1	1 label printer
Graphics	1	1	
Reporters and Crews	3	1	2 portable terminals
News Director	1	1	
Totals:	18	8	

Miscellaneous:
- 2 Modems
- 3 Prompters
- 2 Label Printers
- 2 Portable Terminals

Make a drawing or list of relationships between the terminals and the peripheral equipment. For example, the list above shows only one printer for two Assignment Desk VDTs and no printer for the Editor's Desk VDT. Most systems will permit a single printer to make printouts for several VDTs. In the case above, it might be logical to have the Assignment Desk printer serve both the Assignment Desk's and the Editor Desk's printing needs. Definition of such relationships is part of determining workstation requirements.

Special requirements such as unusual environmental conditions (temperature, humidity, altitude, salt-spray), non-standard electrical power, high RF (radio frequency) fields, etcetera should be defined.

Determine Newswire Requirements

Most newsroom computer systems excel at sorting and distributing incoming newswire stories. The computerized newsroom needs fewer newswire printers, uses less wire printer paper, and provides faster access to stories which "move" on the wire. Planning should answer three questions: "Which wire services are required?"; "How will they be distributed?"; and "How will newswires be processed in the event of a computer failure?".

Which newswire services to buy is normally determined by past practice at a station. However, computerization of a news operation frequently offers cost reduction through elimination of newswire printers and paper supplies. The savings might be used to offset the cost of computerization, or to add additional newswire services which could not be cost-justified previously.

Distribution requirements should be determined from the work-flow diagrams. Newswire stories on most wire services contain "header" information which specifies the story's classification: state, regional, national, business, sports, weather, etc. The computer "reads" each story header and can be instructed to route the story to one or more newsroom users. This can replace the "wireroom clerk" who used to tear, sort, and deliver printed newswire stories to specified newsroom desks. In a computerized newsroom, the users are alerted to an incoming story which relates to their function. The local editor is advised of local stories, the weatherman gets weather stories, sports gets sports, etc. Flashes, bulletins, urgents, and other advisories are frequently distributed to all terminals in a newsroom computer system. A distribution plan should be developed for each terminal in the system.

If the newsroom computer fails, some backup means of processing newswire stories should be available. One approach is to retain at least one newswire printer for each wire in the newsroom. Another, offered by several newsroom computer vendors, is to use the computer system printers to print the newswire stories while the computer is out of service. A switch is provided for each printer which transfers it between the computer system and an incoming newswire line. Newsroom computer system planning should include either, or a combination, of these approaches to keep the newswires flowing when the computer system is unavailable.

Determine Data Communications Requirements

Data communications lines are required in newsroom computer systems whenever terminals, printers, or other computer peripherals are

remotely located. Direct interconnection of computer equipment through twisted-pair or coaxial cable is limited to maximum runs of up to several thousand feet at best. Station newsroom requirements for intercommunication with bureaus or field personnel beyond such cable limitations must include a data communications *network specification.*

A network specification can be as simple as one dial-in auto-answer modem for a tiny station, or as complex as a worldwide communication system serving hundreds of workstations for a major broadcast news organization. It should include, per each location, the quantities and types of equipment required. The location's work-flow diagrams, estimates of remote workstation data communications character-counts over time, and relative costs can then be used by the computer system vendor and/or an outside communications common carrier to define a data communications network architecture which meets station requirements.

CHOOSE A VENDOR

Few, if any, broadcast organizations can commit the resources in manpower, equipment, time, and materials required to create a newsroom computer system "from scratch." Fortunately, there are a number of newsroom computer system vendors active in the marketplace. This section presents suggestions on choosing a broadcast news computer system vendor.

Request for Proposals (RFP)

A "Request for Proposals" (RFP) describing the station's requirements and desired features of a newsroom computer system should be created. This might be a few pages for a single small station or several hundred pages for a group of stations or a major network. At a minimum, the RFP should include the newsroom's present and proposed work-flow diagrams, a description of the broadcasts supported by the newsroom, and an estimate of the workstation requirements. If possible, the RFP should include a job-by-job breakdown of the work done by each person in the news operation, sample forms and documents used in the current manual newsroom, floorplans showing the layouts of the newsroom and studios, descriptions of the station's technical facilities which might be connected to the newsroom computer, timetable requirements for the conversion to a computerized news operation (initial installation and possible phased expansion), business considerations, procurement terms and conditions, etc. Extensive detail in an RFP gives the responding vendors a better chance to propose a system which will meet the station's needs.

Proposal Analysis

The analysis of vendor proposals is more an art than a science. Some vendors will respond to an RFP with specific proposals; others may respond with few specifics but many sales brochures, testimonials from current customers, and a stream of sales-oriented correspondence directed at a station's "decision makers"; still other vendors may not respond at all. Sorting the "wheat from the chaff", discovering and understanding the specific benefits a proposed system can offer a station is important, but often difficult and time-consuming.

Whether a station receives a proposal from one vendor or several, the preparation of a "scoring matrix" will aid proposal analysis. The scoring matrix should show detailed station requirements, one line for each, at the left of the page. A column for each vendor responding should then be established further to the right, leaving space for a score or a "YES/NO" entry for each requirement line item. A short example appears on page 7.6-144; a real station's list of requirements would probably be longer.

A numerical scoring system (a scale of 0 to 10 or 0 to 100%) might be used instead of the "YES/NO" approach in the example above. If a computerized "spread sheet" system is available, it may be useful in proposal analysis based on numerical scoring.

Visit Vendor Installations

Key people in the station's News, Engineering, Financial, and/or Purchasing departments should visit at least one of the leading vendor's newsroom installations and possibly the vendor's plant. Discoveries made in such visits may reinforce or alter tentative vendor selection decisions based on RFP responses alone. Choose a vendor's newsroom of similar size and with similar requirements to those in the RFP.

Demonstration System

Some vendors may be willing to install a small "demonstration system" at a station for evaluation on a no-charge or "token payment" basis —if the station indicates a strong interest in the vendor's system. Such an arrangement is beneficial for several reasons. First, the station can evaluate the vendor's system under actual operating conditions, using the station's own newsroom procedures and information. Second, the vendor will have an opportunity to learn more about the station's news operation and possibly be able to

Radio News Scoring Matrix

RFP Requirement	Vendor A	Vendor B	Vendor C
Workstation Quantities:			
Initially 20	20	20	20
Expansion to 50?	YES	YES	max. 40
Remote Terminal Support:			
Lap-portables	YES	NO	YES
Fixed-site Workstations	YES	YES	YES
Data Communications	YES	limited	YES
Newsroom Functions:			
Assignments	YES	YES	YES
Script Preparation	YES	NO	YES
Newswires	YES	YES	YES
Desk Logs	YES	NO	YES
Studio Functions:			
Change Running Order	YES	n/a	YES
Prompter	YES	n/a	NO
On-line Bulletin Alert	YES	n/a	YES
Installation and Maintenance:			
Installation by Vendor	YES	3rd. pty.	YES
Hardware Maintenance	GOOD	limited	GOOD
Software Maintenance	GOOD	n/a	limited
Costs:			
Turnkey 20 Workstations	$_____	$_____	$_____
Hardware Maintenance/mo.	$_____	$_____	$_____
Software Maintenance/mo.	$_____	$_____	$_____

suggest better ways of using the system when the full computerized newsroom is implemented. Third, the demonstration system can be used to train the newsroom staff prior to cutover to the full system. Finally, vendor and station personnel will gain experience in working together; a rapport or the lack of it will become obvious.

INSTALLATION

The sections below present some guidelines and considerations appropriate to the installation phase of a computerized newsroom. By the time installation is about to begin, the station people responsible should have had a chance for extensive exposure to the vendor's system's capabilities and requirements. Since no two news operations are exactly the same, installation requirements and plans must be tailored to match the station's needs.

Develop Interconnection Plan

Whether the station has chosen a system based on RS-232C, coaxial, or a mixed interconnection scheme, a complete plan of the cable runs should be developed. The plan should show each terminal, printer, workstation, newswire feed, dial-in modem, private line modem, computer port, and the relationship between them. Such a "cable list" can be used by station, vendor, or third party installation personnel to provide the connections between the various equipment in the newsroom system.

Develop Architectural Plan

Newsroom workstations and terminals normally will replace typewriters. Typically, the workstations and terminals require more desk-space than a typewriter and also have interconnection requirements to the rest of the newsroom system. Architectural adjustments to the physical layout of a station's newsroom may be required to accommodate computerization.

This may be a blessing, a curse, or may lie somewhere in between. Stations about to refurbish their newsroom facilities will find the architectural adjustments required for a computerized news operation fairly easy to accomodate. Others may discover that major physical changes will be required to support a computerized news operation.

In any event, the vendor and the station's architectural people should develop a plan to be approved, and possibly modified by the newsroom management and/or staff. This plan should address changes in furniture layout, lighting, HVAC (Heating, Ventilation, and Air Conditioning), electrical requirements, telephone communications, newswire-room facilities, etc.

Develop Installation Schedule

Once the interconnection and architectural plans are finalized, the station and the vendor(s) should develop an installation schedule which specifies the work to be done by each party and establishes "milestone" completion date targets for all project tasks. This schedule should be dynamic; tasks may be completed earlier or later than originally planned, causing inevitable revisions as the work progresses.

Project review meetings between all parties involved should be held on a regular basis to monitor progress and identify and solve problems. These meetings might be informal or formal, depending on the complexity of the newsroom system installation.

Develop Training Schedule

A formal training schedule should be developed by the station and the vendor's instructors. This is important no matter how tiny or large the newsroom system will be. Without proper training, the people who are expected to use the computer equipment can become fearful, confused, disgruntled, or at best, may not be able to use the system efficiently. A good training program can help to avoid these problems.

The station should prepare a training roster which lists each person's name, position, and a brief description of tasks they will need to perform on the computer. Plan to train not only the regular users, but also, their supervisors, engineering personnel, and even station management. The roster should be discussed with the newsroom system vendor to establish a schedule of classes which address specific job functions. Separate sessions might be dedicated to assignment desk people, writers, producers, reporters, etc.

Training sessions should be limited to two to three hours at a time for most people. Lengthier sessions tend to produce diminishing returns. People with several different tasks or with complex tasks will need more sessions than casual users or those with only a primary task or two. If possible, everyone should be scheduled for a minimum of two sessions to permit "learning reinforcement" and to resolve any retrospective questions that may have arisen since the previous session.

The classes should be held in a special training area apart from the trainees' work areas. A conference room with several terminals, a blackboard, chairs and tables would be ideal. The "classroom" is normally a temporary facility just for initial training. However, some of the larger news operations may maintain it permanently.

MAINTENANCE

Newsroom computer systems require several types of continuing maintenance. Hardware failures require either replacement of the failed equipment or a repair technician's attention. Software maintenance includes the installation of *fixes* for *bugs* and the *migration* from one software version to a newer, enhanced *release-level*. The system's data file maintenance includes creation of backups, restoration of damaged files, control of access permissions and user lists, and administration of data archives.

Hardware Maintenance

Hardware maintenance may be done by the vendor, a third-party maintenance organization, the station's engineers, or a combination of the three. Vendors normally offer several hardware maintenance plans from which the station can choose.

Several newsroom computer system vendors offer a 24-hour "Help Line" service which station personnel can call in the event of problems with the computer system. The vendor people staffing such a telephone line will guide station personnel, whether technical or non-technical, through a series of tests which should be able to isolate the cause of the malfunction. Depending on what is discovered and what maintenance arrangements have been made between the vendor and the station, the Help-Line operator may ask for a faulty unit to be returned to the vendor, may dispatch a repair person, and/or may ask that the station exchange the failed equipment with a spare device on hand at the station.

Most vendors propose a regular schedule of preventive maintenance which may include cleaning air filters, vacuuming or spraying circuit cards, wiping video screens, cleaning tape heads, tightening cable connectors, etc. These tasks are usually the responsibility of a station-designated *key operator* from among the newsroom or engineering staff.

Software Maintenance

Newsroom computer software—the programs which cause the hardware to perform as a newsroom computer system—will require maintenance. Few, if any, software systems are without

"bugs" (problems which can adversely affect the user's ability to perform his or her tasks through the computer system). Most software systems are *enhanced* periodically to provide new features and functions for their users. Stations using newsroom computer systems will need to be aware of and/or participate in "software maintenance" both to eliminate bugs and to add enhancements to newsroom systems.

Software updates are delivered in various forms. Some systems use magnetic tape; others use magnetic disks; others use PROM chips; some use a combination of the above *media*. Station personnel may or may not be involved in the installation and maintenance of software, but should be fully advised of any changes proposed by the vendor. The station should approve and schedule installation of such alterations, in advance.

System File Maintenance

A station is normally responsible for maintaining its own system data files. The newsroom computer system usually provides hardware and/or software "tools" to aid the station in this task. Some systems provide extensive file maintenance facilities, while others expect individual users to maintain control of their own data files.

One or more station people may be assigned file maintenance tasks. These people may be termed "Super-users", "Key Operators", "Database Administrators", or "SYSOPs (System Operators)". Their function is to keep the system's information files free of *data corruption* caused by hardware and software problems or user mistakes. Frequently, the SYSOP also controls the *access permission file* which lists the users, their passwords, and their *security levels*.

In most systems, the data files are periodically copied to backup disks or tapes. Later, if a file is damaged or erased, the SYSOP can restore the original file by copying from the backup disk or tape into the active system memory. The backup file copies are often retained long after their contents are outdated. These *data archives* are usually maintained by the SYSOP.

SECURITY

Computer systems are vulnerable to damage from several sources. The system may occasionally damage itself when hardware or software fails. However, external threats are a more frequent cause of harm. Appropriate security measures can reduce a computer system's exposure to damage from sources outside the system.

Passwords

While a computer system exists to serve people, people are a frequent cause of damage to the system that serves them. The damage may be accidental or malicious. Most newsroom computer systems offer *password security* to limit such occurrences.

Password security systems require that each user desiring access to the computer system enters an identifying name. The system then requests entry of a password (a set of letters and/or digits which are known only by the user and the computer system). If the name and the password the user enters match an entry in the system's "access permission file", the user gains access to the system; if not, the user is denied access. Most newsroom systems give a potential user several chances to enter a valid name/password combination to allow for mis-strikes on the keyboard.

The name/password combination is used in some newsroom systems to determine the *file access privileges* of the user. These systems can limit the access of individual users or groups to only certain data files. Some can also limit a given user or group to *read-only* status (no update capability) for specified files.

Telephone Lines

Most newsroom computer systems use dial-in telephone lines to provide computer access for a station's people in the field. These lines are a potential pathway into the system for unauthorized users who may simply be "curious" or who may have malicious intent.

Password security provides a measure of protection, but can be thwarted. Several precautions can be taken. First, users should be encouraged to change their passwords frequently. Second, the SYSOP should maintain tight control of the user access permission list; users leaving employment at the station should be deleted from the list upon termination. Third, the dial-in telephone numbers should be changed periodically.

An additional approach uses *call-back modems*. These units accept incoming data calls and request the caller's identification and/or the caller's telephone number. Some of these devices have their own internal "user lists" which they check for access permission; others *log* the request; both types return the potential user's call, if valid, and establish a data communications path between the user and the computer system. The user then must pass the computer system's password security test.

Some newsroom computer systems provide a log of all users entering and leaving the system, as well as abortive entry attempts. This informa-

tion can be helpful in the identification and containment of security breaches.

Equipment

Computer equipment should be secured from three types of damage. The ac (alternating current) power supply, the environment, and inappropriate human activities can damage a computer system.

The ac power supply should be free of *spikes*, *noise*, RF energy, and remain at a constant voltage throughout *brownouts*, *power dips*, etc. The station may wish to install power-conditioning equipment such as *spike-suppressors* or UPSs (Uninterruptable Power Supplies) to provide clean power to the newsroom computer system. Such equipment permits the computer system to survive during temporary commercial power problems.

Environmental security requirements depend on the equipment types. Most newsroom systems can function in any environment in which a human is comfortable. However, some systems (especially those employing floppy disks) are susceptible to damage from air-borne particles which a human would seldom notice.

Newsroom computer system equipment, where possible, should be kept in a separate, secure area. In the case of centralized or hybrid systems, the central "computer room" should be the secured area. Only people with a valid task to perform should be permitted physical access to the equipment. Distributed systems present a greater security risk; there is no central computer room to lock-up.

Database

Database security is primarily the responsibility of the SYSOP. The backup/restore procedure permits damaged or missing files to be replaced. The user access permission list keeps outsiders out of the system and gives valid users access only to the files they need to do their jobs. The log of access attempts permits speedy detection of potential security breaches. An effective SYSOP uses these tools to maintain database security.

CONCLUSION

This brief overview has concentrated on some of the issues unique to broadcast newsroom computerization. For more information, talk with stations who have computerized their news operation. Talk with the newsroom computer vendors. And finally, talk with the station's own news people.

It has been said that "The question is not *whether* to computerize a newsroom, but *when*".

APPENDIX A

ASCII Code Chart

ASCII Name	Description	Decimal Value	Octal Value
NUL	Null	0	000
SOH	Start of Heading	1	001
STX	Start of Text	2	002
ETX	End of Text	3	003
EOT	End of Transmission	4	004
ENQ	Enquiry	5	005
ACK	Acknowledge	6	006
BEL	Bell	7	007
BS	Backspace	8	010
HT	Horizontal Tabulation	9	011
NL (LF)	New Line (Line Feed)	10	012
VT	Vertical Tabulation	11	013
FF	Form Feed	12	014
RT (CR)	Return (Carriage Return)	13	015
SO	Shift Out	14	016
SI	Shift In	15	017
DLE	Data Line Escape	16	020
DC1	Device Control 1	17	021
DC2	Device Control 2	18	022
DC3	Device Control 3	19	023
DC4	Device Control 4	20	024
NAK	Negative Acknowledgement	21	025
SYN	Synchronous Idle	22	026
ETB	End Transmission Block	23	027
CAN	Cancel	24	030
EM	End of Medium	25	031
SUB	Substitute	26	032
ESC	Escape	27	033
FS	File Separator	28	034
GS	Group Separator	29	035
RS	Record Separator	30	036
US	Unit Separator	31	037
SP	Space	32	040
!	Exclamation Point	33	041
"	Quotation Mark	34	042
#	Pound Sign	35	043
$	Dollar Sign	36	044
%	Percent Sign	37	045
&	Ampersand	38	046
'	Apostrophe	39	047
(	Opening Parenthesis	40	050
)	Closing Parenthesis	41	051
*	Asterisk	42	052
+	Plus Sign	43	053
,	Comma	44	054
-	Hyphen (Minus Sign)	45	055
.	Period (Decimal Point)	46	056
/	Slash	47	057
0	Zero	48	060
1	One	49	061
2	Two	50	062
3	Three	51	063
4	Four	52	064
5	Five	53	065
6	Six	54	066
7	Seven	55	067
8	Eight	56	070
9	Nine	57	071
:	Colon	58	072

;	Semi-colon	59	073
<	Less-than Sign	60	074
=	Equal Sign	61	075
>	Greater-than Sign	62	076
?	Question Mark	63	077
@	At-the-rate ("At Sign")	64	100
A	Uppercase A	65	101
B	Uppercase B	66	102
C	Uppercase C	67	103
D	Uppercase D	68	104
E	Uppercase E	69	105
F	Uppercase F	70	106
G	Uppercase G	71	107
H	Uppercase H	72	110
I	Uppercase I	73	111
J	Uppercase J	74	112
K	Uppercase K	75	113
L	Uppercase L	76	114
M	Uppercase M	77	115
N	Uppercase N	78	116
O	Uppercase O	79	117
P	Uppercase P	80	120
Q	Uppercase Q	81	121
R	Uppercase R	82	122
S	Uppercase S	83	123
T	Uppercase T	84	124
U	Uppercase U	85	125
V	Uppercase V	86	126
W	Uppercase W	87	127
X	Uppercase X	88	130
Y	Uppercase Y	89	131
Z	Uppercase Z	90	132
[	Left square bracket	91	133
\	Back slash	92	134
]	Right square bracket	93	135
↑	Circumflex ("Up Arrow")	94	136
_	Underscore	95	137
`	Grave Accent	96	140
a	Lowercase a	97	141
b	Lowercase b	98	142
c	Lowercase c	99	143
d	Lowercase d	100	144
e	Lowercase e	101	145
f	Lowercase f	102	146
g	Lowercase g	103	147
h	Lowercase h	104	150
i	Lowercase i	105	151
j	Lowercase j	106	152
k	Lowercase k	107	153
l	Lowercase l	108	154
m	Lowercase m	109	155
n	Lowercase n	110	156
o	Lowercase o	111	157
p	Lowercase p	112	160
q	Lowercase q	113	161
r	Lowercase r	114	162
s	Lowercase s	115	163
t	Lowercase t	116	164
u	Lowercase u	117	165
v	Lowercase v	118	166
w	Lowercase w	119	167
x	Lowercase x	120	170
y	Lowercase y	121	171
z	Lowercase z	122	172
{	Opening brace	123	173
|	Vertical line	124	174
}	Closing brace	125	175
~	Tilde	126	176
DEL	Delete	127	177

APPENDIX B

Publications

EIA RS-232C Specification

The EIA RS-232C specification details the electrical and physical parameters of a standard interface between Data Communications Equipment (DCE) and Data Terminal Equipment (DTE), which includes computer systems. Copies of this document are available from:

EIA Engineering Department
Standards Orders Office
2001 Eye Street, N.W.
Washington, DC 20006

Newswire Protocols

Specifications of the communications protocols used by newswire services are presented in "Wire Service Transmission Guidelines" (Special Report Number 84-2) and in "Low-speed Wire Service Transmission Guidelines" (Bulletin #1220), American Newspaper Publishers Association. Copies of these documents are available from:

ANPA, The Newspaper Center
Box 17407
Dulles International Airport
Washington, D.C. 20041

GLOSSARY

The terms and "computerese buzz-words" defined below represent only a portion of the jargon used by computer people (especially the sales persons). When in doubt, require them to "define their terms".

Absolute Code

A computer file containing binary numbers which represent the instructions and data a CPU needs to execute a given program.

Access Permission File

A computer file containing lists of users and the areas of the system to which each has access.

Address

A number which identifies a specific memory location or I/O port in a computer system.

ALU(Arithmetic/Logic Unit)

The circuit which performs mathematical and logical operations on binary numbers as directed by the computer's programming.

Analog

Signals which vary smooothly as opposed to digital signals which vary in steps. In data communications, modems are used to convert computer and terminal digital signals into modulated analog signals which are compatible with telephone lines and other transmission circuits.

ANPA Standards

A set of guidelines published by the American Newspaper Publishers Association (ANPA) defining standard protocols for newswire data transmissions. (See Appendix B)

Applications

In "computerese", a computer program or set of programs which perform a specific function. Functions as large as "a complete newsroom system" or as small as "print an audio-cart label" may be termed "applications".

Architecture

A plan which specifies how hardware, software, and/or communications "building blocks" fit together to form a computer system.

ASCII(American Standards Committee on Information Interchange)

The specification of the binary codes which represent numeric, alphabetic, and special control characters for data transmission. (See Appendix A)

Asynchronous

In data communications, a scheme to maintain synchronization between a data transmitter and far-end receivers through adding special "start" and "stop" bits to each character transmitted. The transmitter and the receiver must have been previously configured to the same bit-rate and number of bits per character. The receiver detects the start bit, counts the data bits as they arrive, and then awaits a stop bit on a per-character basis.

Auto-answer

A device, typically a modem, which detects "ring signal" on a telephone line and automatically goes "off-hook" to answer an incoming data call.

Backup

Redundancy—duplicate hardware, software, and/or data which permits graceful recovery from system faults.

Baud

In data communications, the number of signal states transmitted per second. This is not to be confused with "bits-per-second"; some transmission schemes send two or more bits in every change of signal state. A communications path with a thruput of 9600 bits-per-second may be signalling at only 2400 BAUD, communicating 4 bits of data within each signal transition.

Binary Digit

A numerical digit in the radix 2 numbering system which is based on only two values per digit (zero and one, or "off" and "on"). The binary numbering system is extensively used in computer systems because of the ease with which electronic circuits can assume the two states of "off" or "on".

Bit

An acronym for "Binary digit".

Bit-rate

The number of bits transmitted in a given time period, typically per second.

Bit-width

The number of bits communicated at a time on a given parallel path. Parallel paths are typically used within an ALU, between the ALU and the bus, and between the ALU and I/O ports. An ALU may have a 16-bit internal bit-width but only an 8-bit path to the bus and external I/O devices.

Bits-per-second

In data communications, the number of binary digits transmitted per second; not to be confused with BAUD.

BPS

(See BITS-PER-SECOND)

Bug

Primarily, a term used to characterize mistakes made by software authors which cause the computer system to malfunction or to perform in un-

anticipated ways; sometimes used in reference to hardware or communications faults.

Bus

Electrical connections which permit various modules of a computer system to share system resources. A CPU bus may interconnect the CPU with memory, I/O ports, controllers, etc. LANs with a bus structure connect workstations through a common communications link.

Byte

Eight bits of data (serial or parallel)—a character.

Call-back-modem

A modem which receives an incoming call requiring access to a computer system, requests a password or the caller's phone number, checks a list of authorized passwords, and, if the call is valid, returns the user's call to establish a data communications path.

Carry-on-terminal

A terminal which will fit under an airline seat.

Character

A five to eight bit binary number representing a "printable" or "non-printable" transmission character in any of several communications codes. (See Appendix A for the frequently-used ASCII codes)

Chip

An integrated circuit.

Clock

The circuit which generates timing pulses used by computer hardware to maintain synchronization among the computer system's modules. Or, a name for the pulse-train which permits such synchronization.

Command

Hardware commands are typically program instructions which the hardware executes in response to the binary numbers in an absolute code module. User commands are usually "mnemonic" (intended to be easily recalled) words or phrases which the computer software interprets and acts upon.

Common-carrier

In communications, a "telephone company", a "long-distance company", an International Record Carrier (IRC), or a Postal/ Telegraph/ Telephone (PTT) administration in a foreign country.

Computer

Variously refers to the hardware, the hardware/ software combination, and (to some users) to the terminals connected to a computer system.

Computer-floor

Typically, a raised-floor arrangement which permits computer equipment to be interconnected by running the interconnecting cables under a segmented floor-tile arrangement. The "computer-floor" tiles (usually two-by-two feet square) can each be lifted for access to the under-floor cableway.

Concentrator

Equipment which, with internal program capabilities, handles multiple devices (VDTs, printers, and communications) and appears to a CPU as a single device.

Conditioned line

In data communications, a circuit with transmission parameters adjusted specifically to pass analog data signals at a given speed with a minimum error rate.

CPU

A computer's Central Processing Unit—the ALU, the equipment in a "computer room", or a user's concept of "the computer". Any of these concepts are valid.

Crash

A disastrous failure of computer system hardware and/or software.

Cursor

On a VDT screen, an indicator which points to the current screen selection or the next character position. (See Fig. 9)

Data

In a computer system, information stored and/ or manipulated by the system.

Data archives

Storage, typically on magnetic disk or tape, of outdated computer data for historical purposes. Usually in newsroom computer systems, this archival information is stored separately from the computer system. When needed, archival files can be reloaded into the system for on-line access. Some newsroom systems offer on-line archives: old scripts, a morgue, and/or content descriptions for filed video and audio materials.

Data corruption

Incorrect, missing, or jumbled computer information.

Data file

Information stored in a computer system under a specific heading or title (equivalent to a physical file folder containing one or more pages of information written on paper).

Data line

An electrical, radio, and/or optical path between parts of a computer system which permits the transfer of data signals among the parts.

Database

A collection of data files, sometimes including descriptions of how the files are organized and how they relate to each other.

Database administrator

A person responsible for the maintenance of a database.

Decode

The conversion of information from one representation to another.

Dial-in

A software feature and/or equipment which permits a potential user to access a computer system through a dial telephone network.

Dialtone line

A regular telephone line, supplied by the local telephone company, which permits a user to dial other telephones throughout the country or the world (also known as POTS—Plain Old Telephone Service). It is prudent when using data communications on a dialtone line to use direct "central office" lines instead of those which pass through a switchboard or PBX (Private Branch Exchange). Switchboard and PBX lines often suffer from transmission degradations which can cause errors in data transmission.

Digital

Signals which vary in discrete steps as opposed to analog signals which vary smoothly.

Directory

A list of data files which can be accessed by the user.

Disk

A magnetic storage medium which contains data files and/or programs.

Disk storage

Storage of data or program files on a disk.

Display

A visual presentation of computer-generated information to the user —typically on a CRT (Cathode Ray Tube) or LCD (Liquid Crystal Display) device.

Display attributes

Various forms of video presentations, including: reverse-video, underscored text, high-and low-intensity displays, italics, bold characters, "blinking" fields, colored areas, etc.

Downtime

The duration of a failure (hardware, software, or communications) which affects a computer system's users.

Drain-wire

Typically a bare-wire conductor which maintains electrical contact with an enveloping shield surrounding one or more signal conductor wires within a multi-conductor cable.

Drop

A connection at the end of a data line which services a computer port, a modem, or terminal equipment.

Dumb terminal

Terminal equipment which permits a user, only when connected to a computer system, to perform his or her tasks. This type of equipment

does not allow the user to do useful work in a "stand-alone" mode.

Enhancement

An improvement in hardware and/or software which adds new features or functions to the computer system.

Executable code

(See Absolute code)

File

Information stored in a computer system under a specific heading or title. Files either contain program instructions or data.

File access privilege

Permission to use a file. Users are assigned access privilege "levels" which the system uses to determine whether to grant a user access to a data file.

Fixes

Repairs to software intended to eliminate bugs. Sometimes used to refer to hardware or communications repairs.

Floppy disk

A removable magnetic storage medium shaped like a 45 RPM record and housed in a protective carrier. Floppy disks come in several physical sizes ranging from three-inch to eight-inch diameters. The amount of computer data they can store ranges from about one hundred thousand bytes to several million bytes.

Function key

In a terminal keyboard, one or more buttons which when pressed cause actions to be performed either within the terminal or through the computer's program. Examples are "ERASE", "CURSOR UP", "CLEAR SCREEN", "DELETE LINE", etc.

Graphics

Visual presentations of computer information such as charts, graphs, drawings, and pictures; anything displayed or printed other than the alphabetic, numeric, and punctuation characters found on a normal typewriter.

Hard-wired

A term used to describe the direct electrical connection of two parts of a computer system through metallic conductor(s).

Hardware

The physical equipment in a computer system, including computers, concentrators, terminals, modems, disk drives, and other devices.

Help-line

A telephone number users can call to get human assistance in the use of a computer system or to report equipment or software problems.

I/O

Input/Output; the movement of information into (input) or out of (output) a computer device.

Instruction

A binary number which causes the ALU to perform a function. Or, the mnemonic name a human programmer uses to represent such a binary number.

Instruction register

A circuit within the CPU which holds a binary number representing an instruction to be executed.

Integrated circuit

A microelectronic component, typically containing many semiconductor junctions arranged to perform complex functions.

Intelligent workstation

Typically a desk-top computer system with a communications link to other computer devices throughout a newsroom system. Intelligent workstations have internal microprocessors, memory, and often either disk or tape storage devices.

Interface

A scheme for connecting one part of a computer system to another; or, the hardware and/or software implementation of such a connection.

Key operator

A person responsible for maintaining a useful computer system and aiding users who have questions or problems with the system. Key operators typically deal with relatively non-technical aspects

of a computer operation; they call in hardware or software experts when major problems are encountered.

Keyboard

A set of buttons (keys) which a user strikes to cause a character or command to be transmitted from a terminal to other parts of the computer system. Most terminal keyboards have a set of keys similar to a typewriter. Some have additional keys which are used to invoke computer system features and/or provide a "numeric keypad" which is a set of keys arranged in calculator format.

LAN

A "Local Area Network" which interconnects terminals, workstations, printers, and other computer system devices through relatively short runs of "twisted-pair", coaxial, or optical cables.

Language

In computer programming, a structured syntax which permits a human to manipulate mnemonic symbols instead of binary numbers when creating a list of instructions (a program) for a computer system.

Lap-portable

A microcomputer or terminal which can be operated conveniently while resting on the user's lap.

Link

A data communications path which interconnects two parts of a computer system. Links may be established through hardware, software, or a combination of the two.

Local Area Network

(See LAN)

Log

A record of activities or performance. News people may use the computer system to maintain logs of their activities; most computer systems keep a log of their internal activities and performance.

Mainframe

A central computer system, frequently a large facility serving many users with varied requirements; seldom used to satisfy the requirements of a news operation.

Media

Magnetic disks or tapes which provide data storage.

Memory

In a computer system, the circuits which store binary numbers representing data or program instructions. Two types of memory are prevalent: ROM (Read-Only Memory) and RAM (Random Access read/write Memory).

Menu

A list of choices presented by a computer system's software from which a user can select a computer function to be invoked.

Microcomputer

A computer designed around a microprocessor chip.

Microprocessor

An integrated circuit chip which functions as an ALU. The term is sometimes used to refer to a device which contains a microprocessor.

Migration

The movement toward installation of enhanced or more powerful hardware and/or software in a computer system.

Mini-computer

A computer system on a scale somewhere between a microcomputer and a large mainframe.

Mirror

A backup process which stores data simultaneously on two separate magnetic disk systems so that each has a full copy of the database. If one disk fails, the other will still have a good copy of the data.

Modem

A modulator-demodulator. In data communications, equipment which converts digital signals from a computer or terminal into modulated analog signals which can pass through telephone lines or other transmission paths.

Module

Part of a system, usually with a definable purpose. In software, a list of computer instructions in source, object, or absolute code format which

will perform a specific task. In hardware, an assembly of electronic components with a specific function.

Multiplexer

A device which permits more than one signal to pass through a single transmission path. In data communications, the equipment which permits a number of terminals to share a single communications link.

Network

In data communications, the interconnection of computers and terminals through some combination of facilities such as data lines, modems, multiplexers, hard-wired cable, LANs, and/or dial-in telephone lines.

On-line

A module or system configured and/or connected to perform its function. Sometimes used to refer to a person using a computer system, as in: "John Smith is on-line".

Operating system

Software which logically interconnects the hardware of a computer system and provides the utility functions needed for an application program to be executed by the system. An operating system only makes the computer available as a general-purpose system; in order for the computer to perform newsroom tasks, the newsroom application software must be executed under the auspices of the operating system. Users seldom interact directly with an operating system; their interaction is with the newsroom application software. Key operators and SYSOPs may need to understand parts of the operating system to be able to do their jobs.

Output

Data flowing outward from a hardware or software module. Also, the results of that flow—printed pages, video displays, etc.

Parallel

In hardware interconnection, the simultaneous communication of more than one data bit between equipment modules. Examples are: a printer interface which uses eight conductors to move an entire BYTE of data (eight bits) to the printer at a time, or an internal bus within a CPU which passes sixteen bits simultaneously to the modules connected to the bus.

Password security

A scheme for limiting access to all or portions of a computer system by requiring a potential user to enter a previously established set of keystrokes before the system will permit such access.

Peripheral

A device connected to a computer system. Examples are: printers, terminals, disk storage units, modems, multiplexers, prompters, etc.

Point-to-point

A direct communications link between two parts of a computer system.

Port

In hardware, a module which permits the transfer of data to and/or from a computer system or peripheral; in software, the process through which applications are converted to be able to "run" on different computer hardware or operating systems.

Printer

A terminal device which converts incoming data signals to printed pages.

Private line

In data communications, a dedicated (as opposed to a dial-in) telephone line for transmission of modem analog signals between two or more points.

Program

In computer systems, a list of instructions to be executed by the ALU. A program may be in source, object, or absolute formats.

Program counter

A storage circuit within a CPU which holds the address of an instruction to be executed by the ALU.

Program module

A list of computer instructions in source, object, or absolute code format which performs a specific task.

PROM

Programmable Read-Only Memory. A type of memory chip which is used to store relatively unchanging software and/or data.

Prompt

A character or phrase displayed by software to solicit a response from the user.

Protocol

A set of rules for the interaction between hardware and/or software modules within a computer system.

RAM

Random Access read-write Memory; a computer's "scratch-pad" memory circuits which are used to store both programs and data.

Register

A storage circuit which temporarily holds a binary number representing data, an instruction, or an address—may be part of the ALU or a general purpose module.

Release

An improved, updated, or enhanced version of software and/or hardware.

Reverse video

A video display attribute which reverses the normal "white-on-black" or "black-on-white" screen presentation.

ROM

Read-Only Memory; a memory circuit containing chips which store programs and/or data imprinted at the time of their manufacture.

RS-232C

A protocol specifying the physical and electrical characteristics of a widely-used serial interface between data communications equipment and data terminal equipment.

Screen

The CRT (Cathode Ray Tube) display in a video terminal. Also, the information displayed on the CRT.

Scroll

The process by which more than one screenfull of information is displayed to a user. Most newsroom computer systems permit a user to "scroll down" (see the next one or more lines of a video display longer than the screen can contain) or "scroll up" (see one or more lines previous to the currently displayed data presentation).

Security level

A "permission" attribute associated with the user's name and password which is used by the system to determine which commands and which data files the user can invoke and access.

Selector

Equipment, normally supplied by a newswire service, which permits a station to read (on a printer or through a computer system) only those wire stories which fall under the categories of service to which the station has subscribed.

Serial

In hardware interconnection and data communications, the bit-by-bit communication between modules through a single digital signal path.

Slug

A title phrase and/or story number transmitted by a newswire service to identify a transmitted story.

Software

Lists of binary numbers which represent instructions to be executed by the ALU.

Software release

A new version of software which might include enhancements and/or fixes to either the application or the operating system, or to both.

Stand-alone

In computer systems, a module which can perform all or a subset of its intended functions even when normal interconnection to the rest of the system is disrupted.

Statistical multiplexer

A multiplexer which dynamically allocates a data transmission path's capacity, depending on user needs and pre-set priorities.

Status message

An advisory to a user from software—sometimes from hardware—which describes a situation or event possibly of interest to the user. Status messages may advise the user of a hard-

ware or software problem, announce the arrival of a message from another user, alert the user to a bulletin from a newswire service, display function key labels, or simply inform the user that the "CAPS LOCK" key is depressed and all further keystrokes will produce upper-case characters.

Step

A discrete action to be performed by a CPU, or the program instruction(s) which cause such action—sometimes, a user activity which results in the completion of a discrete user task.

Subset

A device, normally supplied by a newswire service, which provides a current-loop interface for printers and/or computers from a "low-speed" (110 BPS or less) wire.

Super-user

A person responsible for some or all of a computer system's normal maintenance tasks, such as: adminstration of user lists and access permissions, archiving the database, interacting with operating system software to alter configurations or recover from problems, etc.

Synchronous

In data communications, a transmission approach which maintains synchronization between a transmitter and a receiver by passing a clock signal in addition to the data bits.

Sysop

System operator; a person responsible for smooth operation of a system. (Also see KEY OPERATOR and SUPER-USER.)

System

A collection of hardware and/or software modules which performs a specific function.

System console

A terminal with direct access to a computer's operating system for use by key operators, super-users, and the SYSOP to control system operation. System console configurations often include a printer which produces a log of events affecting the system.

System manager

A administrator responsible for the planning, installation, operation, and maintenance of a computer system. In small systems the system manager may also function as the super-user and/or the SYSOP.

System software

The operating system. Occasionally, the term is incorrectly used to refer to applications software.

Tap

A means of connecting an existing newswire circuit to a computer system by "bridging" the circuit.

Terminal

Equipment connected to a computer system which permits a human user to enter and/or receive information stored in the system. Examples are: VDTs, printers, prompters, and the portable devices which have a keyboard and either a screen or a printing unit.

Thruput

A measure of work or traffic processed by a module or system within a given period. Examples are: a newsroom system whose thruput on March 9th was 127 stories; a modem with a maximum thruput of 120 characters-per-second.

Time division multiplexer

A multiplexer which allocates a data line's transmission rate to several lower speed channels by dividing the line's thruput into discrete "time slices" during which a given channel's data is transmitted.

Transmission

The movement of information from one point —the transmitter—to other point(s)—the receiver(s).

User

A person who interacts with a computer system.

VDT

Video Display Terminal; a device which displays computer output on a video screen and usually includes a keyboard which permits a user to enter information and control the display.

Word

In describing computer architecture, the number of bits processed at a time by the ALU.

Word-length is frequently expressed in BYTEs: an eight-bit ALU's word-length is one BYTE, a sixteen-bit ALU's word-length is two BYTEs, etc.

Word processor

A feature of applications software which permits the user to create, manipulate, and update text stored in the computer system.

Work-flow diagram

A graphical representation of the interactions between the various members of a news operation; a drawing showing "who does what", "when they do it", and the sources of the information they use to do their jobs.

Workstation

An equipment configuration which permits a single user to interact with a computer system. The term is most frequently used in reference to a desk-top computer system connected to others through a LAN, but may also be used to refer to a terminal connected to a central computer system.

Y-cable

An adaptor cable which permits two devices to be connected to the same RS-232C pathway.

7.7

Weather Radar Systems and Radar Displays

James Fine
ColorGraphics, Inc.
Madison, Wisconsin

Radar History

The principles of radar were discovered at the Naval Research Laboratory (NRL) in 1930, almost accidentally, by Lawrence H. Hyland. Hyland noticed that radio signals, transmitted from the ground, were reflected back by passing aircraft. Another member of NRL, Leo Young, used the information, and he paved the way for accurate detection of aircraft. Young developed a system which scanned the sky with high frequency beams of short pulses, each of which was separated by relatively long intervals. The bearing of the reflected beam gave the bearing of the aircraft. By determining the time it took the pulse to go out to the target and return, the distance from the transmitter could be determined. This was the beginning of Radio Detection And Ranging, or RADAR.

The use of radar for detecting weather was developed after World War II. In 1953, the use of radar in tracking severe weather began with the detection, by the Illinois State Water Survey, of a hook shaped echo from a thunderstorm which produced a tornado. Since then, radar has been adapted for use by the National Weather Service and by private concerns for tracking storms, and providing increasingly better warnings in hazardous weather situations.

Radar Principles

Radar is defined as "the art of detecting, by means of radio echoes, the presence of objects, determining their direction and range, recognizing their character, and employing the data thus obtained."

A radar wave is an electromagnetic beam of energy which travels at the speed of light, 2.998×10^8 m/sec. The speed of light varies only slightly in the atmosphere. Those variations are based on the index of refraction of the atmosphere, and they are predictable.

The radar beams will bounce back to their transmitter from objects they hit. The wavelength of the beam determines the smallest size of the object which will reflect it. The smaller the wavelength, the smaller the object will be that reflects the beam. Examples of meteorological objects, or targets, are raindrops, cloud droplets, ice particles, snowflakes, atmospheric nuclei, insects and birds.

The radar microwave spectrum is traditionally divided into the following bands:

BAND	WAVELENGTH	FREQUENCY
K	1 cm	30.0 GHz
X	3 cm	10.0 GHz
C	5 cm	6.0 GHz
S	10 cm	3.0 GHz
L	20 cm	1.5 GHz

An S-band radar can detect rain but not cloud droplets. A K-band radar can "see" many clouds even if they are not producing any rain, and it is useful for studying microphysical processes in

clouds. Generally, the frequency (and, thus, wavelength) of each radar is fixed.

The wavelength and frequency of a radar beam are related by the equation:

Speed of light = frequency x wavelength

A radar set consists essentially of a transmitter, an antenna, a receiver, and a scope or television screen. The transmitter produces the beam power at a given frequency (wavelength). The antenna both radiates the power and detects the reflected signals. The receiver detects, amplifies and transforms the received signals into video form. The scope displays the returned signals in a meaningful form.

Most radars employ the same antenna for both transmitting and receiving signals. An automatic switch turns off the receiver while the transmitter is sending the beam out, and then it turns on the receiver so that it can detect the reflected beam.

The power of a transmitted radar beam can be as high as 10^6 watts, while the received reflected power can be as low as 10^{-13} watts, which is close to the noise level of radiation. An important characteristic of a radar, in addition to the smallest detectable target size, is the minimum detectable signal. Several methods can be used for detecting very weak signals.

To summarize up to this point, a radar will transmit a beam of electromagnetic radiation, it may or may not be reflected back to the antenna (receiver), and then, if reflected, the returned signal must be displayed so that it can be studied.

Radar Displays

There are two main displays on a meteorological radar, the plan-position indicator (PPI scope), and the range-height indicator (RHI scope). Both of these displays are cathode ray tubes.

The PPI scope is the most widely used display in radar meteorology. It displays the reflected signals on a horizontal polar coordinate system. That is, the bearing and distance from the radar are given. The bearing is determined by the angular direction from true north of the antenna when it receives the reflected signal. The distance from the radar is determined by timing the round trip (at $3x10^8$ m/sec) of the transmitted and reflected beam.

The RHI scope is used with radars which have vertical scanning antennae. The antenna scans vertically by sending out beams at different angles. The RHI scope has an abscissa (horizontal axis) of range, and an ordinate (vertical axis) of height.

Both the PPI and RHI scopes use intensity modulation, which means that the brightness of the returned signal on display is directly proportional to its strength.

In most meteorological applications of radar, it is useful to quantify the precipitation rate of the weather system being observed, over the full intensity range of the radar. This means that a signal strength handling capability in excess of 60 dB, representing precipation rates from 0.01 inch per hour to over 5 inches per hour, is necessary; this requires a fixed gain logarithmic receiver. Passive fixed attenuators cannot readily perform precipitation rate quantification with a log receiver, therefore an active signal processor becomes necessary. The Digital Video Integrator Processor, or DVIP, performs this function.

The DVIP accepts the video (high frequency data) output of the radar logarithmic receiver, digitizes and processes the data, and produces contoured logarithmic (C-log) data for CRT or color monitor display. Typically, C-Log data are in the form of six precipation levels. Level one is greater than receiver noise, and less than 0.1 inch per hour, while level 6 might represent any precipitation rate greater than 5 inches per hour. The remaining four levels would represent specific rates between 0.1 and 5 inches per hour. When displayed on a CRT or on a color monitor, these levels form the contour bands of the weather system, much like pressure and temperature are presented on conventional charts.

The processing functions of the DVIP include range averaging, pulse interval integration, and range normalization. Range averaging produces a digital value representing the average rainfall rate for a number of samples, each taken at every ¼ km, would be averaged to produce a value representing a 1 km range "bin". Each of these range bins is integrated, on a pulse-to-pulse basis, to smooth the data (minimize the fluctuations common to radar echoes from rainfall droplets), and the averaged and integrated data are then normalized with respect to range. Range normalization corrects the data such that a given precipitation rate will be properly contoured regardless of of the distance of target from the radar antenna.

There are two families of radar: non-coherent (conventional) and coherent (Doppler). Conventional radars supply information about a target's position and strength (reflectivity). Movement of areas of targets can also be determined. Doppler radars can obtain the same information as conventional radars, but, in addition, they can also determine the radial movement of targets.

This can be done because the Doppler radar measures the shift in the frequency of the radar beam as it is reflected by a moving target. Beams

directed toward a target that is approaching the sending unit will return at a higher frequency than they would if the target were moving away. Since this technique is not effective if the target is moving at right angles to the radar unit, two or more units are used. Doppler radar is thus capable of seeing not only the movements of storms, but the movement of tiny particles within the storm. Changes in wind direction and velocities within individual thunderstorm cells can be detected and thus give a better picture of the severity of a storm and its likelihood of producing a tornado. The relationship between the Doppler shift and the radial velocity is demonstrated below.

Let r be the radial distance of a target from the radar, which is operating at a frequency of f. Then the total distance traveled by a reflected pulse is $2r$. Translating this into wavelength, we get a distance of $2r/L$, where L is the wavelength of the beam. Converting this to radians gives a distance of $(2r/L)\ 2\pi$ or $4\pi r/L$. If the radar beam has an initial phase of ϕ_o, then its phase after reflection back to the radar is

$$\phi = \phi_o + 4\pi r/L$$

Then the change of phase in time is

$$\frac{d\phi}{dt} = \frac{4\pi dr}{Ldt}$$

But dr/dt is simply the radial velocity of the target. If the target is not moving along the radius of the beam, then $V = dr/dt = O$, and there is no phase shift.

Now $d\phi/dt$ is the angular frequency, and $d\phi/dt = 2\pi F$, where F is the frequency.

So $d\phi/dt = 4\pi dr/Ldt$ becomes

$$F = \frac{2vr}{L} \qquad [1]$$

Equation [1] gives the relationship between the frequency shift and the radial velocity. The frequency shifts are very small with respect to the beam frequencies of Doppler radars, but it is possible, using sophisticated techniques, to determine the Doppler shift frequencies. It is then easy to convert the shifts into radial movements using [1].

The Pulse Pair Processor (PPP) is one method of estimating the mean velocity of rainfall, using the Doppler effect. To perform this function, the dynamic phase relationship between the transmitted RF pulse and the received (and Doppler shifted) echo is compared, on a pulse-to-pulse basis, to determine the amount of phase change from one transmitted pulse to the next. This change in phase between pairs of transmitted pulses is a measure of the Doppler shift caused by target radial velocity, hence the name Pulse Pair Processor. The real (in phase) and imaginary (quadrature, or 90 degree out-of-phase) components of phase change are translated to target velocity by applying an arc tangent function to the imaginary component divided by the real component. A group of these velocity estimates, e.g. 32, 64, or 128 pulse intervals, is averaged in order to smooth the data. Once the PPP has produced an estimate of radial velocity, the variance (or spectral width) of the Doppler shift may be readily determined.

The PPP will produce accurate estimation of radial velocity up to the point where the pulse-to-pulse change in phase is the equivalent to 180 degrees of the pulse repetition frequency of the radar. For example, with a 5 cm radar a radial velocity of 8 meters per second will cause a Doppler shift of 320 Hertz; if the PRF of the radar is 650 pulses per second, the velocity estimate produced by the PPP will be accurate. If the PRF should be 630, or less than double the Doppler frequency, then the PPP will produce an ambiguous (erroneous) estimate. Therefore, selection and control of the PRF becomes an important tool in the interpretation of PPP data.

The Fast Fourier Transform (FFT) signal processor is another method employed to estimate the radial velocity of rainfall echoes. Where the PPP estimates only velocity and variance directly from the real and the imaginary components of phase change, the FFT first performs an analysis of the spectral analysis to velocity and spectral width. A multi-point Fourier transform is employed, with 32, 64, or 128 point analysis typical. The FFT processor can, among other functions, reduce ground clutter.

The FFT suffers the same PRF vs. target velocity ambiguity as the PPP, because change in phase from pulse-to-pulse is the input data common to both.

History of Colorizers and Remoting

The use of radar remoting and color displays of PPI information came into being in the middle of the 1970s. Technical Services Corporation (TSC) in southern California developed some color displays for local radars there, but the most extensive development was done by Enterprise Electronics Corporation (EEC) in Enterprise, Alabama.

In October 1976, they installed the first remoting of a PPI display from the Athens, Georgia NWS radar to WJBF-TV in Augusta. The data was sent over telephone lines, and that is still the medium of transferring radar data at this time.

In May, 1977, they installed the first real-time color display at KTVY-TV in Oklahoma City using the data from the radar at the station.

In August, 1977, Enterprise combined the above two concepts by installing a remote color display at the FAA Control Center near Atlanta using the data from the NWS Athens radar. Enterprise introduced a meterological Doppler radar system using both pulse-pair and fast fourier transform (FFT) processing in 1980. Since then, EEC has offered modification kits for existing MET radars to provide Doppler data in addition to intensity information.

At this time, the Enterprise and Kavouras (in Minneapolis) have data repeater transmitters at many radar sites, primarily at NWS radars. Collins Air Transport Division of Rockwell International in Cedar Rapids, Iowa, currently has introduced in 1984 a new low-cost Doppler radar system. Collins does not sell direct, but uses authorized dealers including ColorGraphics Systems, Inc. (Madison, Wisconsin); Advanced Designs, Inc. (Bloomington, Indiana); Kavouras, Inc.; and Environmental Satellite Data (Washington, D.C.).

Typical Applications

There are several reasons for the purchase of a radar system. Improving the quality of the weathercast is the overall objective. This can be done in two different ways. First the introduction of a new radar system into the weathershow lends a visual benefit. It presents the viewer with a very sophisticated and impressive looking display which helps promote a state-of-the-art image for the weather department.

Secondly, it will upgrade the quality of short-term weather forecast, and provide more reliable and up-to-the-minute tracking of potentially severe storms. A properly used and well maintained weather radar system can give the station an edge over competitors in providing accurate forecasts of when and where storms are about to strike. It can depict possible duration of the event, and approximately how much of a certain type of precipitation will accumulate.

The advantages of owning and using a weather radar system are numerous. Although cost may be a problem in the smaller stations or smaller markets, competition often dictates stations can ill-afford *not* to have "live" local radar. It is, however, often difficult to justify expensive radar equipment.

One means of lowering the financial burden is to share the costs, and thus the benefits of the radar system with other weather-sensitive operations.

One possible partner is the electric power utility. Radar can benefit them by tracking lightning storms that often cause power outages. Knowing where the storms are can help the utility to pinpoint where power outages may occur. This will help them to better direct their repair crews, and thus save time in restoring service—and also save money.

Another possible cost sharer would be smaller municipal or private airports without the benefit of National Weather Service radar.

Any weather-sensitive operation, such as shipping, mining, heavy industry and many others, could potentially aid in cutting costs. Especially helpful for use in radio (and in some cases, television) are regularly scheduled and sponsored radar weather reports where part of the advertising revenue generated would be applied to the costs of radar equipment.

Another widely used alternative is a joint television and radio station ownership in which a local radio station would share the costs in return for a set number of weather reports from the weathercaster(s) at the television station, as well as special reports when weather conditions justify.

Once the decision has been made to purchase a system, it then must be decided what type of system to buy, and from what manufacturer. In general, all weather radars work on the same principles, sending out microwave radiation pulses which bounce off precipitation particles in the atmosphere and return an "echo" to the antenna, which acts as both transmitter and receiver.

The time elapsed between the pulse and return is used in computing the position of the precipitation, while the strength of the return indicates its intensity. A wavelength of 3.2 cm is most often used, with frequency and power differing with each individual type of system. The 3.2 cm wavelength is the X band, while C Band (5 cm) and S Band (10 cm) are used by the National Weather Service. The X Band has a higher resolution than the C and S Bands due to the shorter wavelength, but for the same reason, it will also have a higher attenuation. Recent technological advances have decreased the attenuation of some units using the X Band, thereby further enhancing its appeal.

The power and range of individual radar units varies widely. Marine radar systems now being marketed as weather radars typically operate at a lower power with shorter range, up to about 64 miles. One major drawback with a marine radar is that its initial development treated weather as a detriment to shipping interests, concentrating on large targets such as bridges, ships, aircraft, etc. In general, marine radar makes a poor weather radar, and a weather radar makes a poor marine radar. The most attractive feature of the marine radar system is its relatively low price. Typical prices range near $10,000.

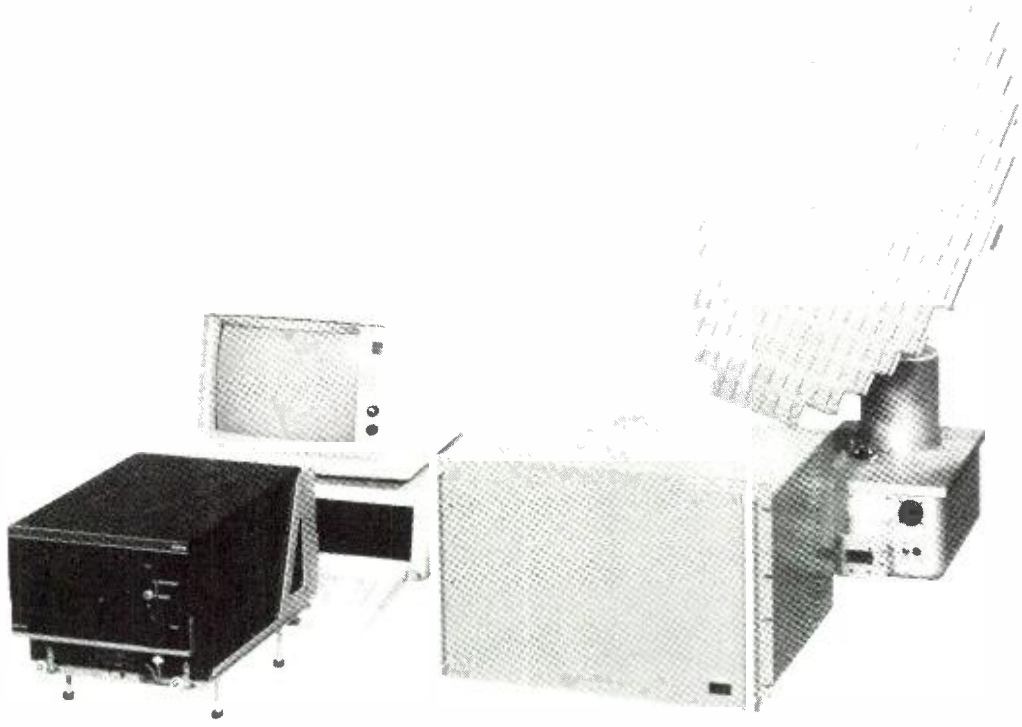


Fig. 1. Doppler hardware—note flat plate antenna. (Photo courtesy of Collins Radar, Rockwell International).

Higher power radar units can attain ranges in excess of 200 miles. Due to the curvature of the earth, anything over 200 miles is of limited use in that precipitation cannot be detected at longer ranges except in extreme cases. Price ranges of these systems can run from less than $30,000 to in excess of $80,000. Most of these systems are designed to interface directly with television inputs with non-fading square display, a sweeping-line synchronized with this antenna position, range scale selection and typical four intensity levels displayed. Some systems feature as many as six levels of rainfall intensity.

Doppler radar is now becoming widely used because of the capability for indicating severe winds and possible tornadoes. Doppler systems are somewhat more costly than conventional systems, with typical prices in the order of $80,000 to $100,000.

Any radar, regardless of type and size, radiates RF energy and, therefore, must be licensed by the FCC before it can be put into operation. This simply entails filling out the proper forms and submitting them to the FCC for approval. Information on FCC procedures is covered in Section 1 of this Handbook.

Siting radar equipment can usually be done on existing structures. The weight of the transmitting equipment can range from less than 50 pounds to nearly 1000 pounds. A high flat roof makes a suitable position. Most antennae are mounted on a tripod and can be bolted onto a flat plate. Smaller units can be affixed to existing towers. Available in most cases is a radome assembly for protection of the antenna from strong winds. The tower's designer should be consulted on the effects of weight and wind loading before a radar unit is selected.

Choosing a site for the radar transmitter-receiver may also be dictated in part by your station's location. One consideration is nearby terrain. Hills and other masses will reflect the radar signal and show up on the screen as the perpetual "ground clutter". The antenna should be located high enough to clear these sources of clutter. And, although a filter is employed to avoid interference with other microwave sources, it is still best to locate the radar antenna as far as possible from other satellite or terrestrial communication dishes. A high location is preferable but going too high, more than 100 to 200 feet, can reduce the accuracy of some information, and it puts the antenna in jeopardy from strong winds or airborne debris. However, the only part of the unit that needs to be situated outdoors is the antenna dish or plate, and its motor drive, which can be covered by a fiberglass radome, while the transmitter and associated hardware are safely indoors.

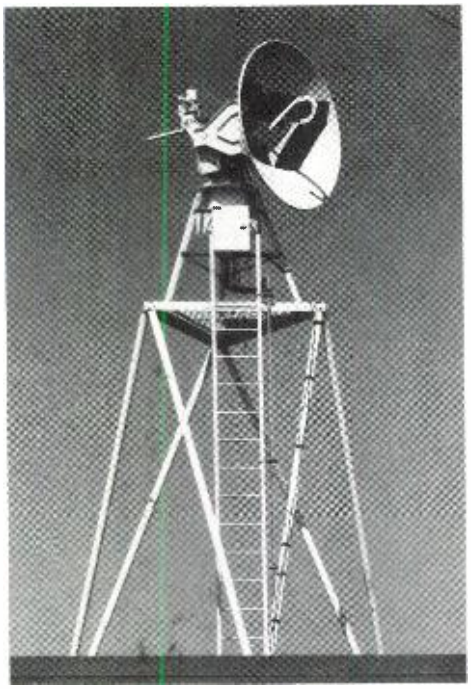


Fig. 2. Typical radar dish antenna—roof mount Vitro Model #1.

Power needed to operate the radar unit is minimal, on the order of 8 to 9 amps; although older radar units drain more electricity than newer units currently on the market.

Since the radar unit is set up outside the station, with the exception of the transmitter, few problems occur having to do with overheating of any of the internal hardware. Most of the internal transmitter components are solid state and have a low failure rate.

A broadcast interface is necessary to tie the radar unit into the central station switcher, and it usually includes a colorizer. Basically, the interface accepts station sync and formats the information obtained by the radar unit available to show the viewer on a plan position indicator or similar cathode ray tube.

All personnel who repair and adjust radar must have or work under the supervision of someone with an FCC General Class license. National Weather Service sites usually employ an engineer around the clock in case of unit malfunction, as do most television stations making use of a C or S Band radar. It is expected that the engineer will have some knowledge of how the radar unit works, and this knowledge can be obtained through a variety of ways. Learning from other engineers is often the case. The manual which comes with the unit is also useful but may be comparatively difficult when employed by a novice. There are also schools where the engineer may learn about the specific unit. Any radar manufacturer can provide such training. If the station's engineering staff are not familiar with radar, it may be possible to locate someone in the area who has the experience. An airport, military base or communications company may have someone willing to work part-time or on-call as needed.

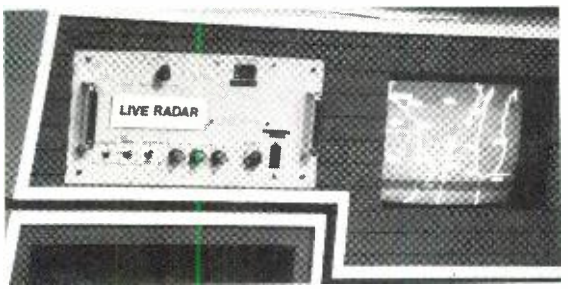


Fig. 3. Studio components and display monitor—by TSC.

Aside from regular lubrication of the moving parts, there is little that has to be maintained on a typical radar unit. Consult the manual for the schedule as well as the parts to oil and grease. Generally, lubrication once per year is necessary. Of course, the older the radar, the more care required. Besides lubrication, it is necessary to check the power or pulse frequency being emitted by the transmitter. This can be done by employing a Voltage Standing Wave Ratio (VSWR) test, which determines the condition of the pulse. This should be done every month, but performing this test quarterly will help the engineer avoid most trouble.

Most of the actual radar transmitter is solid state, which keeps the failure rate low; however, most systems include two vacuum tubes. These are the Magnetron and the transmit-receive (T-R) tube.

The Magnetron is the heart of the radar transmitter, and it delivers radio frequency power on the order of 2,000 to 5,000,000 instantaneous peak watts for each emitted pulse. A common value for broadcast weather units is in the range of 250,000 watts peak, and the typical duty cycle is on the order of 0.0001 or 0.01%, giving an average power on the order of 250 watts. These Magnetrons generally last 2-3 years and can be expensive to replace. It is highly recommended to keep a spare Magnetron available if the budget allows. Cost for each Magnetron is approximately $3,000 to $4,000.

The T-R tube generally lasts much longer. This tube is a high speed switch which effectively couples and decouples the transmitter and receiver alternately to the antenna as dictated by the emitted pulse and pulse interval. If this switch fails, the unit will not function, and it is highly recommended to keep a spare on hand. Besides lubrication, annual expense would depend on the use

of the radar and whether the two main components, magnetron and T-R tube, need replacement.

It has generally been proven that the radar antenna is adequately insulated and durable to last through most weather situations. If your climate is adverse and your unit is subject to high winds or falling debris, it would be wise to purchase a radome for the external parts. This is a plastic of fiberglass dome which completely encompasses the outside unit and is sufficiently large enough to allow the radar disk to turn. Generally speaking, most adverse weather will not be sufficient to damage the radar unit. It is recommended, though, to turn the radar unit off when winds hit 50 miles per hour or higher. Of course, with a radome, this is unnecessary. Some TV stations have towers or cables elevated over the building, and in the winter, ice can form on these cables. Thus, when a warming trend commences, the ice starts to fall off in large chunks. If one of these strikes the radar unit, it may cause damage. A radome is the only protection.

When installing or working around radar equipment, precautions should always be taken to avoid exposure to the beam. Power levels for weather radar are not as high as those used in some aircraft tracking or communications applications; however, the transmitter should be turned off any time someone is near the antenna unit. Antennas are usually installed in areas of limited access, roof tops or towers, so it is unlikely that anyone would be near the unit casually. On the other hand, someone, such as a tower maintenance or air conditioning repair worker, could be near a radome-covered unit without being aware that it is operating or even what it is.

In planning a new installation or making changes in an existing one, current information about standards and precautions regarding exposure to non-ionizing radiation should be consulted.

Dial-up Weather Radar Data

An alternative to purchasing a radar unit is a "dial-up" radar system. This allows the user access to National Weather Service radar sites all over the country. For the price of a phone call (in addition to a receiving unit and a subscription fee), the user can reach a nearby radar or one of the other 117 National Weather Service S and C Band sites in the contiguous 48 states.

A typical system includes a color graphic video terminal to display data from their transmitters at NWS sites. Voice-grade telephone lines carry the data, which are then displayed in 6 color images. These images are coded according to precipitation intensity and can be stored for later use.

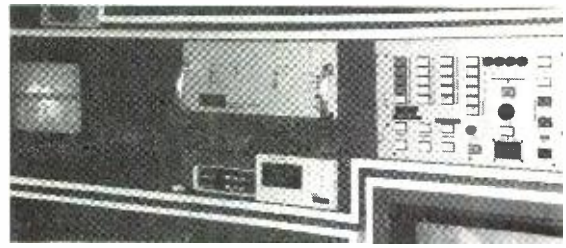


Fig. 4. Studio components Radac Model 1000 by Kavouras.

Units range in price from around $10,000 to $30,000, depending on features and functions. That price includes a maintenance fee for the transmitter units and for the use of express dial-up facilities out of their headquarters. Service is available whenever the particular NWS site is in operation.

The Radar Remote Weather Display System (RRWDS) is a next generation dial-up alternative now being made available to owners of computers with graphics display capabilities. Many television weather departments make use of such computers to generate and air their weather maps. Now they can contract with several vendors for an annual fee, and access any of 77 NWS radar sites. This alternative does not require the user to buy additional hardware if they already have a graphics computer and a telephone modem. Image resolution is 4 times higher than previously available from the dial-up radar systems available before 1984.

The RRWDS images are not processed and distributed instantaneously. Data are approximately 5 minutes behind real-time. There is also the capability, through the use of the graphics computer, to combine several images on a single map to show storms over a wider area, and to time-lapse a series of images. Vendors supplying RRWDS interfaces (as of mid-1984) include ColorGraphics Systems, Inc.; ESD, Inc.; and Kavouras, Inc.

In contrast to the locally owned unit, filters and echo timing are not necessary with RRWDS. There are no special power or cooling requirements either. A standard broadcast interface is needed to connect with the studio and control room. A "clean" ordinary business phone line (either dial-up or dedicated) is a necessity, though, for both types of dial-up radars.

Summary

Perhaps the ideal system in today's competitive broadcast market is a combination of all of the above in a state-of-the-art weather center. The locally owned radar unit and the new advance-

ments in Doppler technology are certainly useful in providing real-time warnings to listeners and viewers. The dial-up systems available can provide a "double check" for stations which have a problem spotting nearby storms lost in the ground clutter in their vicinity. Cost is certainly a factor in determining how far a station can go. Other factors affecting any such purchase are the needs of the market and its concerns about weather and also the geographic size of the market area... not to mention whatever gear the station down the street is using.

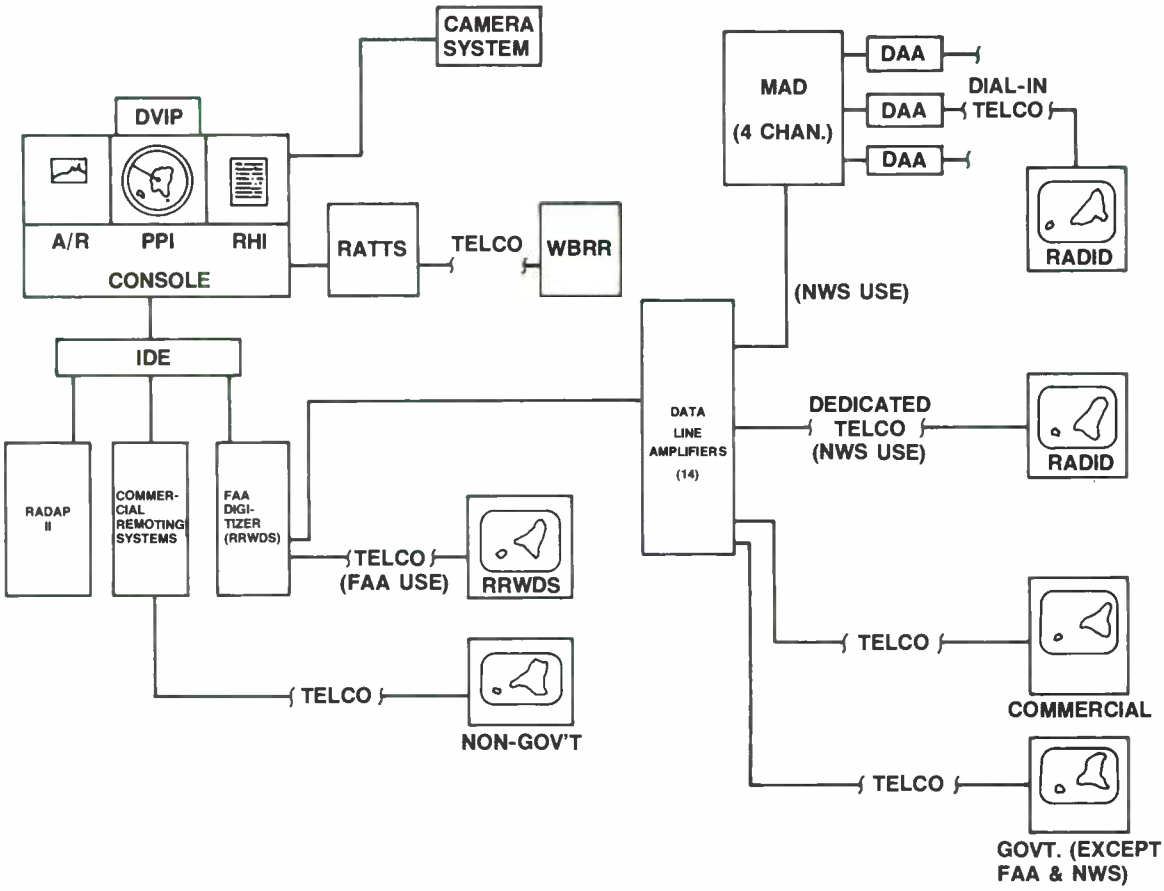


Fig. 5. Radar Remote Weather Display System.

7.8

The Emergency Broadcast System

Raymond Seddon
Chief, Emergency Communications Division
The Federal Communications Commission
Washington, DC

The role of communications in defending the Nation and protecting the life and property of its citizens has been recognized since the Federal Communications Commission was established in 1934. Over the intervening years, as the international situation has changed and as the Nation's communications systems have vastly expanded and improved, the role of communications in promoting the national defense and protecting life and property has likewise undergone farreaching changes.

Today when the United States has capability of responding to a national emergency in a matter of minutes, it is imperative that the President be able to communicate with the entire Nation on a few moments' notice. Similarly, other federal officials, as well as state and local authorities, must be able to quickly transmit vital information to the public in times of emergency.

The Emergency Broadcast System (EBS) has been devised to provide the President and the federal government, as well as heads of state and local governments, or their designated representatives, with a means of communicating with the general public during emergency situations. Every home, business and institution will be able, when the EBS is activated, to receive Presidential messages and other pertinent announcements and news by tuning to an emergency broadcast station serving their local area.

The responsibility of the broadcast industry for providing emergency communications capability had its origins a number of years ago with the birth of CONELRAD, and acronym for *CO*ntrol of *EL*ectromagnetic *RAD*iation utilizing specially authorized standard broadcast stations. It was developed by the Federal Communications Commission during the period 1951-1953 at the joint request of the USAF Air Defense Command and the Federal Civil Defense Administration and remained in effect until early 1964. It was designed to satisfy the following two requirements:

1. Warn the general public and transmit emergency information during a period of declared national emergency (i.e., imminent threat of war, attack warning).

2. Minimize any radio navigational aid that the signals of the participating stations might furnish to attacking enemy aircraft.

Navigational aid denial was accomplished by restricting all authorized stations to operate on only two channels in the standard broadcast band (640 kHz and 1240 kHz). All nonparticipating stations were required to cease operations during such emergencies, and no transmissions were permitted on the remainder of the standard broadcast channels. In addition, the authorized stations transmitted intermittently. The combination of intermittent operation from any given station, plus the high concentration of signals originating from many different directions rendered radio direction-finding techniques practically useless.

However, the high degree of co-channel interference that resulted from this operational mode severely limited the service areas of the participating stations. Intitially, there were approximately 200 broadcast stations participating operationally in CONELRAD. This figure increased to approximately 1300 by late 1953 and stayed constant for the remainder of the program. In 1961, as a result of the development of ballistic missiles and the consequent diminishing importance of the tactical role of manned bombers, the Air Defense Command dropped the stringent technical restrictions they had imposed upon CONELRAD operation, and agreed that the authorized stations could operate with their regularly licensed facilities (power, frequency, etc.). The resulting increased service areas produced an improved emergency communication facility.

In 1964, a new and improved system designated as the *Emergency Broadcast System* (EBS) was implemented. This name change was accomplished in order to differentiate the former (CONELRAD) two-channel 640 and 1240 kHz restricted communication system from station operation with regularly assigned facilities. It was during this change-over period that provision was made for FM broadcast stations to participate in the establishment of State Defense (relay) Networks.

Prior to 1972, in the event of a national emergency, participants in CONELRAD and the later EBS operation were required to possess a special emergency operating authorization called a National Defense Emergency Authorization (NDEA). Stations desiring to participate had to submit an informal application for an NDEA to the Commisssion, accompanied by a documentary assurance that the station would comply with certain qualifying criteria set forth in the Basic EBS Plan.

In early 1972, all outstanding NDEAs were cancelled and replaced by new emergency operating authorizations called Emergency Broadcast System Authorizations, and the former qualifying criteria were abolished. All existing broadcast stations (unlike during the CONELRAD and early EBS periods which did not include television and all FM Station) were furnished with new EBS Authorizations, accompanied by a memorandum advising them if they elected not to actively participate in the EBS they were instructed to return their authorizations, accompanied by a written request that they be cancelled. Similarly, all new broadcast stations licensed subsequent to the initial authorization period have been tendered EBS Authorizations, again accompanied by a letter advising that the authorizations should be returned with a written request for cancellation, in event the licensee does not want to actively participate. The abolishment of stringent EBS authorization qualifying criteria plus the expedited authorization distribution procedures have resulted in an increase in active station participation in the EBS from approximately 40 percent to over 94 percent of the total broadcast stations in the United States.

The term "key station" has no official status, and is not formally defined in the Commission's EBS Rules. However, the Number 1 Common Program Control Station (CPCS-1) in an EBS Operational Area is a key station in the system.

Current State Emergency Broadcast System (EBS) Operational Plans have been completed for the 50 states, the District of Columbia, and the four territories (American Samoa, Guam, Puerto Rico, and Virgin Islands). These plans are subdivided into at least 575 Operational Areas, each area containing at least one Common Program Control Station (CPCS). There are other CPCSs in an Operational area but they are considered backups. Therefore, there are 575 CPCS-1 stations in the Emergency Broadcast System that may be considered key stations.

589 broadcast stations participate in the EBS Broadcast Station Protection Program. They maintain government loaned auxiliary power generating and other equipment in a fallout protected enviroment. There are 214 of these stations which are not the CPCS-1. Thus it may be said that there is a total of 799 key stations in the Emergency Broadcast System; 575 stations who are in the BSPP and are also the CPCS-1 station, 214 stations who are only in the BSPP.

SYSTEM ORGANIZATION

The Emergency Broadcast System (EBS) uses the facilities and personnel of the entire communications industry—broadcast stations, telephone companies and national press services—on a voluntary, organized basis to establish an emergency broadcasting network. This network is operated by the industry under government regulations and procedures and in a manner consistent with national security requirements. Broadcast station licensees participating in the EBS have been issued Emergency Broadcast System (EBS) Authorizations by the Federal Communications Commission. Under peacetime conditions, Presidential broadcasts are handled by existing non-government radio and television facilities. Under conditions that would call for the activation of the EBS the normal flow of communications could be disrupted, altered, or destroyed.

A national-level EAN will be released only upon Presidential authority, and the White House will direct release of the Emergency Action Notification (EAN) which constitutes the notice to all broadcast stations and participating radio and

television networks of an emergency situation. Both the Emergency Action Notification and Termination are transmitted only over the Emergency Broadcast System. Upon activation of the National-Level EBS, the White House Communication Agency (WHCA), which is responsible for providing all communications for the President under all conditions, will deliver the Presidential messages to selected originating points. From these points, the Presidential messages or broadcast will be distrubuted to participating EBS stations via the nationwide Radio and Television Broadcast Network program distribution facilities.

The Federal Communications Commission has been assigned the overall responsibility for the development of the Emergency Broadcast System. The FCC ensures effective coordination between that agency, the Federal Emergency Management Agency (FEMA), other required government agencies and nongovernment entities concerned. The National Industry Advisory Committee (NIAC) has been organized to advise and assist the FCC and other appropriate authorities. It is to study and submit recommendations for emergency communications policies, plans, systems, and procedures for all licensed and regulated communications in order to provide continued emergency communications service during emergency situations.

Key in development of the EBS is the National Level Emergency Broadcast Services Subcommittee. This subcommittee, with the assistance of Special Working Groups, provides the NIAC and the FCC with continuing advice and recommendations to ensure a workable EBS. Members are responsible for providing advice and assistance in programming guidance, production, and other operations of the National-Level interconnecting facilities and systems voluntarily participating in the EBS.

A State Emergency Communications Committee (SECC) has been organized in each of the 50 States, American Samoa, Guam, Puerto Rico, Virgin Islands, and the District of Columbia. The function of the SECC is to prepare coordinated operational emergency communications plans, systems, and procedures for their areas. A Broadcast Services Subcommittee is responsible for a state EBS Plan. State plans must be consistent with the approved National-Level plans.

An Operational Area Emergency Communications Committee, which functions as a subcommittee of the SECC, has been organized within geographical Operational (Local) Areas designated in coordination between SECC and State authorities. An Operational (Local) Area may include one or more communities; portions of two or more states may be included in borderline situations. The function of a Broadcast Services Subcommittee of the Operational Area Emergency Communication Committee is to develop operational emergency communications systems, plans, and procedures for inclusion in the state EBS Plans for use during local level day-to-day emergency situations.

Again, participation in the EBS by FCC licensees is on a voluntary basis. The FCC sends new licensees an EBS authorization and a letter requesting their voluntary participation in the EBS. Licensees subsequently receive an appropriate EBS checklist, an Operational Area Mapbook, relevant state and local EBS plans, a special instruction card to be posted at AP/UPI teletypewriter machines and the EBS Rules and Regulations.

Participating stations that remain on the air during a National-Level emergency situation must carry Presidential messages "live" at the time of transmission. Activities of the National-Level EBS will preempt operation of the state or operational (Local) area EBS.

National programming and news which is not broadcast at the time of original transmission will be recorded locally by the Common Program Control Station (CPCS) for broadcast at the earliest opportunity consistent with operational (Local) area requirements.

SYSTEM OPERATION

National Level Activation and Termination (Fig. 1)

Implementation

The Emergency Action Notification (EAN) will be released at the National level upon request of the White House. When the White House directs activation of the National-Level EBS, the White House Communications Agency (WHCA), after a series of interim steps, issues instructions to implement the EBS. The Emergency Action Notification (EAN) message is then released and is eventually received by the Nation's broadcast stations. A dedicated teletypewriter net connecting the radio and television broadcasting networks and wire services transmits these messages. Following the EAN, there is a one-minute pause to allow time for the broadcasting networks to transmit a message over their internal alerting facilities, alerting stations that normal programming will be preempted by the EBS. Simultaneously, the EAN is transmitted over the respective Radio Wire Teletype Networks to alert those stations equipped to receive this service. Broadcast stations not equipped to receive either network alerting information or Radio Wire Teletype Network transmissions must rely on receipt of the EAN

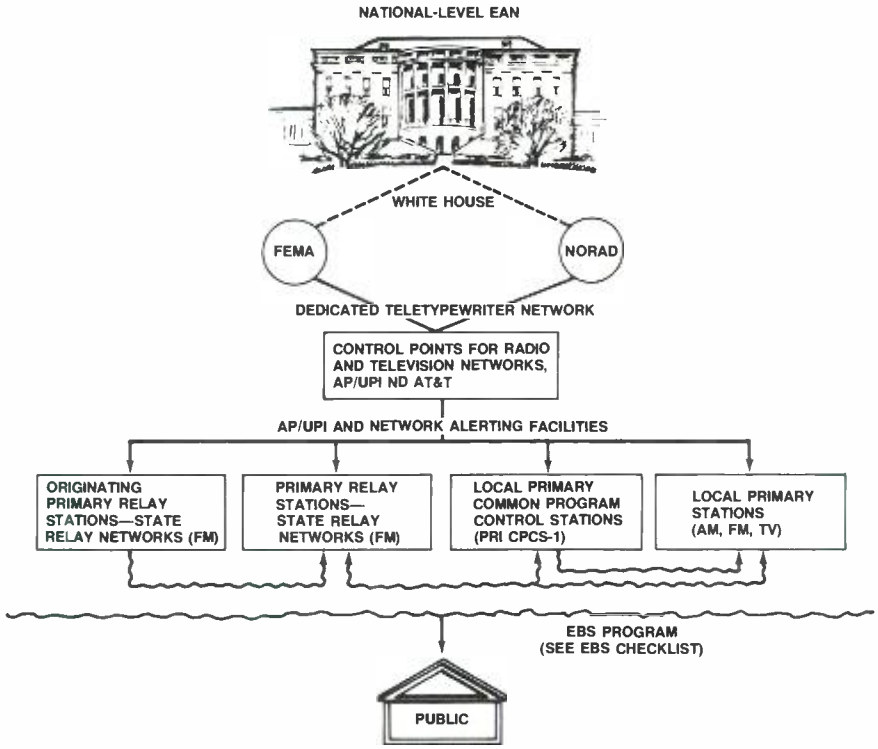


Fig. 1. Off-the-air-monitoring.

via off-the-air monitoring from other stations. Receipt of the EAN by any one of the methods discussed above is sufficient for the broadcast stations to commence emergency actions.

Station Responsibility

Upon receipt of the EAN certain actions are taken by all stations. These actions are:

a. Authenticate the EAN.

b. Discontinue normal programming and broadcast a special announcement alerting the public to the fact that important instructions are forthcoming.

c. Transmit the Attention Signal.

d. Broadcast the message which informs the public of the fact that an emergency situation exists, that some stations will remain on the air, and that additional news and information will follow. Those stations required to cease transmitting will so inform their listeners.

The actions taken by the broadcast stations following transmission of the attention signal depend on the station designation. Stations fall into the categories of:

a. Primary Station (Primary)

b. Primary Relay Station (PRI Relay)

c. Common Program Control Station (CPCS)

d. Originating Primary Relay Station (Orig. PRI Relay)

e. Nonparticipating Station (Non-EBS)

Participating stations monitor the CPCS or PRI Relay station in their area or radio and television broadcasting networks for further instructions and broadcast emergency programming when it becomes available. Nonparticipating stations remove their carriers from the air and monitor for the termination of the emergency. Should it become apparent the CPCS or PRI Relay stations may not be able to provide appropriate emergency program feed, other participating stations may elect to assume the duties by providing program feed.

When the National-level EBS is no longer needed, the Emergency Action Termination Message is transmitted. Broadcast stations receive the notification in the same manner as activation. The Common-Carriers then return the networks to normal configuration, and broadcast stations resume normal programming in accordance with their regular station authorization.

System Tests

Periodic Teletype Test Transmissions. The wire services will separately conduct test transmission to AM, FM, and TV broadcast stations on their Radio Wire Teletype Networks, a maximum of twice a month on a random basis at times of their choice. The subscribing broadcast stations enter the date and time of receipt of these tests consistently in their logs or records.

Closed Circuit Tests . These tests of the EBS will be conducted on a random or scheduled basis not more than once a month and not less than once every three months but only after FCC approval. Scheduled Closed Circuit Tests will be conducted at a time selected by the White House, the National Industry Advisory Committee (NIAC) representatives, and the FCC Defense Commissioner. The Closed Circuit Test Activation Message is disseminated to the various radio stations by:

1. The internal alerting facilities of the radio networks.
2. The Radio Wire Teletype Networks to all subscribers.

The common-carriers do not add participating independent stations to any of the Radio Networks during a Closed Circuit Test, unless ordered by the FCC.

During a Closed Circuit Test, broadcast stations do not interrupt programming and do not broadcast the message. The radio stations are required to:

a. Monitor the Radio Network for the Test Program;

b. Check the wire services teletype;

c. Authenticate the message and;

d. Record the time of the test consistently in station logs or records.

Because of the limited time available for the Closed Circuit Test, the **Termination** of the test will occur on the following Closing Cue as it appears in the text of the program:

"This concludes the Closed Circuit Test of the Emergency Broadcast System."

Weekly Transmission Tests. All radio and TV stations are required to conduct a weekly test of the Attention Signal. This must be done once a week at a random day and time between 8:30 am and local sunset. *Note:* Activation of the EBS may be substituted for the weekly test during the week the activation occurred.

State Level EBS Operation (Fig. 2)

Implementation

Upon receipt of a State-Level EAN all broadcast stations, including stations operating under equipment or program test authority, may, at the discretion of management, conduct operations in accordance with the provisions of the state-level EBS Plan. Day-to-day emergencies posing a threat to the safety of life and property which could cause activation of the State-Level EBS include tornadoes, hurricanes, floods, tidal waves, earthquakes, icing conditions, heavy snows, widespread power failures, industrial explosions,

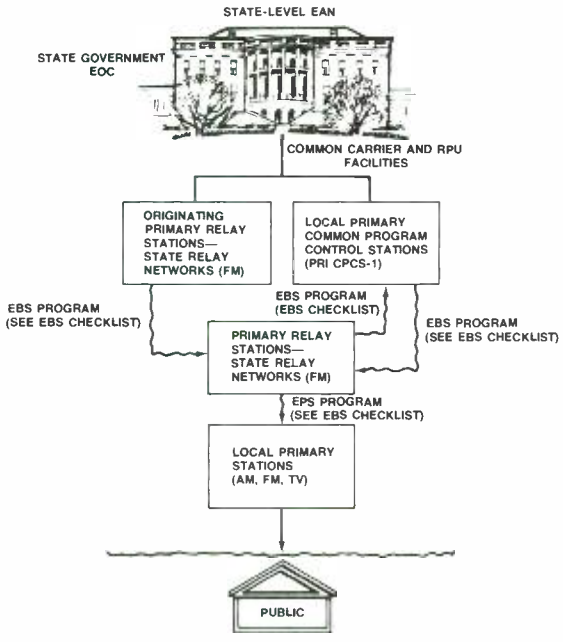


Fig. 2. Off-the-air-monitoring.

and civil disorders. In most instances the State-Level EAN will be released from the State Emergency Operations Center (EOC). Common-Carrier or Remote Pickup Units (RPU) are used to provide communications from the EOC. An FCC EBS authorization is not required for a broadcast station to participate in the operation of the State-Level EBS. Receipt of the State-Level EAN will be through the means of Off-the-Air Monitoring or as otherwise stipulated in the State EBS Plan.

Station Responsibility

Actions to be taken by the broadcast stations after receipt of the EAN are as follows:

a. Monitor the State Relay Network (PRI Relay Stations) for receipt of any further instructions from the original PRI Relay Station.

b. Monitor the Primary Station designated as the CPCS-1 for your Operational (Local) Area for receipt of any further instructions.

c. Discontinue normal program operation and broadcast the alert message.

d. Transmit the Attention Signal.

e. Broadcast the State-Level EBS-EAN Message.

f. Upon completion of the above transmission, resume normal programming until receipt of the cue from the CPCS for the Operational (Local) Area, or Primary Relay Station for the State EBS Network. Then begin broadcasting the common state-level program.

Upon receipt of notification of the termination of the State-Level EBS, participating broadcast stations will resume regular operations in accordance with the station authorization.

Operational (Local) Area EBS (Fig. 3)

Implementation

Upon receipt of an Operational (Local) Area EAN, all broadcast stations, including stations operating under equipment or program test authority, which are voluntarily participating, may, at the discretion of management, conduct operations in accordance wtih the provisions of the local EBS Plan. Day-to-day emergencies posing a threat to the safety of life and property which could cause activation of the Operational (Local) Area EBS include tornadoes, hurricanes, floods, tidal waves, earthquakes, icing conditions, heavy snows, widespread power failures, industrial explosions, and civil disorders. The Operational (Local) Area EAN will be released from the local government Emergency Operations Center (EOC) or a National Weather Service (NWS) office. Common Carrier or Remote Pickup Units (RPU) are used to provide communications from the EOC. An FCC EBS Authorization is not required for a broadcast station to participate in the operation of the Operational (Local) Area EBS. Receipt of the Operation (Local) Area EAN will be through the means of Off-the-Air Monitoring or as otherwise stipulated in the State and local EBS Plans.

Station Responsibility

Actions to be taken by the broadcast stations after receipt of the EAN are as follows:

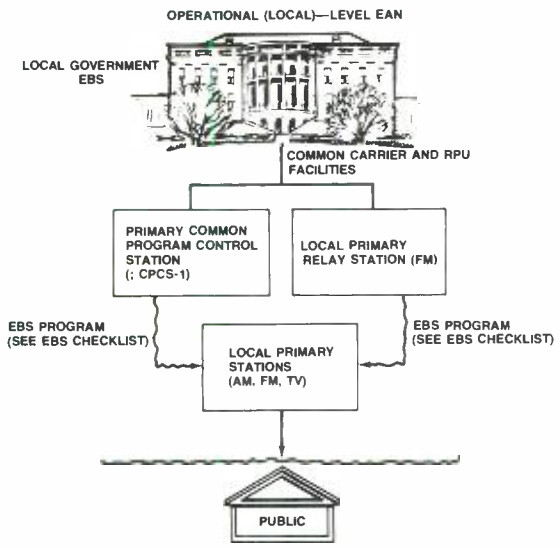


Fig. 3. Off-the-air-monitoring.

a. Monitor the Primary Station designated as the CPSC-1 for the Operational (Local) Area for the receipt of instructions.

b. Discontinue normal program operation and broadcast the alert message contained in the EBS Checklists.

c. Transmit the Attention Signal.

d. Broadcast the Operational (Local) Area EBS EAN Message.

e. Upon completion of the above transmission, resume normal programming until receipt of the cue from the CPCS-1 for the Operational (Local) Area. Then begin broadcasting the common program.

Upon receipt of the termination of the Operational (Local) Area-Level EBS, participating broadcast stations will resume regular operations in accordance with the station authorization.

State and Local Tests

Tests of implementing procedures developed at the state and local level may be conducted on a day-to-day basis as indicated in the State EBS Operational Plans. Coordinated tests of EBS operational procedures for an entire State or Operational Area may be conducted in lieu of the weekly transmission tests.

EMERGENCY BROADCAST SYSTEM (EBS) CHECKLIST FOR PARTICIPATING STATIONS

The following checklist is a condensation of the Basic Emergency Broadcast System Plan, and contains simpified instructions for each type of situation. The checklist contains step-by-step procedures for stations to follow when receiving a National-Level Emergency Action Notification. Also the termination procedures to be followed by all licensees at the conclusion of the National-Level Emergency. The checklist provides detailed procedural information as to what action must be taken when in receipt of National-Level Closed Circuit Tests, the periodic Teletype Tests, and the Weekly Transmission Tests. Lastly, step-by-step instructions are included for state and local level procedures and tests. More detailed information may be found, concerning these simplified instructions, by referring to Part 73 of the Commission's Rules and Regulations.

National Level Instructions

When EBS is activated by the White House, all broadcast stations must take the following actions. Stations should record all emergency broadcasts (including notification) and log or record all significant events.

Activation Procedures—All Stations

1 RECEIVE EMERGENCY ACTION NOTIFICATION—EAN

(This is the notice which activates EBS—Presidential messages may be received as soon as 5 minutes.)

Notification by one of the following methods is sufficient to commence action:

- **AP and UPI TELETYPE**—Preceded and followed by a line of "X's" and 10 bell alarm.
- **RADIO-TV NETWORKS**—Affiliates only—preceded by network alerting signal—Continue to monitor for further instructions.
- **EBS MONITOR RECEIVER**—Preceded by Two-Tone Attention Signal—Step 5 for message format—Continue to monitor for further instructions—Your EBS Monitoring assignment is specified in the State EBS Operational Plan.

EMERGENCY ACTION NOTIFICATION MESSAGE—AP AND UPI SUBSCRIBERS /NETWORK AFFILIATES ONLY

"This is an Emergency Action Notification requested by the White House. The AUTHENTICATOR WORD for this notification is (—). All stations follow procedures in the EBS Checklist for national level emergency. The President of the United States or his designated representative will shortly deliver a message over the EMERGENCY BROADCAST SYSTEM. The Authenticator Word is (—)."

2 AUTHENTICATE NOTIFICATION

AP and UPI Subscribers/Network Affiliates Only

Compare authenticator words in notification with words on current EBS authenticator list. *(Red envelope inside front cover of EBS checklist.)*

Take no further action if words do not match.

Different activation and termination words are provided for each date. Words are effective 12:01 a.m., Washington, D.C. time.

3 DISCONTINUE NORMAL PROGRAMMING AND BROADCAST ANNOUNCEMENT

(TV Stations shall display an appropriate EBS slide and transmit all following announcements visually and aurally in the manner required by Section 73.1250(h) of the FCC Rules. Foreign language stations report all announcements in foreign language.)

"We interrupt this program; this is a national emergency. Important instructions will follow."

4 TRANSMIT ATTENTION SIGNAL

Broadcast the Two-Tone Attention Signal (see section 73.906 of the Rules) for 20 to 25 seconds. *Note.* Noncommercial educational FM broadcast stations of 10 watts or less, and low power TV stations, which are exempt from having the capability to transmit the Two-Tone Attention Signal.

Primary Stations Only

(Including PRI CPCS Stations)

5 BROADCAST ANNOUNCEMENT

"This is an Emergency Action Notification. All stations shall broadcast this Emergency Action Notification Message. This station has interrupted its regular program at the request of the White House to participate in the Emergency Broadcast System. During this emergency, some stations will remain on the air broadcasting news and official information to the public in assigned areas. This is station (call letters)**. We will remain on the air to serve the** (operational area name) **area. If you are not in this area, you should tune to other stations until you hear one broadcasting news and information for your area. You are listening to the Emergency Broadcast System serving the** (operational area name) **area. Do not use your telephone. The telephone lines should be kept open for emergency use. The Emergency Broadcast System has been activated to keep you informed. I repeat..."** (Repeat Announcement)

6 MONITOR FOLLOWING SOURCES FOR FURTHER INSTRUCTIONS AND BROADCAST EMERGENCY PROGRAMMING AS SOON AS AVAILABLE:

Sources

- Common Program Control Station for Operational Area
- Radio-TV Network Lines
  Affiliates & Non-affiliates serviced by participating communications common carriers
- Primary Relay Station of State Relay Network
- Any other source that may be available

Priorities

Record lower priority programming for rebroadcast at earliest opportunity.

First—Presidential messages—Must be carried "live"
Second—Operation Area (LOCAL) Programming
Third—State Programming
Fourth—National Programming and News

7 USE THIS STANDBY SCRIPT UNTIL EMERGENCY PROGRAMMING AVAILABLE—LATER AS FILLER

"We interrupt our program at the request of the White House. This is the Emergency Broadcast System. All normal broadcasting has been discontinued during this emergency. This is station (call letters). **This station will continue to broadcast, furnishing news, official information and instructions, as soon as possible, for the** (operational area name) **area. If you are not in the** (operational area name) **area, tune to a station furnishing information for your area. I repeat—We interrupt our program at the request of the White House. This is the Emergency Broadcast System. All normal broadcasting has been discontinued during this emergency. This station will continue to broadcast, furnishing news, official information and instructions, as soon as possible, for the** (operational area name) **area. If you are not in the** (operational area name) **area, tune to a station furnishing information for your area."** (Repeat as needed.)

8 MONITOR FOR EMERGENCY ACTION TERMINATION

Same methods as for notification—Upon receipt, proceed to termination procedures.

Primary Relay Stations Only

(Including Originating Primary Relay Stations)

1-4 See above

5 BROADCAST ANNOUNCEMENT

"This is an Emergency Action Notification. All stations shall broadcast this Emergency Action Notification Message. This station has interrupted its regular program at the request of the White House to participate in the Emergency Broadcast System. During this emergency, some stations will remain on the air broadcasting news and official information to the public in assigned areas. This is station (call letters). **We will be serving as a program distribution and relay channel to other stations. We will remain on the air to serve the** (operational area name) **area. If you are not in this area, you should tune to other stations until you hear one broadcasting news and information for your area. Do not use your telephone. The telephone lines should be kept open for official use. The Emergency Broadcast System has been activated to keep you informed. I repeat..."** (Repeat Announcement.)

6 MONITOR FOLLOWING SOURCES FOR FURTHER INSTRUCTIONS AND BROADCAST EMERGENCY PROGRAMMING AS SOON AS AVAILABLE

Sources

- Common Program Control Station for Operational Area
- Radio-TV Network Lines
  Affiliates & Non-affiliates serviced by participating communications common carriers
- Primary Relay Station of State Relay Network
- Any other source that may be available

Priorities

Record lower priority programming for rebroadcast at earliest opportunity.

First—Presidential messages—Must be carried "live"
Second—Operation Area (LOCAL) Programming
Third—State Programming
Fourth—National Programming and News

7 USE THIS STANDBY SCRIPT UNTIL EMERGENCY PROGRAMMING AVAILABLE—LATER AS FILLER

"We interrupt our program at the request of the White House. This is the Emergency Broadcast System. All normal broadcasting has been discontinued during this emergency. This is station (call letters)**. This station will continue to broadcast, furnishing news, official information and instructions, as soon as possible, for the** (operational area name) **area. If you are not in the** (operational area name) **area, tune to a station furnishing information for your area. I repeat—We interrupt our program at the request of the White House. This is the Emergency Broadcast System. All normal broadcasting has been discontinued during this emergency. This station will continue to broadcast, furnishing news, official information and instructions, as soon as possible, for the** (operational area name) **area. If you are not in the** (operational area name) **area, tune to a station furnishing information for your area."** (Repeat as needed.)

8 MONITOR FOR EMERGENCY ACTION TERMINATION

Same methods as for notification—Upon receipt, proceed to termination procedures.

Termination Procedures—All Stations

1 RECEIVE EMERGENCY ACTION TERMINATION

(Same methods as for notification)

EMERGENCY ACTION TERMINATION MESSAGE—AP/UPI SUBSCRIBERS/ NETWORK AFFILIATES ONLY

"This is an Emergency Action Termination. The AUTHENTICATOR WORD for this termination is (—). All stations follow the EBS Checklist for termination procedures. The Authenticator Word is (—)."

2 AUTHENTICATE TERMINATION

Compare authenticator words in termination with words on current authenticator list. Do not initiate termination if words do not match. *(Red envelope contained in pocket on inside front cover of EBS checklist.)*

3 BROADCAST ANNOUNCEMENT:

"This concludes operations under the Emergency Broadcast System. All broadcast stations may now resume normal broadcast operations." (Repeat announcement.)

4 RESUME NORMAL PROGRAMMING

(In accordance with regular station authorization)

National Level Tests

National interconnecting arrangements and facilities (Networks, Key Stations, AP/UPI, AT&T) will be tested periodically. See Basic EBS Plan for detailed instructions. Procedures for tests which affect all stations are described below.

Closed Circuit Tests

(Radio Network Affiliates and AP/UPI Subscribers)

DO NOT INTERRUPT PROGRAM—DO NOT BROADCAST TEST MESSAGE

Notification Methods

- **RADIO NETWORKS:** Affiliates only—Preceded by network alerting signal
- **AP and UPI TELETYPE**—Preceded and followed by a line of "X's" and 10 bell alarm.

CLOSED CIRCUIT TEST ACTIVATION MESSAGE—AP/UPI SUBSCRIBERS/ RADIO NETWORK AFFILIATES ONLY

"This is notification of a closed circuit test of the the EMERGENCY BROADCAST SYSTEM. The test program will begin at -----, Washington, D.C. time. Radio stations do not broadcast this message and do not broadcast the audio program. The test Authenticator Word is ----. This message authorizes a closed circuit test of the Emergency Broadcast System. Broadcast stations monitor radio network lines for closed circuit test program. All stations follow procedures in the EBS Checklist for closed circuit test. The test Authenticator Word is -----."

Action By Station:

1 **MONITOR RADIO NETWORK FOR TEST PROGRAM**

2 **CHECK AP AND UPI TELETYPE**

3 **AUTHENTICATE TEST MESSAGE**

Compare Authenticator Words with test words printed on outside of EBS AUTHENTICATOR LIST (Red envelope). If words do not match, take no further action.

4 **RECORD TIME TEST RECEIVED IN STATION LOG OR RECORDS**

Termination Methods:

• **RADIO NETWORKS**—Affiliates only—receive following aural Closing Cue: *"This concludes the Closed Circuit Test of the Emergency Broadcast System."*

• **AP and UPI TELETYPE**—Preceded and followed by a line of "X's" and 10 bell alarm.

Closed Circuit Test Termination Message (AP and UPI Subscribers Only)

"This is an EBS Closed Circuit Test Termination. The Authenticator Word for this termination is (—). The Closed Circuit Test was terminated at (Date and Time), Washington, D.C. Time. The Authenticator Word is (—)."

Action By Station:

1 **RADIO NETWORK AFFILIATES MONITOR NETWORK FOR CLOSING CUE**

2 **AP AND UPI SUBSCRIBERS CHECK TELETYPE FOR CLOSED CIRCUIT TEST TERMINATION MESSAGE**

3 **AUTHENTICATE TEST TERMINATION MESSAGE**

Compare Authenticator Word with test words printed on outside of EBS Authenticator List (Red Envelope). If words do not match, take no further action.

4 **RECORD TIME TEST TERMINATION MESSAGE RECEIVED IN STATION LOG OR RECORDS**

Periodic AP and UPI Test Transmissions

(AP AND UPI SUBSCRIBERS ONLY)

DO NOT INTERRUPT PROGRAM—DO NOT BROADCAST TEST MESSAGE.

Notification Method

• **AP and UPI TELETYPE**—Preceded and followed by a line of "X's" and 10 bell alarm.

Periodic Teletype Test Message

"This is a test of the Emergency Action Notification Procedures. If this were not a test, you would receive an Emergency Action Notification Message containing Authenticator Words. This is a test of the Emergency Action Notification Procedures. All stations follow procedures in EBS Checklist for periodic teletype tests."

Action by Station:

1 **RECORD TIME TEST RECEIVED IN STATION LOG OR RECORDS**
(NO AUTHENTICATION PROVIDED)

Weekly Transmission Test of the Attention Signal and Test Script

ALL RADIO AND TV STATIONS MUST PERFORM THIS TEST A MINIMUM OF ONCE A WEEK AT RANDOM DAYS AND TIMES BETWEEN 8:30 A.M. AND LOCAL SUNSET UNLESS THEY HAVE PARTICIPATED IN ONE OF THE FOLLOWING ACTIVITIES DURING THE TEST WEEK PERIOD: (1) A STATE OR LOCAL EBS ACTIVATION OR (2) A COORDINATED STATE OR LOCAL EBS TEST

Action By Station:

1 **DISCONTINUE NORMAL PROGRAMMING**

2 BROADCAST ANNOUNCEMENT

(TV stations shall display an appropriate EBS slide and transmit all following announcements visually and aurally in the manner described by Section 73.1250(h) of the FCC Rules. Foreign language stations repeat all announcements in foreign language.)

"This is a test. This station is conducting a test of the Emergency Broadcast System. This is only a test."

3 TRANSMIT ATTENTION SIGNAL

BROADCAST THE TWO-TONE ATTENTION SIGNAL (SEE SECTION 73.906 OF THE RULES)

4 BROADCAST ANNOUNCEMENT:

"This is a test of the Emergency Broadcast System. The broadcasters of your area in voluntary cooperation with Federal, State and local authorities have developed this system to keep you informed in the event of an emergency. If this had been an actual emergency, the Attention Signal you just heard would have been followed by official information, news or instructions. This station serves the (operational area name) **area. This concludes this test of the Emergency Broadcast System."**

5 RESUME REGULAR PROGRAMMING

6 RECORD TIME TEST CONDUCTED IN STATION LOG OR RECORDS

State and Local Level Instructions

These procedures may be amended or altered as set forth in procedural guides, SOP's, and other implementing instructions which are considered an appendix to the State EBS Operational Plan.

1 ACTIVATION

• **STATE LEVEL**—A request for activation may be directed to the Originating Primary Relay Station by the Governor, his designated representative, the National Weather Service, the State Civil Defense or State Office of Emergency Services.

• **LOCAL LEVEL**—A request for activation may be directed to the Common Program Control Station (CPCS-1) by the Weather Service, local Civil Defense, and local government or public safety officials.

2 AUTHENTICATION

The Originating Primary Relay Station and/or Common Program Control Station will authenticate request for activation according to the State EBS Operational Plan and associated implementing instructions.

3 IMPLEMENTATION

(a) Record emergency program material (Optional)

(b) Broadcast the following announcement:
"We interrupt this program because of a (state/local) emergency. Important information will follow."

(c) Transmit the EBS Attention Signal for 20 to 25 seconds.

(d) Broadcast the following announcement:
"We interrupt this program to activate the (name of State or Operational Area) Emergency Broadcast System at the request of (activating official) at (time)."

(e) Broadcast emergency program material (from (a) above).

Note: TV stations participating in the State or local level EBS shall display an appropriate EBS slide and transmit all announcement visually and aurally in the manner required by Section 73.1250(h) of the FCC Rules. Foreign language stations may transmit emergency announcements in the foreign language prior to broadcasting such announcements in English.

4 TERMINATION

(a) Upon receipt of the termination notice from activating official, make the following announcement:

"This concludes operations under the (name of State of Operational Area) Emergency Broadcast System. All broadcast stations may now resume normal broadcast operations."

(b) Record emergency operation in station operating or program log. Send brief summary to FCC (Optional).

State And Local Tests

Tests of implementing procedures developed at the State and local levels may be conducted on a day-to-day basis as indicated in State EBS Operational Plans. Coordinated tests of EBS operational procedures for an entire State or Operational Area may be conducted in lieu of the Weekly Transmission Tests of the Attention Signal and Test Script required by Section 73.961(c) of the Rules.

Station Notes

NONPARTICPATING STATION

National Level Instructions

When EBS is activated by the White House, all broadcast stations must take the following actions. Stations should record all emergency broadcasts (including notification) and log all significant events in the event these records are required at a later date.

Activation Procedures—All Stations

1 RECEIVE EMERGENCY ACTION NOTIFICATION—EAN

(This is the notice which activates EBS—Presidential messages may be received as soon as 5 minutes.)

Notification by one of the following methods is sufficient to commence action:

- **AP and UPI TELETYPE**—Preceded and followed by a line of "X's" and 10 bell alarm.
- **RADIO-TV NETWORKS**—Affiliates only—preceded by network alerting signal—Continue to monitor for further instructions.
- **EBS MONITOR RECEIVER**—Preceded by Two-Tone Attention Signal—Step 5 for message format—Continue to monitor for further instructions.

Your EBS Monitoring assignment is specified in the State EBS Operational Plan.

EMERGENCY ACTION NOTIFICATION MESSAGE—AP UPI SUBSCRIBERS/ NETWORK AFFILIATES ONLY

"This is an Emergency Action Notification requested by the White House. The AUTHENTICATOR WORD for this notification is (—). All stations follow procedures in the EBS Checklist for national level emergency. The President of the United States or his designated representative will shortly deliver a message over the EMERGENCY BROADCAST SYSTEM. The Authenticator Word is (—)."

2 AUTHENTICATE NOTIFICATION AP AND UPI SUBSCRIBERS/NETWORK AFFILIATES ONLY

Compare authenticator words in notification with words on current EBS authenticator list. Take no further action if words do not match.

Different activation and termination words are provided for each date. Words are effective 12:01 a.m., Washington, D.C. time.

3 DISCONTINUE NORMAL PROGRAMMING AND BROADCAST ANNOUNCEMENT

(TV Stations shall display an appropriate EBS slide and transmit all following announcements visually and aurally in the manner required by Section 73.1250(h) of the FCC Rules. Foreign language stations repeat all announcements in foreign language.)

"We interrupt this program; this is a national emergency. Important instructions will follow."

4 TRANSMIT ATTENTION SIGNAL

Broadcast the Two-Tone Attention Signal (see section 73.906 of the Rules).

Note: Noncommercial educational FM broadcast stations of 10 watts or less, and low power TV stations, which are exempt from having the capability to transmit the Two-Tone Attention Signal.

5 BROADCAST ANNOUNCEMENT

"This is an Emergency Action Notification. All stations shall broadcast this Emergency

Action Notification Message. This station has interrupted its regular program at the request of the White House to participate in the Emergency Broadcast System. During this emergency, most stations will remain on the air broadcasting news and official information to the public in assigned areas. This is station (call letters)**. We will be leaving the air. You should now tune to other stations until you hear one broadcasting news and information for your area. Do not use your telephone. The telephone lines should be kept open for official use. The Emergency Broadcast System has been activated to keep you informed. I repeat...''**
(Repeat Announcement)

6 REMOVE CARRIER FROM AIR

7 MONITOR FOR EMERGENCY ACTION TERMINATION

Same methods as for notification—Upon receipt, proceed to termination procedures.

Termination Procedures—All Stations

1 RECEIVE EMERGENCY ACTION TERMINATION

(Same methods as for notification)

Emergency Action Termination Message
AP/UPI Subscribers/Network Affiliates Only)

''This is an Emergency Action Termination. The AUTHENTICATOR WORD for this termination is (—). All stations follow the EBS Checklist for termination procedures. The Authenticator Word is (—).''

2 AUTHENTICATE TERMINATION

Compare authenticator words in termination with words on current authenticator list. Do not initiate termination if words do not match. (Red envelope contained in pocket on inside front cover.)

3 BROADCAST ANNOUNCEMENT

''This concludes operations under the Emergency Broadcast System. All broadcast stations may now resume normal broadcast operations.'' (Repeat Announcement)

4 RESUME NORMAL PROGRAMMING

(In accordance with regular station authorization)

STATE AND LOCAL LEVEL INSTRUCTIONS

Note: All the above National Level Tests and State and Local Level Instructions also apply to Non-participating stations.

EBS Monitoring Requirements

All stations can obtain their monitoring assignments from the FCC.

Over-the-air EBS Station Monitoring

In order to insure the effectiveness of the Emergency Broadcast System, all licensees must have installed and in operating condition, equipment capable of transmitting and receiving the Attention Signal. The receiving equipment must be maintained in operating condition, including arrangements for human listening or automatic alarm devices and shall be installed at the designated transmitter control point and/or studio location in such a way that it enables the broadcast station staff, at normal duty locations, to be alerted instantaneously upon the receipt of Attention Signal and to immediately monitor the emergency programming.

The Attention signal consists of the simultaneous transmission of two audio tones for not less than 20 seconds nor more than 25 seconds. The characteristics of the two-tone signaling system are as follows:

Encoder

Function. To give an alert by demuting a monitoring receiver at the station receiving the signal. The monitor is continuously tuned to the sending station for EBS information.

Signal. Two simultaneous audio frequencies, 853 Hz and 960 Hz, each +/- 0.5 Hz.

Harmonic Distortion. Not to exceed 5 percent of each tone at encoder output.

Minimum level of modulation. Each tone must be capable of modulating the transmitter to not less than 40%, with all equipment ordinarily used in the audio line between the encoder and transmitter. To assure this, the specification further

says that the output at each audio tone shall be at least +8 dBm into a 600-ohm load. The unit shall allow calibration of each tone separately.

Time period. On activation, the two tones shall be generated for not less than 20 seconds nor more than 25 seconds.

Operating temperature. All foregoing specs maintained in ambient temperature 0 degrees to 50 degrees Centigrade.

Humidity. All specs must be maintained up to 95 percent relative humidity.

Supply voltage variation. Operation must be within tolerances with supply voltage from 85 percent to 115 percent of the rated value.

Testing conditions. Must maintain the frequency, distortion, and time period specs in a minimum RF field of 10 v/M at a frequency in the AM broadcast band, and with a minimum RF field of 0.5 v/M in either the FM or TV frequency band.

Indicator device. A visual and/or aural indicator must show clearly that the device has been activated.

Switch guard. The activation switch must have protection which will prevent accidental operation; this must include remote-control switches.

Decoder

The decoder must be activated only on *simultaneous detection* of the two audio tones, 853 Hz and 960 Hz. This simultaneous reception must demute the monitoring receiver. The additional capability of activating an external alarm is not *required*, but has obvious value.

To prevent falsing, the decoder must have: a time delay not less than 8 seconds, and not more than 16 seconds; must have bandwidth such that there is no response to tones that vary more than +/- 5 Hz from each of the frequencies, 853 Hz and 960 Hz.

The decoder must have a reset switch, for returning the receiver to a muted state after activation.

The decoder must maintain all the foregoing specifications in ambient temperature from 0 degrees to 50 degrees Centigrade.

For the convenience of operating personnel, the EBS decoder is in most cases muted for normal periods of operation. Such devices are, of course, activated upon receipt of the alert signal.

Special Reception Techniques

In certain instances either where stations are at a critical distance from another station or where receiving conditions are generally difficult by reason of directional operation, atmospherics, etc., extraordinary means are sometimes necessary to ensure the reception of the alert signal from another station. The Federal Communications Commission has provided information concerning the use of special receiving antennas which are applicable for such purposes. The application of this information, in many situations, will enable satisfactory reception of stations which ordinarily are completely unintelligible.

Shielding and Filtering

In cases where applicable, it is advisable to locate the antenna as far from a source of interference (or radio transmitter antenna) as possible and use coaxial or shielded transmission line to the receiver input terminals. Appropriate filtering and bypassing of power leads in order to eliminate the possible effect of high RF fields on the reception of the desired signal may be required. The antenna transmission line to the receiver may have to incorporate trap circuits to filter out the local transmitter radiation. For low-impedance receiver input, the circuit may be a parallel-resonant trap connected in series with the inner conductor of the coax. For high-impedance receiver input, the trap will perform most satisfactorily if connected directly across the input terminals, tuned to the frequency of the local station. Sometimes, both traps are required when the local RF field is high and/or when the cross-modulation products produced in a superheterodyne receiver cause adverse reception effects or when the undesired radiation is on a difference frequency from the desired frequency.

Loop Antenna

When the desired and undesired stations are on the same or very near the same frequencies, a directional antenna is often necessary. Such an antenna is also necessary in areas of weak signal strength from the desired station. A simple type of such antenna is the loop antenna, which is of maximum effectiveness only when the signals under consideration are within the ground-wave area. When this antenna is used, the null (obtained broadside to the plane of the loop) is oriented toward the undesired station. Maximum voltage is induced in the loop when the plane of the loop points toward the desired station. Since the antenna is bidirectional, a station on the back side may produce sufficient signal to cause interference, in which case a more elaborate directional receiving antenna may be required. (Fig. 5)

Beverage, or "Wave", Antenna

A very effective receiving directional antenna is the Beverage type. The theory of this antenna has been well covered in texts for many years and is not included here. Among the desirable properties of the Beverage, or the "wave," antenna for the reception are:

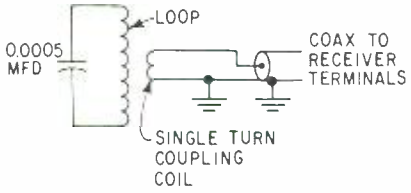


Fig. 5. Simplified schematic of a loop antenna with construction details. *Loop dimensions:* 13 turns of No. 20 wire wound on a 12-in. square form, with 1/8 in. spacing between turns. The coupling coil is a single turn wound inside the loop and spaced approximately 1 in. from the loop. The mechanical mounting is optional, but for best results the loop should be mounted in the clear and away from metallic objects. Experiments with various turns in the coupling coil and using a coaxial cable from the loop to the receiver might prove beneficial. Shielding the loop is important in direction-finding work but is not important for ordinary reception.

1. It delivers a stronger signal over the entire standard broadcast band than a good, simple antenna of the single-wire variety.

2. When terminated, it is unidirectional but can be used as a bidirectional antenna either by switching the termination or by being unterminated.

3. Atmospherics and industrial interference are considerably reduced, especially when the source is in a direction other than that of the main lobe of the antenna.

4. The antenna is low in cost, has long life, and is usually easy and simple to erect provided the space is available.

National Industry Advisory Committee

Introduction

A National Industry Advisory Committee (NIAC) has been organized to advise and assist the Federal Communications Commission, and

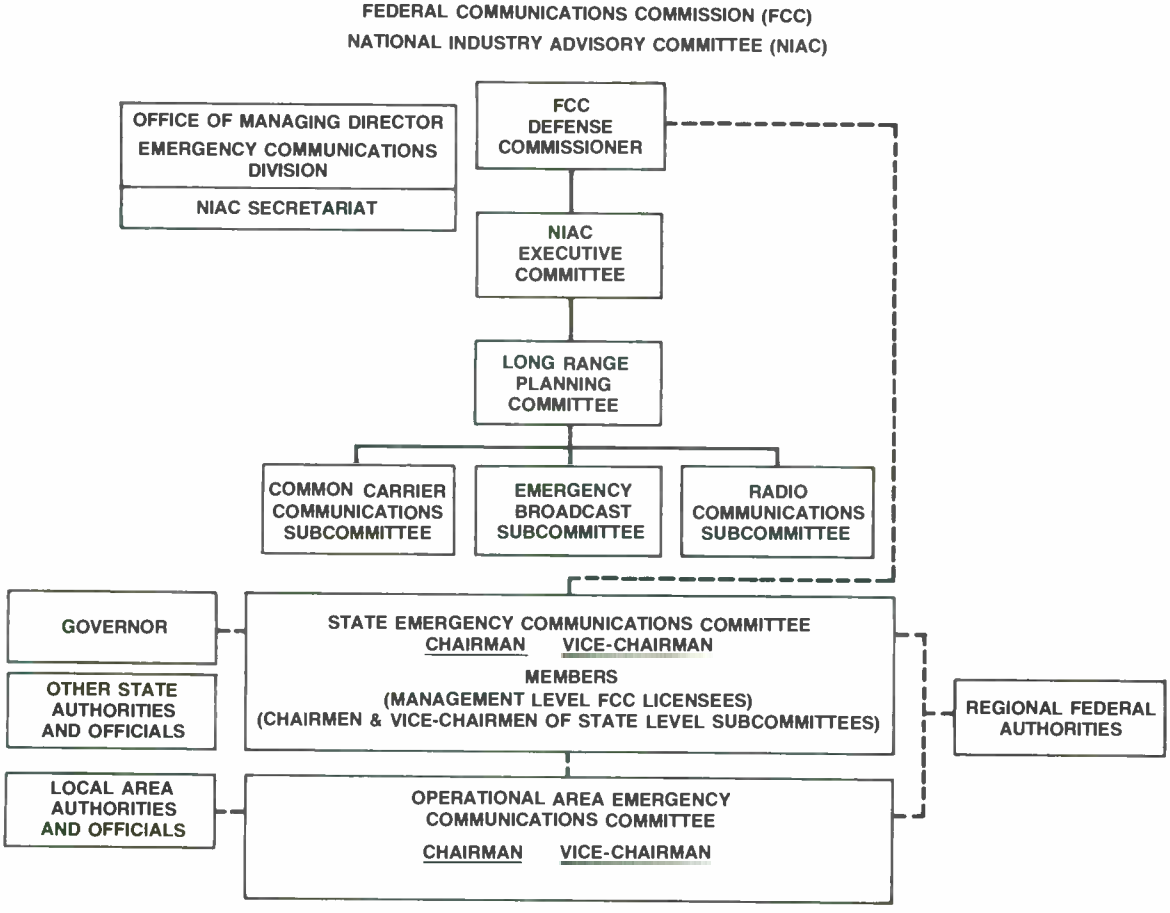


Fig. 4. Industry Advisory Committee organization chart.

other appropriate authorities. NIAC's function is to study and submit recommendations for emergency communications policies, plans, systems, and procedures, for all FCC licensed and regulated communications in order to provide continued emergency communications services under conditions of crisis or war. In addition, NIAC considers the adaptation and use of the systems, arrangements, and interconnecting facilities set forth in approved Operational Plans on a voluntary, organized basis during national, state, and operational (local) situations posing a threat to the safety of life and property. Included also are those conditions constituting a state of public peril or disaster. Such use of these capabilities during emergency situations is in accordance with the Commission's emergency and preparedness responsibilities, as defined in sections 1, 4(o), 301, 308(a) and 606 of the Communications Act of 1934, as amended, and Executive Order 11490.

Organization

The National Industry Advisory Committee:
Chairman
Vice Chairman
Executive Secretary
Executive Committee partly composed of the Chairman and Vice Chairman of National Level Subcommittees
Long Range Planning Committee
National Level Subcommittees:
Emergency Broadcast Services Subcommittee
Private Radio Service Subcommittee
Common Carrier Communications Service Subcommittee

Members of the NIAC are appointed for a term not exceeding two years by the Federal Communications Commission, subject to appropriate security clearance when warranted. Membership in the NIAC and its subcommittees is restricted to officers and employees of nongovernment Federal Communications Commission licensees (communications industry), subject to formal waiver when it is deemed in the public interest, convenience, and necessity. ("Nongovernment," as used herein, excludes federal government but includes state and local government agencies which are not licensed by the Federal Communications Commission.) Since all appointees serve at the pleasure of the Commission, any appointment may be terminated without cause. Such termination will be effective upon receipt of written notification from the Commission.

The Executive Secretary serves as the official correspondent for the National Industry Advisory Committee.

Functions and Responsibilities

The NIAC is concerned with operational emergency communications policies, plans, systems and procedures to fulfill stated requirements under a broad range of emergency contingencies posing a threat to the safety of life and property. The principal functions and responsibilities include but are not limited to:

a. Studying and submitting recommendations to the Federal Communications Commission concerning operational emergency communications.

b. Providing advice and recommendations through the Federal Communications Commission to appropriate federal, national, state and local authorities and organizations to enhance emergency communications operations.

c. Maintaining liaison with the nongovernment communications industry.

d. Maintaining liaison with all subcommittees, Special National Industry Advisory Committee Working Groups, and ad hoc committees to coordinate and assist in the planning for the utilization of nongovernment communications facilities during emergencies.

e. Coordinating with the Federal Communications Commission in the establishment of authentication procedures for use during emergencies.

f. Advising the Federal Communications Commission concerning industry opinion relative to any proposed test or exercise of emergency communications systems, plans, and procedures. Also assisting, observing and evaluating the effectiveness of such activities.

g. Evaluating proposals for the development and use of operational emergency communications systems, plans, and procedures.

h. Encouraging studies and research directed towards the improvement of existing and development of new systems, plans, and policies which will improve the overall effectiveness of emergency communications.

i. Maintaining liaison with State Emergency Communications Committees.

Procedures

Detailed procedures with respect to operation, management, and functioning of the National Industry Advisory Committee, Subcommittees and Working Groups are published in separate documents and are available from the Executive Secretary, National Industry Advisory Committee, Federal Communications Commission, Washington, D.C. 20554.

REFERENCES

1. FCC Rules and Regulations, Subpart G, Emergency Broadcast System.

2. Broadcasting Emergency Information, FCC Rules Section 73.1250.
3. Detailed State EBS Plans.
4. Operational (Local) Area EBS Plans.
5. EBS checklist

7.9

Broadcast Audio Measurement

Stanley Salek
Product Development
Circuit Research Labs, Inc.
Tempe, Arizona

AUDIO MEASUREMENT

The ability to quantify audio signals in terms of characteristics and qualities is paramount in audio engineering. This allows comparisons to be made with reference to established standards and requirements. Of interest include measurements relating to amplitude, frequency content, distortion, noise, relative loudness, and phase. The observation of such attributes allows complete characterization of an electrical audio system.

In the broadcast environment, audio measurements are used to gauge the overall quality of equipment such as amplifiers, tape recording systems, transcription equipment, mixing consoles, and other networks including the overall broadcast signal path. These types of measurements are detailed below. Other common audio measurements are of an acoustic nature and relate to the characteristics of microphones and speakers. These are not covered in this section.

Amplitude Measurement

The most basic of needs in audio measurement is to determine a value relating to the size, or amplitude, of an audio signal. Since an audio waveform is rapidly changing, methods have been developed to convert peak, r.m.s. and average values of the changing waveform into corresponding proportional dc voltages which can then be more easily observed.

There are specific cases where the peak value is the most direct measure of magnitude. It gives an indication of the largest excursions (either positive or negative) of an audio waveform. As is shown in Fig. 1, the signal is applied to an absolute value circuit, which rectifies the waveform such that the output is all positive. A diode is then used to couple into C and R. These serve as memory and decay time elements, respectively, which can then be adjusted in value to conform to the ballistics desired. Although the output is still changing with time, along with the input, the excursions corresponding to the peak values of the original waveform are much slower and more easily observed on metering devices. As the value

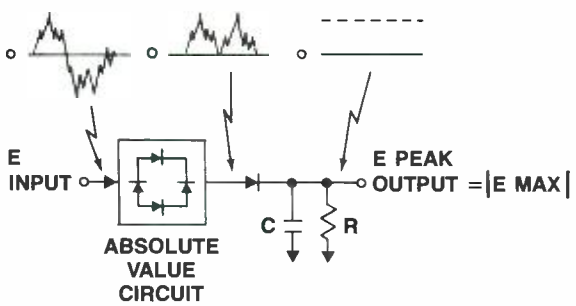


Fig. 1. Peak value detection.

NOTE: Superscript numbers refer to references at the end of this chapter.

of resistor R is increased, the decay time of the output is proportionally increased as well. If the resistor is completely removed, a "peak hold" circuit results.

Peak (actually "peak to peak") functions can also be observed on an oscilloscope, although this technique is often impractical because of the difficulty in reading the random waveforms typical in most audio material. Storage oscilloscopes can perform a "peak-to-peak hold" function.

While there are many cases where the peak value is of considerable use, the r.m.s. value of a signal is generally most meaningful since it gives indication of the energy content of the signal without regard to its waveform. In audio measurement, however, it is usually simpler to detect the average amplitude of a given waveform and relate it to an associated r.m.s. value, with reference to a sine wave. The r.m.s., or "root mean square" level can be defined as follows:

$$E_{r.m.s.} = \sqrt{\frac{E_1(t)^2 + E_2(t)^2 + \ldots + E_n(t)^2}{n}} \quad [1]$$

where E_1 through E_n are successive measurements over time of a total of n samples. As can be seen from its name, the value is computed by taking the average of n samples of E squared. Performing the square root function completes the calculation. This is also commonly referred to as "true r.m.s.".[1] Fig. 2 shows how this is accomplished electrically.

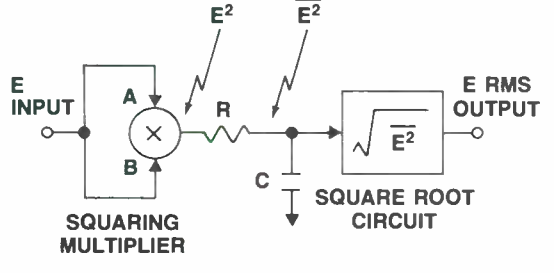


Fig. 2. True RMS detection.

Through the use of the absolute value circuit of Fig. 1 and the R/C configuration found in the r.m.s. detector of Fig. 2, an average detector can be made. This is shown electrically in Fig. 3 and mathematically below:

$$E_{average} = \frac{E_1(t) + E_2(t) + \ldots + E_n(t)}{n} \quad [2]$$

In terms of audio perception, the average value of an audio signal is related to program material

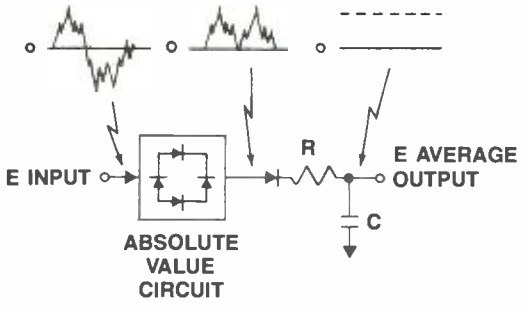


Fig. 3. Average value detection.

density, where the peak value described earlier relates to a maximum. Since the peak value defines the upper limit of allowable modulation in a transmission system, it is often desirable that the peak to average ratio be as low as possible to attain highest perceived loudness and signal to noise ratio.

The decibel, or dB, is a unit for comparing relative levels of voltage or power signals in transmission systems. In broadcast audio systems, the most common representation of decibels is dBm. This is the value of a signal with reference to 1 mW into 600 ohm load. The level in dBm of a signal can be found using the following relation:

$$dBm = 20 \log \left(\frac{E}{0.775} \right) \quad [3]$$

where E is the voltage level to convert. The number 0.775 represents the voltage level found at the reference. Quantities from the peak, r.m.s., and average circuits described above can be used for possible values of E. When this is done, some common types of metering can be synthesized to observe the activity of audio material.

Metering

Two popular types of metering for the characterization of program audio are the standard volume indicator, commonly known as the "vu meter," and the peak program meter (referred to as ppm). Although vu metering has been the more common in U.S. broadcast equipment, the standard ppm indicator is gaining popularity.

The vu meter (see Fig. 4) was introduced in 1939 to serve as a standard program level indicating device.[2] Its original purpose was to be the reference between broadcasters (as well as other programming suppliers) and the telephone company. A vu meter is the combination of a bridge rectifier, a resistive attenuator, and an ammeter with an approximately voltage linear scale to produce an average responding ac voltmeter. The vu meter is calibrated such that it reads 0 vu across

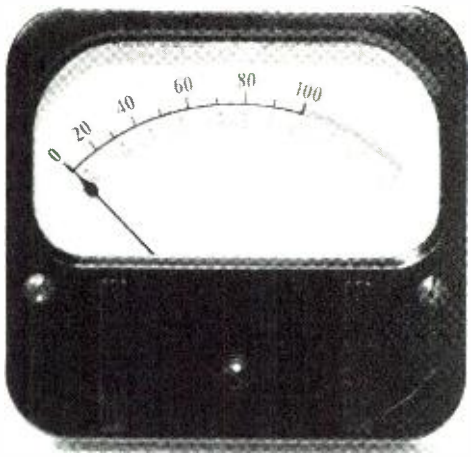


Fig. 4A. VU meter.

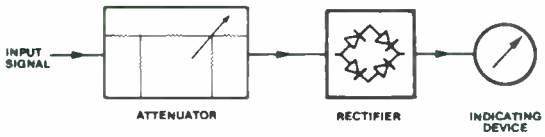


Fig. 4B. Block diagram of the stages of a typical volume unit indicator.

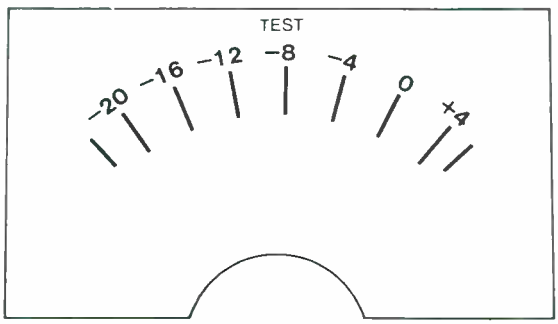


Fig. 4C. Arrangement of a typical peak-program meter scale.

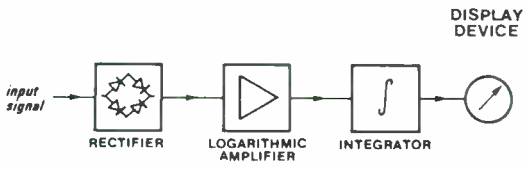


Fig. 4D. Block diagram of the stages of a typical PPM.

a circuit in which sinusoid develops 1 mW in a resistance equal to the circuit impedance (e.g., 0.775 volts r.m.s. across 600 ohms). This allows the meter to be powered directly by a 600 ohm program line, with the attenuator typically set to read 0 vu at +8 dBm.

Beyond reading continuous tones, the dynamic characteristics are set so that it will display 99 percent of its steady-state reading on a sine wave tone burst 300 milliseconds long, with a fall to 5 percent of the reading in 300 milliseconds. Essentially an average responding device, the vu meter will not respond to short duration program peaks. Therefore, levels should be set with a 10 dB margin (headroom) to the point of clipping.[3]

The peak program meter (ppm) is designed to read nearly the full peak value of the audio signal (See Figs. 4C, 4D). It uses a rectifier and an integrator producing a fast rise and slow fall effect on the display device. Typical standards require the ppm to read −2 dB, ± 0.5 dB of the steady state value for a tone burst of 10 mS, and take 2.8 seconds for the pointer to fall 20 dB.[4]

Typically, a ppm exhibits flat frequency response and are calibrated such that the nominal peak program level corresponds to a 0 dB meter reading near full scale (generally +16 dBm).

Other types of metering devices have been developed to read wide band audio in a simultaneous mode. One such system consists of an LED bar graph display exhibiting peak program content. "Riding" upon this is a brighter display (utilizing the same display elements) corresponding to vu standards. Such an indicator allows continuous monitoring of program material compression and dynamic characteristics. Another system combines a vu movement meter with peak indicating LED flashers. A "hold" function is sometimes associated with these to allow an operator sufficient time to observe the approximate peak content.

Frequency Analysis

Amplitude analysis methods as described in the previous section are generally used to provide an indication of signal levels simultaneously over the entire audio range. It is sometimes more desirable however, to be able to measure discrete frequencies in an audio system. This allows frequency response measurement as well as dynamic measurement of energy content throughout the audio spectrum.

Simply stated, frequency response is the capability of a device or system to pass or amplify equally, all frequencies within a specified range.[5] As far as audio in the broadcast environment is concerned, the range of interest is generally 50 Hz to 15 kHz. Although few musical instruments

produce fundamental frequencies greater than 4 kHz and the human voice much above 1 kHz, the reproducing device or system must be able to pass the harmonics which accompany the fundamental frequency. Without adequate bandwith or with uneven frequency response, an unnatural "coloration" of the perceived sound becomes evident. To solve this, a great deal of care is taken to construct amplifiers with very flat frequency response to high frequencies. Since the responses of series-connected amplifiers are additive, care must be taken to verify the flatness of each in a system.

Several methods are available to measure audio frequency response. They include discrete measurement and swept frequency methods. Parallel analysis and Fast Fourier Transform (FFT) techniques can also be used.

The discrete frequency measurement method is uncomplicated and inexpensive. A simple measurement system consists of a low distortion audio frequency oscillator and a wide band ac voltmeter. The oscillator output is connected to the input of the device or system to be characterized. The voltmeter is used to observe the level at the output of the device or at a desired intermediate point in a system.

The measurement is done by first setting the generator output level to a value which represents nominal input operating level of the device. Generally, a 1 kHz frequency is chosen initially in high fidelity audio systems. The output level is read on the ac voltmeter, and this quantity is noted as a zero dB relative reference. Provided the generator itself has a flat frequency response, measurements at frequencies through the audio band can be measured while recording the corresponding dB output levels with respect to the reference. A convenient and commonly used technique is to increment the frequency in a 1, 2, 5 sequence (i.e., 20 Hz, 50 Hz, 100 Hz, 200 Hz, etc.). This permits plotting the final response data on 4-cycle "Log/Lin" graph paper providing regularly spaced frequency increments horizontally. The logarithmic amplitude data are plotted along the horizontal axis, with the zero dB relative reference placed in a convenient position as the linear vertical axis.

Although the discrete frequency measurement technique is straightforward, it is also often tedious and time-consuming. Numerous frequency measurements must be made to insure adequate testing. This method is most usable in the response measurement of single ended devices which do not have suitable input ports for connection to an audio generator. Transcription equipment, such as turntables and compact disc players are examples of these types of devices. Test recordings supplied by the equipment manufacturer and others are used to provide the tones necessary for discrete frequency response characterization.

Swept Frequency

A faster and more efficient means of measuring frequency response is the *swept frequency* method. This process employs a sweep frequency generator as a signal source and measures response over the entire range of interest in one sweep. The detector for these measurements is most often a tracking type which follows the signal source and measures a narrow band of frequencies centered around the source frequency. Use of a tracking detector is a better guarantee that the amplitude measured is that of the tone generator and is not influenced by spurious tones, noise, or harmonics.

Devices specifically designed to do swept frequency measurements include wave analyzers and spectrum analyzers. Wave analyzers must be used with plotters to provide a hard copy data plot, while spectrum analyzers directly produce response images on a built-in display. A representative spectrum analyzer is shown in Fig. 5 while the one displayed in Fig. 6 is specifically intended for audio frequency use.

Fig. 7 shows a typical setup for measuring amplifier frequency responses using the swept frequency method. The signal source used to drive the test device is the tracking oscillator output

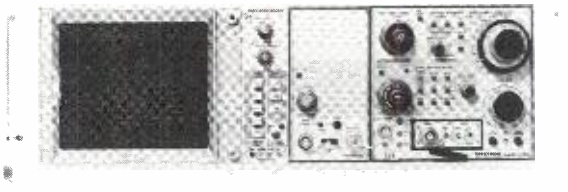


Fig. 5. Spectrum analyzer suitable for audio and low frequency RF use.

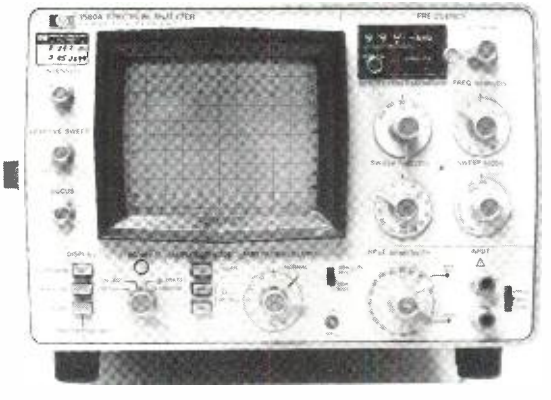


Fig. 6. Spectrum analyzer intended for audio use.

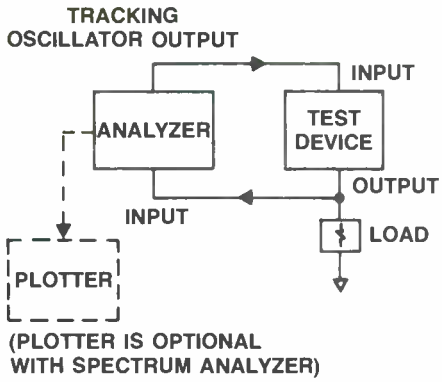


Fig. 7. Frequency response measurement using swept method.

of the analyzer. The device's output is terminated with an appropriate characteristic load impedance and connected to the analyzer input. Measurement of the frequency response is made by manually or automatically sweeping the analyzer across the frequency range of interest. A plotter connected to either type of analyzer or a scope-type camera used with the spectrum analyzer can provide a permanent record of the device's response characteristics.

The swept frequency method can also be used to measure overall frequency response of multiple-head tape recorders. The tracking oscillator signal is connected to the record amplifier input and the output is taken from the playback amplifier output. This allows recording and playback frequency response measurement to be done all at once and eliminates the necessity of synchronizing the analyzer sweep to the recorded signal. But a time delay between input and output signals exists, caused by the physical displacement between record and playback heads. This can be corrected simply by using a very slow sweep speed or a wider measurement bandwidth.

Real Time Analyzer

A real time audio analyzer (RTA) consists of a sequential collection of one octave or one-third octave filters having individual detectors and indicators at each output. The program audio is simultaneously fed to the inputs of all the filters. The output signal of each filter is proportional to the amount of energy occurring in that particular frequency band. This is also referred to as *parallel analysis*.

A simplified version of an RTA is presented in Fig. 8. As shown, it is intended to break the audio band into three sections using low, mid-band, and high-pass filtering. Signal detectors are then used to condition the audio for display on a suitable indicator, one set for each of the three bands. The detectors can be (and often are) the same peak, r.m.s. or average circuits described earlier. Typically, readout indicators are bar graph displays with dB-calibrated scales. When arranged side by side, the readouts provide a graphical presentation of amplitude versus frequency, just as the spectrum analyzer does. Unlike the spectrum analyzer, however, an RTA does not rely on a fixed sweep speed. An advanced audio analysis system with RTA function is shown in Fig. 9. Fig. 10 shows a typical RTA display of the same unit.

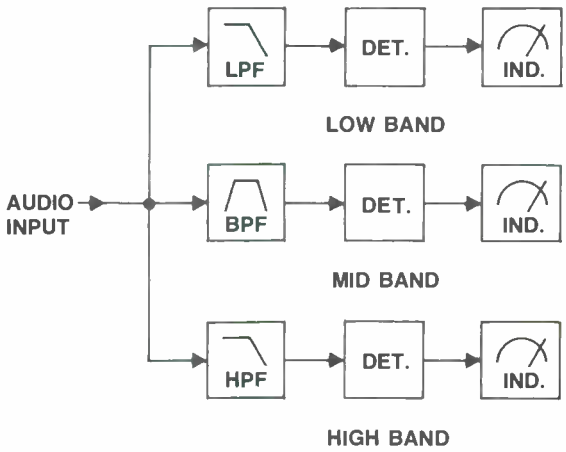


Fig. 8. Basic real-time analyzer.

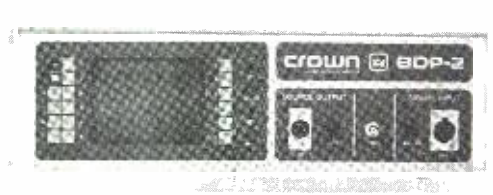


Fig. 9. Advanced audio analyzer with RTA functions and CRT display.

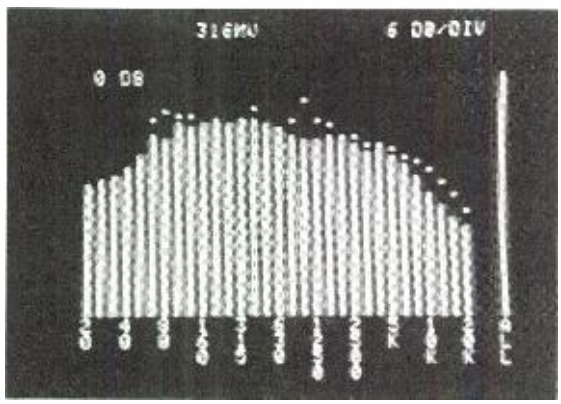


Fig. 10. Typical RTA display.

Parallel techniques using the RTA are often used for dynamic program material and room acoustics analyses.[6] This type of analyzer is also useful for measuring frequency response of audio devices when used in conjunction with a "pink" noise source. Pink noise has a constant mean squared voltage per octave. This makes it popular in audio work since it allows correlation between successive octaves by ensuring the same voltage amplitude is available as a reference. By connecting the pink noise source to the input of a device to be characterized, and the RTA to its output, a response curve can be displayed.

Although often prohibitive in cost, network and FFT analyzers are also exceptionally useful in audio frequency domain measurements. Network analyzers are swept-analysis instruments and used to characterize 2-port networks (i.e., devices having an input and output) as to frequency, phase, and delay responses. They are employed where substantial accuracy in the measurement of these parameters is required. RF sub-system and semiconductor device design have been the major application for network analyzers, although some newer generation equipment includes audio-frequency coverage. This allows precision response measurement of amplifier and filter designs.

FFT (Fast Fourier Transform) analyzers have the ability to convert a snapshot sampling of an audio or other time-varying source and mathematically transform the result into a display of the frequency components present. Because the conversion process is done by a specialized microcomputer, an FFT analyzer can often produce a spectrum display as much as an order of magnitude faster than conventional swept-spectrum analyzers. This is most helpful in low frequency measurement, where a swept analyzer would require a very slow sweep time to resolve closely spaced components. Although often helpful in audio system measurements, FFT analyzers are used mostly in industry for vibrational analysis and other mechanically-oriented testing.

Distortion Measurement

When a device is driven beyond its range of linear operation, or through areas of discontinuity, signal distortion occurs. As a result, additional frequencies appear at the output which are not present at the input. In cases where distortion becomes extreme, it can be identified through listening. Odd-order distortion (commonly "clipping" distortion) can become audible around 1.25 percent. Even-order distortion, characterized by a "coloration" of the program material, becomes audible at about 5 percent. Generally, systems with a wider frequency response capability need lower distortion levels to be acceptable. Since distortion is not always obvious to many people, techniques are available to measure its various types.

Distortion can be characterized in two basic ways: harmonic distortion and intermodulation distortion. While the two associated methods produce uncorrelated measurement values, each gives a quantitative result of the device's quality in terms of a single number. Although total harmonic distortion (THD) content is determined by only one method, intermodulation distortion (IMD) has several accepted measurement practices. These include the SMPTE and CCIF methods. Transient Intermodulation Distortion (TIM) is another commonly measured type of IMD.

Harmonic Distortion

Harmonic distortion is a measure of individual harmonic amplitudes with respect to the amplitude of the fundamental frequency. In practice, harmonics greater than the third often add little to the resultant value because of their negligible amplitude. THD is defined as:

$$THD\% = 100 \frac{\sqrt{A_2^2 + A_3^2 + A_4^2 + .. + A_n^2}}{A_1} \quad [4]$$

where A_2 through A_n are the amplitudes of the individual harmonics and A_1 is the amplitude of the fundamental. As seen in Fig. 11, a 1 kHz signal with harmonic distortion can display only minor differences when it is overlaid with an undistorted signal. The amplitude and slope errors do not lead directly to a numeric result. But when a spectrum photo of the same waveform is observed (Fig. 12), the relation above can be applied. With the fundamental at 0 dBm (0.775V), the second harmonic at -26 dBm (38.8 mV), and

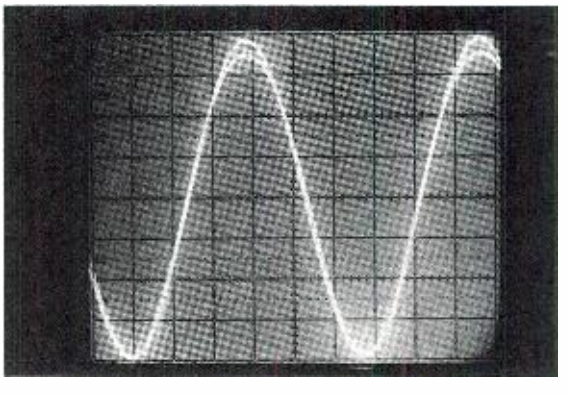


Fig. 11. Comparing the distorted output with an undistorted 1 kHz tone with its undistorted component.

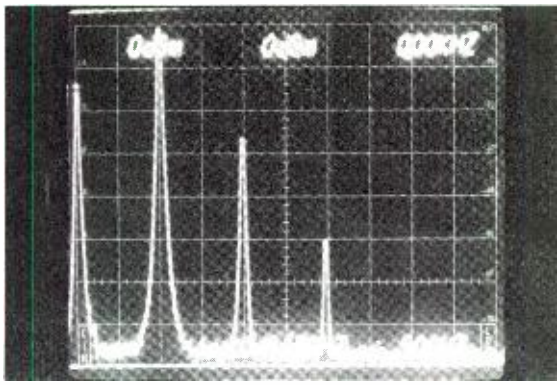


Fig. 12. Measuring THD with a spectrum analyzer. (V:10^{dB}/div.; H:500Hz/div)

the third harmonic at -50 dBm (2.5 mV), the harmonic distortion can be calculated:

$$THD\% = 100 \frac{\sqrt{(0.0388)^2 + (0.0025)^2}}{0.775} = 5.0\% [5]$$

Although spectrum analysis can produce accurate THD measurement results, a simpler and more cost effective procedure which produces a direct numeric quantity is the most popular method.

Fig. 13 shows the block diagram of a typical THD analyzer. An oscillator (having much less harmonic distortion than the device or system to be measured) is connected to the device's input. The distorted output signal of the device is filtered to remove A_1, the fundamental component. This produces a signal which, when r.m.s. detected, is proportional to the THD imposed by the device being tested.

THD measurement is often done over the same 1,2,5 sequence of frequencies as mentioned for discrete response measurement. The THD results can be plotted on the same graph to characterize better the device under test. THD measurements may be taken over various input levels, but as the level is reduced, noise characteristics will affect the readings. In such a case, the spectrum analyzer method produces more meaningful results.

Intermodulation Distortion

The intermodulation method of measuring distortion uses a test signal composed of two sinusoidal signals of different frequencies (except for TIM measurement, to be covered shortly). After summation, they produce the effect of an amplitude modulated carrier when applied to a circuit having IM distortion. The intermodulation method is useful because the harmonic distortion of the signal sources do not affect the measurement.

The SMPTE method uses a low frequency (f_1) and a relatively high frequency (f_2) signal (usually 60 Hz and 7 kHz, respectively) which are mixed at a four to one amplitude ratio (see Figs. 14 and 15). This method involves the measurement of the relative amplitude of the modulation sidebands of the higher frequency signal. For diag-

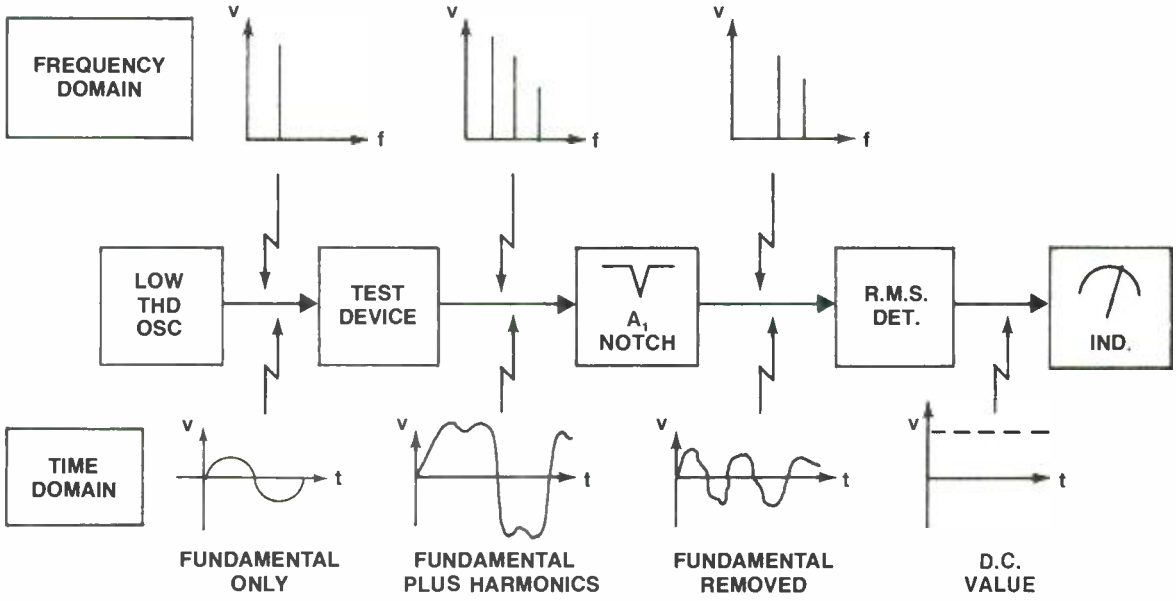


Fig. 13. THD analyzer.

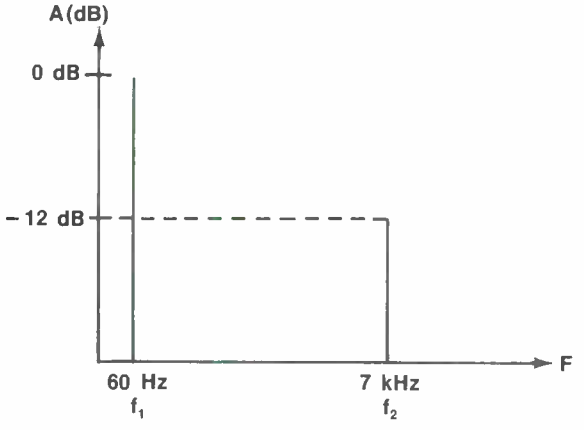


Fig. 14. Spectrum of SMPTE IM input test signal ratios.

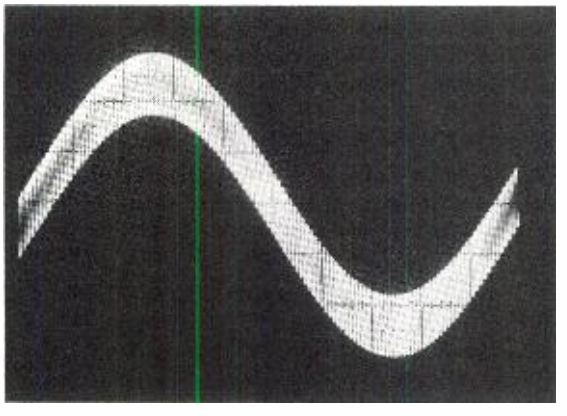


Fig. 15. SMPTE IM test signal.

nostic purposes, it is often useful to determine even-order and odd-order distortions separately, although this is best done by spectrum measurement techniques. Even-order distortion usually can be characterized by the ratio of the sum of the amplitudes of only the two second-order spurious frequencies, $f_2 - f_1$ and $f_1 + f_2$, to the amplitude of the "carrier" signal, f_2:

$$SMPTE\ IMD\%\ (\text{second order}) = \left[\frac{A_{(f_2 - f_1)} + A_{(f_1 + f_2)}}{A_{f_2}}\right] \times 100 \quad [6]$$

In a similar manner, odd-order distortion can be characterized by the ratio of the sum of the amplitudes of the two third-order spurious frequencies, $f_2 - 2f_1$ and $2f_1 + f_2$, to the amplitude of f_2:

$$SMPTE\ IMD\%\ (\text{third order}) = \left[\frac{A_{(f_2 - 2f_1)} - A_{(2f_1 + f_2)}}{A_{f_2}}\right] \times 100 \quad [7]$$

Fig. 16 shows the output signal of an amplifier with IM distortion as viewed on an oscilloscope.

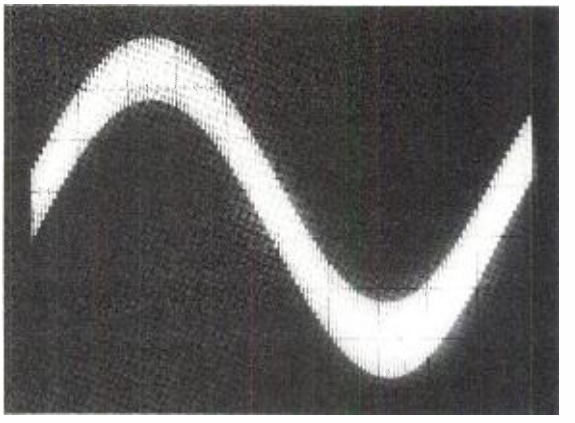


Fig. 16. SMPTE IMD measurement - time domain output signal.

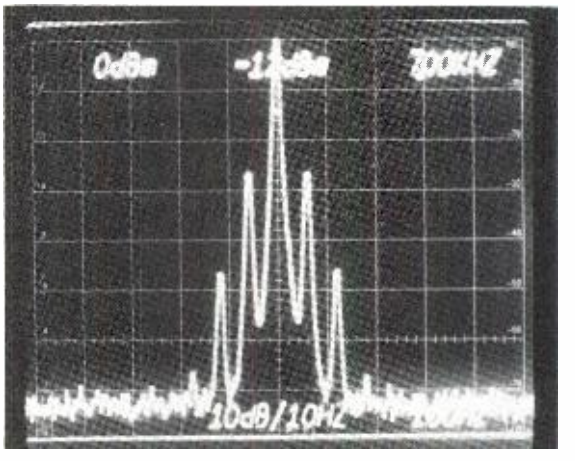


Fig. 17. SMPTE IM distortion measurement. (V:10dB/div; H:100Hz/div.)

Note the elongated trough as compared to Fig. 15. As in THD, spectrum analysis can be used to determine the numerical amount of distortion present. Intermodulation sidebands can be seen around f_2 in the spectrum photo of Fig. 17. Second and third order distortion percentages for this example are calculated as follows:

$$A_{f_2} = -12\ dBm = 195\ mV$$

$$A_{(f2\ -\ f1)} = A_{(f_1 + f_2)} = -38\ dBm = 9.76\ mV$$

$$SMPTE\ IMD\%\ (\text{second order}) = \left[\frac{9.76 + 9.76}{195}\right] \times 100 = 10.0\%$$

$$A_{(f2\ -\ 2f1)} = A_{(2f_1 + f_2)} = -58\ dBm = 0.98\ mV$$

$$SMPTE\ IMD\%\ (\text{third order}) = \left[\frac{0.98 + 0.98}{195}\right] \times 100 = 1.0\% \quad [8]$$

As is shown, the contribution of even-order distortion products is usually greater than that of the odd order. To express the result as a single quantity, the vector sum of the two quantities is taken:

$$SMPTE\ IMD\%\ (total) = \sqrt{((IMD\%\ Even)^2 + (IMD\%\ Odd)^2} = \sqrt{10^2 + 1^2} = 10.05\% \quad [9]$$

As with THD, SMPTE IM has a direct method of numeric solution, as shown in the block diagram of Fig. 18. The two test frequency oscillators are summed to produce the $f_1 + f_2$ signal which is applied to input of the device to be tested. The distorted output signal is high-pass filtered to remove the f_1 fundamental component leaving only the amplitude modulated f_2 component. Using a standard a.m. demodulator and low-pass filter, the residual f_1 component is obtained. After r.m.s. detection, a dc level proportional to the distortion is present and can be viewed on a direct-reading indicator.

"Wow and Flutter" is a term which describes a special case of IM distortion normally associated with analog tape recorders. It is caused by variations in tape velocity across the recording and/or reproduction heads due to imperfections in the mechanical drive system. These variations result in frequency modulation of the recorded and reproduced signal. The frequency spectrum obtained is similar to that of the SMPTE IM distortion measurement method, except the f_1 low frequency signal is generated by fluctuations in tape speed and is not of any set amplitude.[5]

To measure wow and flutter, a test tape containing a prerecorded 3 kHz tone is played. Using an audio spectrum analyzer, for example, the amplitude of the first sideband (A_m) with reference to the 3 kHz amplitude (A_o) is measured. The frequency of the flutter (F_m) must also be known. Then the following relation can be used to approximate the percent of wow and flutter present:

$$\text{WOW \& FLUTTER \% (peak-to-peak)} = \frac{2\,(A_m)\,(F_m)}{(A_o)\,(3\,kHz)} \times 100 \quad [10]$$

For example, if the first sideband (either upper or lower) amplitude is 10 dB below the 3 kHz maximum amplitude (0.316 volts with reference to an arbitrary 1 volt 3 kHz level) and is at a frequency of 4 Hz, the wow and flutter would be 0.084 percent.

The CCIF intermodulation method uses a combination of two higher frequency sinusoidal signals (f_3, f_4) of equal amplitude. They are typically 1 kHz apart and found at 5/6 kHz, 14/15 kHz, or 19/20 kHz in most applications. One of the spurious frequencies generated is low in frequency while others are gathered around the two driving frequencies. Fig. 19 and 20 spectrally show the driving frequencies before and after

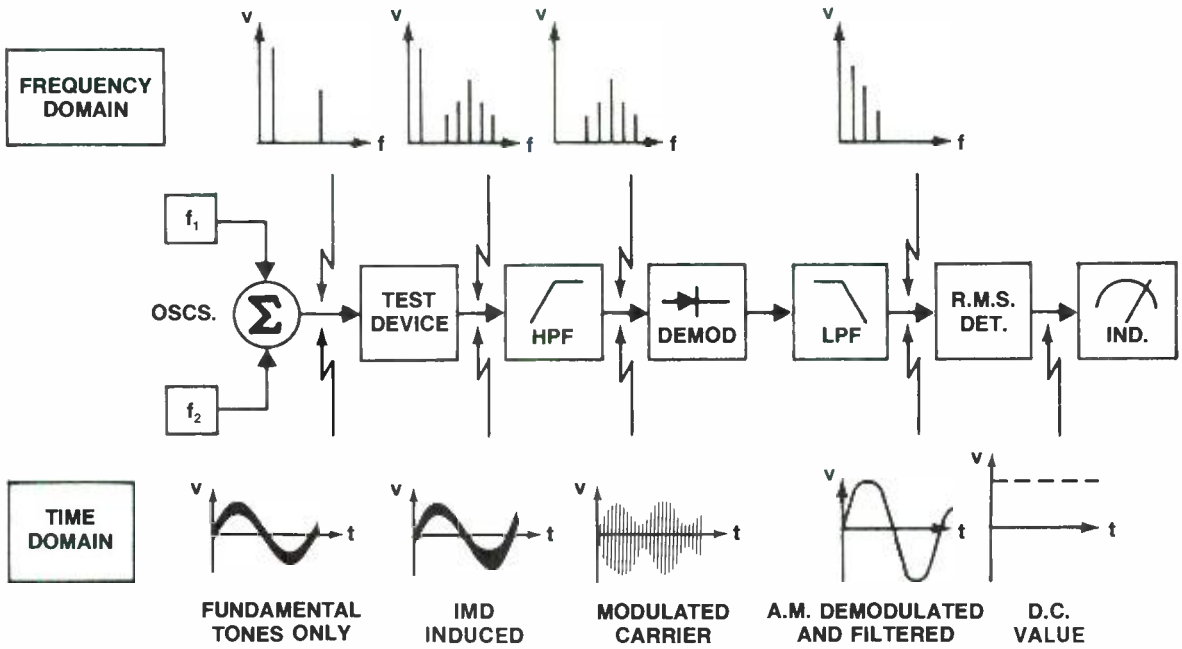


Fig. 18. SMPTE IMD analyzer.

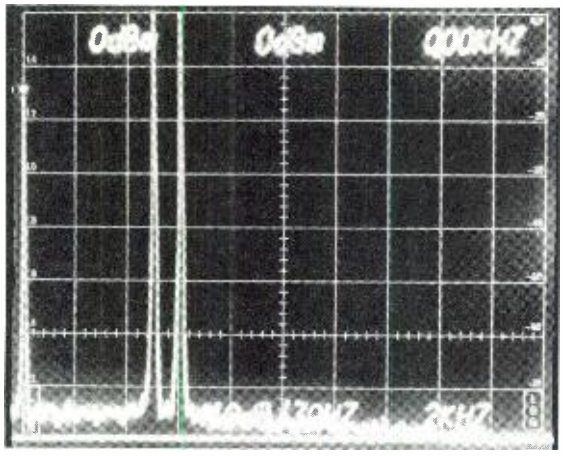


Fig. 19. CCIF IM test signals.
(V:10 dB/div.; H:2 kHz/div.)

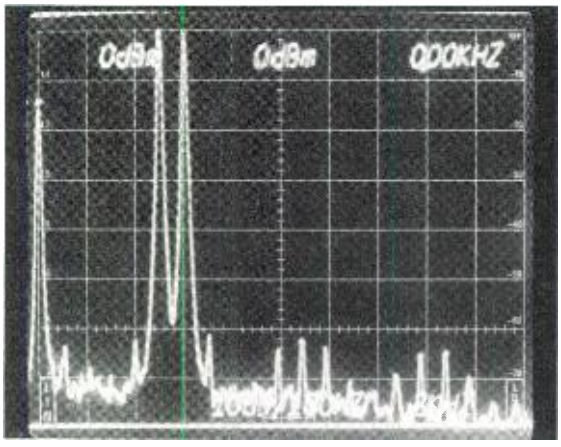


Fig. 20. CCIF IM distortion measurement.
(V:10 dB/div.; H:2 kHz/div.)

passing through a test amplifier. As with SMPTE IMD measurement, the generated spurious products can be classified as even-order or odd-order. Even-order distortion is expressed as the ratio of the amplitude of the difference component ($f_4 - f_3$) to the sum of the two driving frequencies (f_3, f_4):

$$CCIF\ IMD\%\ (second\ order) = \left[\frac{A\ (f_4 - f_3)}{Af_3 + Af_4}\right] \times 100 \qquad [11]$$

Odd-order distortion is determined by calculating the ratio of the sum of the amplitude of the two third-order products, $2f_3 - f_4$ and $2f_4 - f_3$, to the sum of the amplitudes of the two driving frequencies, f_3 and f_4:

$$CCIF\ IMD\%\ (third\ order) = \left[\frac{A\ (2f_3 - f_4) + A(2f_4 - f_3)}{Af_3 + Af_4}\right] \times 100 \qquad [12]$$

In the case of Fig. 20, the driving frequencies f_3 and f_4 are at 5 kHz and 6 kHz, even-order product at 1 kHz, and third-order products at 4 and 7 kHz, respectively. Distortion percentages for this example are calculated below:

$$Af_3 = Af_4 = 0\ dBm = 775\ mV$$

$$A(f_4 - f_3) = -64\ dBm = 0.49\ mV$$

$$CCIF\ IMD\%\ (second\ order) = \left[\frac{0.49}{775 + 775}\right] \times 100 = 0.032\%$$

$$A(2f_3 - f_4) = -62\ dBm = 0.62\ mV$$

$$A(2f_4 - f_3) = -61\ dBm = 0.69\ mV$$

$$CCIF\ IMD\%\ (third\ order) = \left[\frac{0.62 + 0.69}{775 + 775}\right] \times 100 = 0.085\% \qquad [13]$$

It is a common practice for direct-reading metered analyzers to measure only the amplitude of the difference product ($f_4 - f_3$) with respect to the driving signal amplitudes. A device which performs this task is called a CCIF second-order difference frequency distortion analyzer. Fig. 21 shows how the measurement is made.

Transient Intermodulation (TIM) distortion is found only in amplifiers that utilize negative feedback which, when excessive, causes a fast-rising transient signal applied to the input of the amplifier to produce an internal overshoot which saturates the circuits in the amplifier.

The most popular procedure used to measure TIM distortion is called the "Sine-Square Wave Method". The test signal employed uses a square wave (f_{sq}) to induce nonlinearity in the test device by saturating the amplifier's internal current, caused by its alternate rises and falls. Mixed with this square wave is a low level, high frequency sine wave (f_{si}), which is unrelated harmonically. As defined, the frequency of the square wave is 3.18 kHz and that of the sine wave 15 kHz, where the peak-to-peak amplitude ratio of the former to the latter is four to one. Before summation, the square wave is low-pass filtered using a first order design having a cutoff frequency of 30 kHz. This reduces the harmonics outside of the band of interest which could damage the device being tested. The composite waveform produced is shown in Fig. 22 and spectrally in Fig. 23.

Using the test setup shown in Fig. 24, an amplifier can be measured for TIM. Mathematically, TIM distortion produced by the sine-square wave method is defined as:

$$TIM\% = \frac{\sqrt{A1^2 + A2^2 + \ldots + A9^2}}{A_{si}} \times 100, \qquad [14]$$

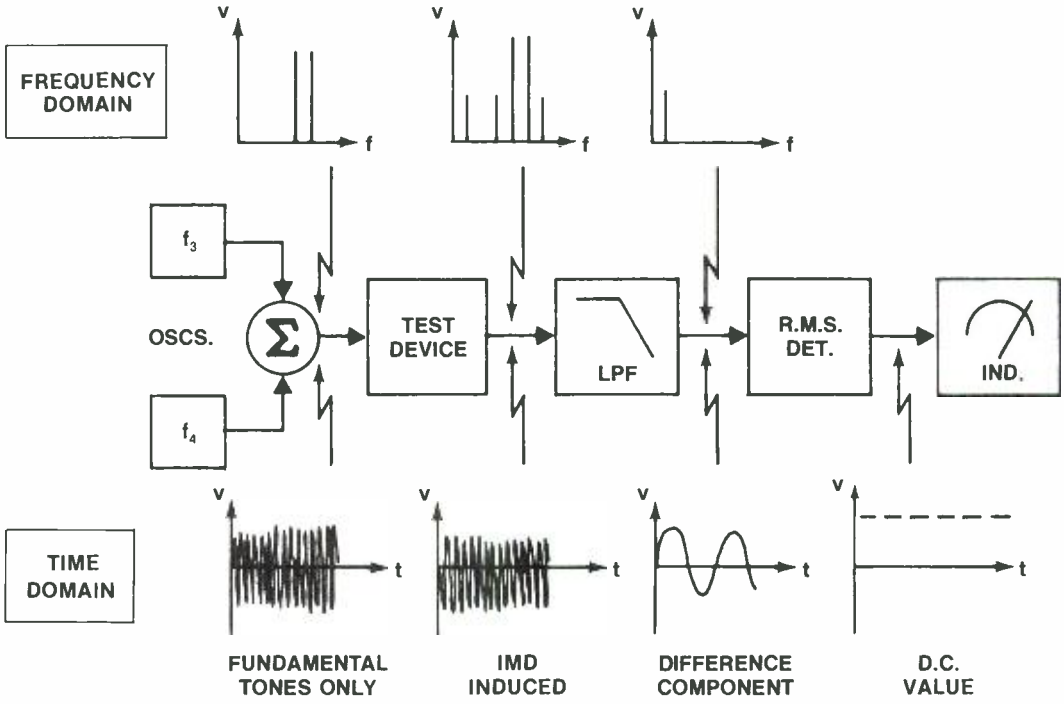


Fig. 21. CCIF second-order IMD analyzer.

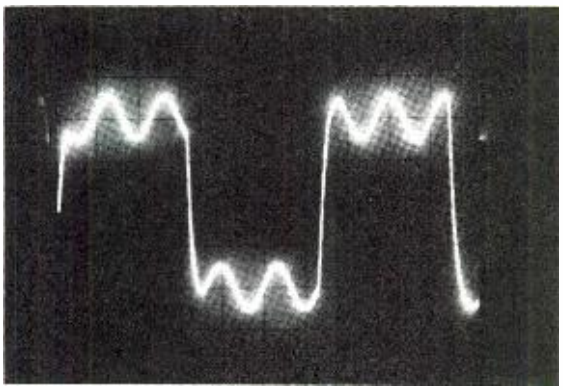


Fig. 22. TIM test signal.

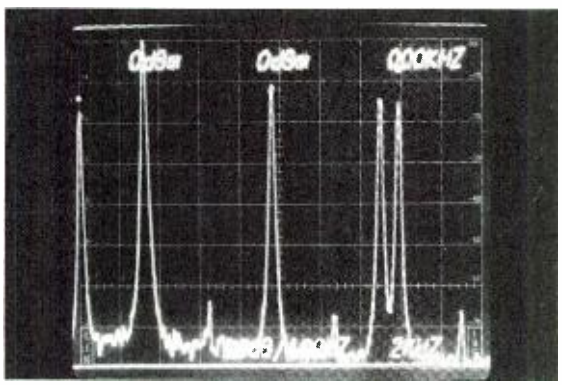


Fig. 23. TIM test signal, spectral view. V:10 dB/div.; H:2 kHz/div.)

where *A1* through *A9* represent the amplitudes of the distortion products present in the audio band and A_{si} is the amplitude of the sine wave. Values for the *A1—A9* components are shown in the table below:

Component	Relation	Frequency,kHz
A1	fsi—fsq	11.82
A2	fsi—2fsq	8.64
A3	fsi—3fsq	5.46
A4	fsi—4fsq	2.28
A5	| fsi—5fsq |	0.90
A6	| fsi—6fsq |	4.08
A7	| fsi—7fsq |	7.26
A8	| fsi—8fsq |	10.44
A9	| fsi—9fsq |	13.62

Fig. 25 shows the TIM distortion products produced by an amplifier that only displayed negligible THD, SMPTE IMD and CCIF IMD percentages. By using equation 14, it can be determined that this amplifier is producing about 20% TIM distortion.

Other TIM measurement methods include a sawtooth wave method which takes amplifier slew rate into account and a noise-square wave method where the sine wave of the sine-square wave method is replaced by a narrow-band noise spectrum.[8] These have not been as commonly used as the sine-square wave method at the time of this writing.

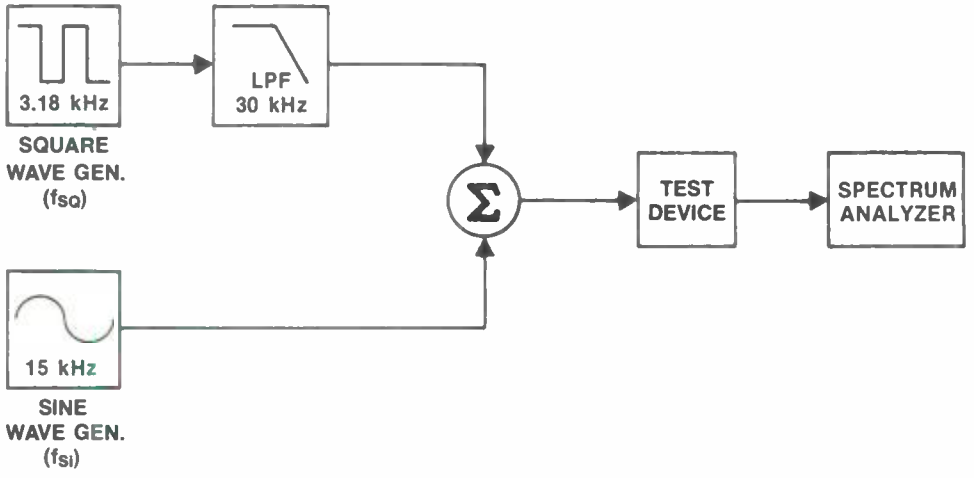


Fig. 24. TIM distortion analysis.

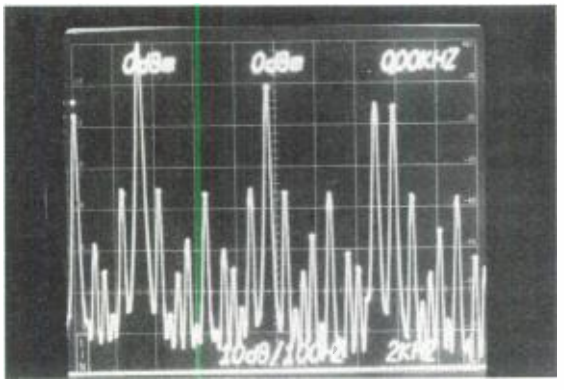


Fig. 25. TIM distortion products.
(V:10 dB div.; H:2 kHz/div.)

Fig. 26. Audio measuring set.

Filtering as part of distortion measurement is often useful to remove components which are of little interest and as a diagnostic aid.[9] This is especially true with THD measurement. A 20 or 30 kHz high-pass filter placed in series with the output of the device being measured is useful in testing broadcast equipment. This is often acceptable to do since the harmonics produced outside the transmission bandwidth can be eliminated, producing a more realistic result.

A high-pass filter also can serve as an important analytical aid. With a cutoff frequency in the 400 Hz range, it can be placed in series with the test device's output and used to determine the contribution of line frequency hum (60 Hz) to a THD measurement utilizing a fundamental frequency of 1 kHz or greater. Verification of adequate grounding used in the test setup can also be observed.

Care must be taken, however, when filtering is used in IM measurement. It is important to verify that in-band distortion components are not inadvertently removed. Also, extremely sharp cutoff filter designs may produce overshoot components which could affect measurement results.

A device capable of performing many of the distortion tests described above, as well as frequency response measurements, is shown in Fig. 26.

Noise Measurement

In audio engineering, noise is random energy where individual spectral components are not clearly resolved. Primary sources of noise are in the resistive elements from which amplifiers are made.[10] It is important to control noise in amplifiers as their gain increases to preserve a high signal to noise ratio, which is the ratio of the operating signal level to the noise level inherent in the amplifier itself.

To understand the origin of noise, we can model a passive resistive element as a noiseless resistor in series with a noise voltage generator, E_r:

$$E_r = \sqrt{4KTBR} \quad \text{(volts)} \qquad [15]$$

Where K = Boltzman's constant (1.38×10^{-23} W-Sec/°K)
T = temperature in degrees Kelvin
B = noise bandwidth (Hz)
R = resistance in ohms

Although noise bandwidth is not equivalent to amplifier 3 dB bandwidth, it can be related.

As can be seen from the above equation, noise voltage is a physical phenomenon which can be worsened by an increase in any of the variable factors. Therefore, noise cannot be eliminated but it can be reduced. This is often done by proper selection of the resistive components used, because an additional factor known as excess noise, which is proportional to the voltage drop across the resistor and related to the material from which it is made. Carbon composition resistors are prone to the most excess noise contribution while metal-film devices show the least.

At times the actual spectral distribution of noise is of less importance than the noise voltage in a given bandwidth for comparison purposes. For audio frequencies, a 15 or 20 kHz bandwidth is of interest. With a low-pass filter in this range connected in series with an amplifier output, and the input of the amplifier grounded, an unweighted but band-limited noise measurement can be made. When the noise output level is obtained, it can be related logarithmically to a standard operating level and reference frequency. This produces an indication of the amplifier's signal-to-noise (S/N) ratio.

When the gain of the amplifier is known, this same technique can be used to determine equivalent input noise voltage, i.e., the voltage of the noise which would be found at the input of the amplifier if the amplifier were completely noiseless.[10]

The measurement of a noise voltage quantity over a given frequency bandwidth in order to determine a S/N ratio does not provide a complete characterization. This is because the noise spectrum can occupy all or part of the same bandwidth.[11] For example, two amplifiers with identical S/N ratios can sound very different because one may have a uniform noise spectrum and the other may have most of the noise concentrated over a limited frequency range. Hence, the latter amplifier would sound "noisier" than the other. This has to do with the way the ear perceives the loudness of a signal which is uniform in amplitude across the audio band. To make comparative noise measurements more meaningful, several weighting filters have been used to alter noise spectra over the frequency band of interest.

NAB A weighting is based on the inverse of early measurements by Fletcher and Munson of the ear's sensitivity at low sound pressure levels.

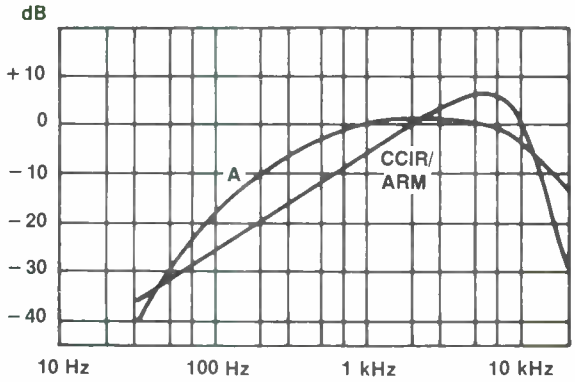


Fig. 27. Noise measurement weighting schemes.

A more recently developed weighting curve utilizes the CCIR/ARM method, an updated scheme which places the zero dB reference at 2 kHz instead of 1 kHz.[12] It is believed that this method, which is based on the obtrusiveness as well as the levels of different kinds of noise, provides a more commercially acceptable result when used to characterize modern, wide-range audio equipment. Fig. 27 compares the two curves.

Noise on telephone circuits has been investigated in detail by the Bell System (now AT&T) and others.[13] Terms used to describe this type of noise correspond to the use of specially developed noise meters which incorporate weighting filters specifically intended to characterize communications channels of 3 kHz bandwidth.

The abbreviation dBrn stands for dB above reference noise. It was introduced when the Bell System released the 2A noise meter. The meter is calibrated so that a 1 kHz, zero dBm tone will produce a reading of +90 dBrn. The same energy produces a reading of +82 dBrn when spread over a 300 to 3400 Hz band, subjected to "144-line" weighting.

A more recent standard is incorporated into the 3A noise measuring set which includes a "C-Message" weighting to suit the characteristics of newer handsets. The unit used is dBrnc; a zero dBm, 1 kHz tone will read +90 dBrnc. The weighting is flatter than "144-line" and therefore the 3 kHz band of noise will read +88.5 dBrn.

Relative Program/Loudness Measurement

Broadcasters and the FCC have received numerous complaints concerning loud commercials being broadcast on radio and television. Until recently, little was known about either what makes commercials loud or how to control this loudness. Since individual listeners vary in their judgments of loudness, the matter becomes further complicated. Indicators such as vu meters proved to be of little use in loudness measurement.

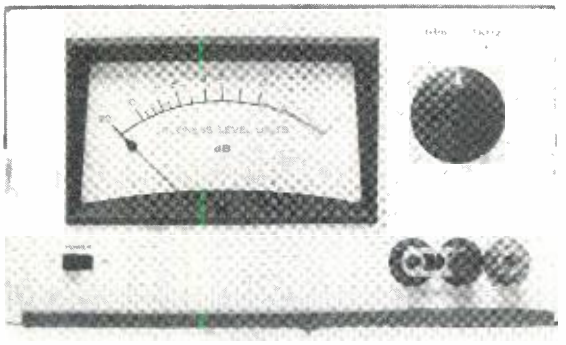


Fig. 28. Original CBS loudness meter.

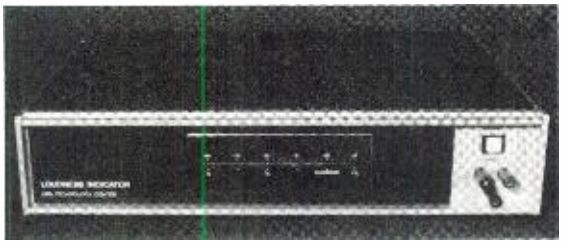


Fig. 29. Current CBS loudness indicator. (Courtesy CBS, Inc.)

The CBS Technology Center in Stamford, Connecticut has been working for many years on methods to measure and control loudness.[14] The first loudness monitor developed by CBS had the ability to perform loudness level additions on wide spectrum signals. This was done in accordance with studies performed investigating the characteristics of human hearing. Fig. 28 shows this original system.

In further research, the spectrum of hearing was separated into "critical bands". By definition, a critical band is that maximum bandwidth below which loudness does not diminish as the bandwidth is decreased. Subjective testing revealed a total of 24 critical bands. CBS felt that an ideal loudness measuring device should sample energy in each band to process and display a result. However, the hardware would require 24 filtering and processing sections. The critical band concept was used, but every three of the bands were combined to produce a total of 8 bands. The latest loudness indicator has a frequency response weighted in accordance with a subjectively derived frequency response of the human ear at a reference level (see Fig. 29). A block diagram of this meter is shown in Fig. 30.

Another device intended for real-time program analysis is the Audio Program Analyzer pictured in Fig. 31. It allows material from devices such as receivers, modulation monitors and audio processing equipment to be characterized in several ways. Peak-to-average ratios are quickly determinable, as well as maximum peak levels. Peak density can be measured which allows evaluation of audio processing effectiveness. The unit also contains a four band RTA; analysis of tonal balance and pre-emphasis characteristics can be done using this function. Provisions are also available for the monitoring of stereo program material.[3]

Phase Monitoring and Measurement

L + R is the monophonic compatible signal for AM, FM, and TV stereo. Separation information is transmitted via an L-R signal. Since these two signals are created through a summation and difference process of the original left and right channel stereophonic source, it is important that they be recombined properly at the receiver.[15] To accomplish this, amplitude and *phase* errors must be minimized in the transmission system. Phase measurement is important in accomplishing this task. [For further information see Chapter 3.4 of this *Handbook* and reference 15.]

In a stereo system, if left and right audio information is correlated but delayed in phase, the error would not be evident on a stereophonic receiver. A monophonic signal, however, will be degraded because of inexact summation. This problem is most common in audio tape recording. Periodic azimuth adjustment or "phasing" of the heads is often done. A test tape containing a high frequency tone is played while azimuth is adjusted to minimize the difference between the two channels.

A phase meter can be used to simplify this task. A simple version would take phase and amplitude variances into account simultaneously by functioning as a two-input subtractor. When both characteristics are identical in each of the channels, the output becomes zero. A meter which

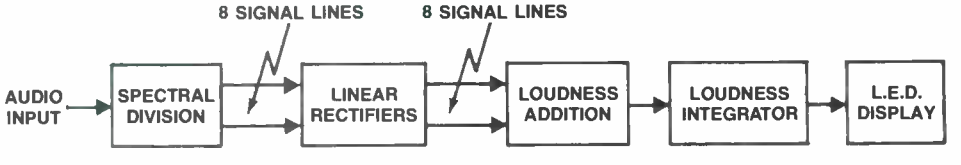


Fig. 30. 2nd generation CBS loudness indicator. (Courtesy CBS, Inc.)

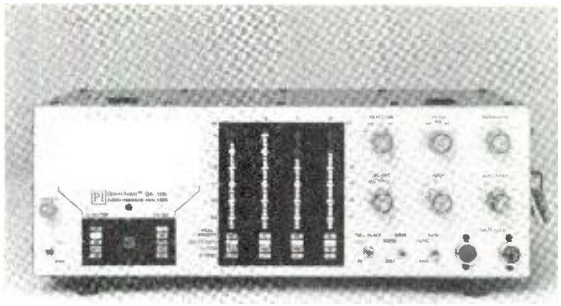


Fig. 31. Audio program analyzer. (Courtesy Potomac Instruments, Inc.)

measures only phase compares the zero-crossing times of the two signals, and time difference is used to generate a dc voltage proportional to the phase difference.[16] Phase detectors which operate in this manner often limit the input signals in order to remove all amplitude information.

More popular, however, is the "Lissajous Figure" method, involving the use of an oscilloscope in the x-y mode. The patterns produced are shown in Fig. 32. An oscilloscope is connected such that the left channel audio causes an x-axis sweep and right channel audio produces a y-axis sweep as shown in Fig. 32A and 32B respectively. When each channel is producing the same program material, the pattern of Fig. 32C is produced. This is the "L + R" axis. If one of the channels is inverted, the pattern of Fig. 32D becomes evident. This is often called the "L-R" axis. Program material which follows this axis is said to be "inverted in phase", because no sum or L + R information is present.

During alignment of tape reproduction equipment when discrete tones are used, the patterns of Fig. 32E, F, and G are often seen when phase errors exist between the two channels. Stereo program material, in unprocessed form, generally modulates the L + R axis while simultaneously deviating in the L-R direction to a lesser amount as shown in Fig. 32H.

References

1. Graeme, J. *Applications of Operational Amplifiers,* McGraw-Hill, 1973 pp.132-139, 202-203.
2. "A New Standard Volume Indicator and Reference Level," *Proceedings of the IRE,* January 1940, pp.1-17.
3. Harry, D. "Audio Program Analysis," As presented to the National Association of Broadcasters, April 1985.
4. IEEE Standard: *Recommended Practice for Volume Measurements of Electrical Speech and Program Waves,* [old number 152-1953 (Reaff 1971)].
5. Hewlett-Packard Co. "Using a Narrow Band Analyzer for Characterizing Audio Products," AN192, Oct. 1975.
6. Crown International Inc., *BDP-2 The Audio Micro Computer,* equipment manual, September 1981.
7. Skritek, P. and H. Pichler, "Extended Application of T.I.M. Test Procedures," preprint no. 1557, 64th AES Convention, Nov. 1979.

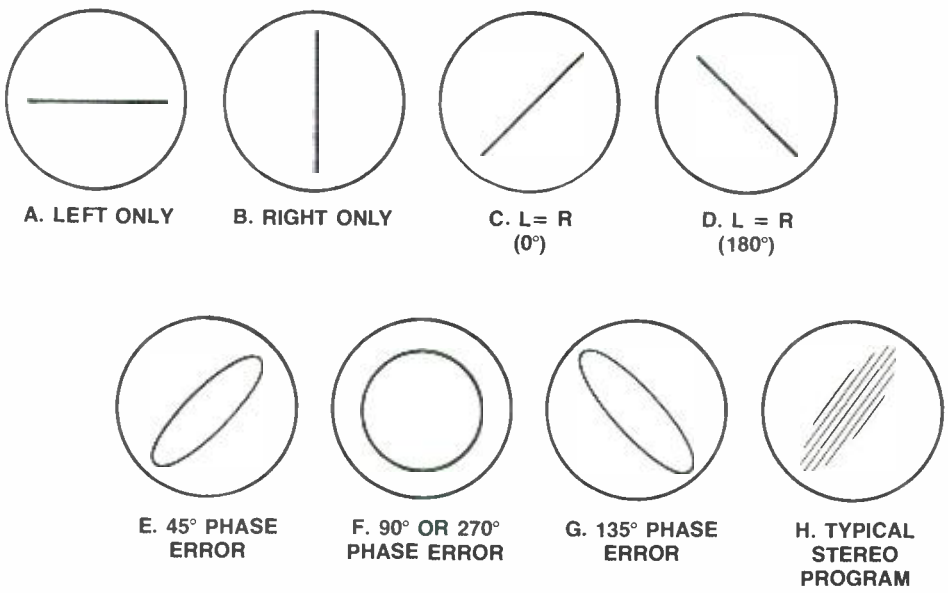


Fig. 32. Interpretation of Lissajous patterns.

8. Takahashi, S. and S. Tanaka, "A New Method of Measuring Transient Intermodulation Distortion: A Comparison with the Conventional Method," preprint no. 1539, 64th AES Convention, Nov. 1979.

9. Tektronix, Inc., *AA501 Distortion Analyzer,* equipment manual, February 1984.

10. National Semiconductor Corporation, *Audio/ Radio Handbook,* 1980, pp.2.3-2.10.

11. Hewlett-Packard Co., "Spectrum Analysis ... Noise Measurements," AN150-4, April 1974.

12. Dolby, R., D. Robinson and K. Gundry, "CCIR/ARM: A Practical Noise-Measurement Method," *Journal of the Audio Engineering Society,* vol. 27, March 1979, pp.149-157.

13. Panter, P. *Communications Systems Design: Line-of-sight and Tropo-scatter Systems,* McGraw-Hill, 1972, pp.72-77.

14. Haller, R. "An Update on the Technology of Loud Commercial Control," F.C.C. Office of Science and Technology, February 1983.

15. G. Mendenhall, "The Composite Signal-Key to Quality FM Broadcasting," Broadcast Electronics.

16. Graeme, J., *Designing with Operational Amplifiers,* McGraw-Hill, 1977, pp.76-77, 251-253.

17. Driscoll, F. F., *Analysis of Electric Circuits,* Prentice-Hall, Inc., 1973, pp.39-49.

18. Hewlett-Packard Co., "Spectrum Analysis ...Distortion Measurement," AN150-11, Oct. 1976.

19. The Institute of Electrical and Electronics Engineers, Inc., *IEEE Standard Dictionary of Electrical and Electronics Terms,* Third Edition (1984).

INDEX

INDEX

—A—

AM (Amplitude Modulation) (*See* AM directional arrays, AM nondirectional AM antenna, AM stereo)
AM Directional Arrays, 2.4-67—92
  antenna monitor, 2.4-101—102
  augmented pattern equation, 2.4-89—92
  detuning and decoupling system, 2.4-102—105
    filter systems, 2.4-104
    intermodulation, 2.4-104—106
    power lines, 2.4-103
    tower current minimums, 2.4-104
    tower sectionalization, 2.4-102-103
    transmitter load, 2.4-105
  diplexers and multiplexers, 2.4-105—106
  directional antenna block diagram, 2.4-94
  field strength, 2.8-217 (*See* listing)
  ground system, 2.4-110
  horizontal RMS field strength (*See* field strength)
  insulated tower base impedance, 2.4-64—65
  maintenance of AM antenna systems, 2.4-109
  matching networks, 2.4-95—100
    L networks, 2.4-95—97
      diagram, 2.4-96—97
    power divider, 2.4-97—100
      diagrams, 2.4-98
      ohms-law divider, 2.4-97
      simplification, 2.4-99
      tank-type divider, 2.4-97
    T networks, 2.4-95
  multiplication of two tower patterns, 2.4-69
  mutual-impedance curves, 2.4-76—77
  pattern shape, 2.4-73
    space configuration, 2.4-73
    vector diagram, 2.4-73
  phasing systems, 2.4-93—94
    input impedance, 2.4-94
    radiation patterns, 2.4-94—95
    VSWR, 2.4-94
  radiation pattern shape, 2.4-67—69
  sampling loops, 2.4-101
    sampling lines, 2.4-101
    sampling transformers, 2.4-101
  sampling system, 2.4-101—102
  soil conductivity, 2.4-113
  systematization of patterns, 2.4-69—72, 78—88
  theoretical pattern equation, 2.4-89
  theoretical self-loop and base radiation resistance, 2.4-76
  (*See* AM proof of performance, partial proof, transmission lines)
AM Field Strength Measurements (*See* AM Proof of Performance, Field Strength)
AM Nondirectional Antenna (*See* Nondirectional AM Antenna listing)
AM Proof of Performance, 2.8-217—234
  antenna monitor system, 2.8-223
  construction permit, 2.8-219
  FCC license, 2.8-223—224
  FCC program test authority, 2.8-219—220
  measurements, 2.8-219, 221
    graphical analysis, 2.8-221
    plotting data, 2.8-221—223
  partial proof, 2.8-220—221
  reference proof of performance, 2.8-219
  regulations, 2.8-225—234
  special temporary authority, 2.8-223
AM Stereo, Definition, 3.2-37—38
  Belar AM Stereo, 3.2-53
  Harris linear AM stereo system, 3.2-43—46
    compatibility with human ear, 3.2-44—45
    controlled compatibility linear quadrature, 3.2-45—46
    linear systems, 3.2-44
    nonlinear systems, 3.2-44
  Kahn-Hazeltine independent sideband system, 3.2-47—51
    asymmetrical sideband selectivity, 3.2-48—51
    receiver, 3.2-48
    transmitting equipment, 3.2-47
  Motorola C-Quam AM stereo system, 3.2-39—42
    audio performance, 3.2-39
    audio preemphasis, 3.2-39
    audio processing, 3.2-39
    C-Quam, compatible quadrature, 3.2-39—41
      decoding, 3.2-40—41
      encoding, 3.2-39—40
      transmitter, 3.2-39—40
    heavy modulation, 3.2-41
    performance, 3.2-41
    receiver, 3.2-42
    spectrum, 3.2-39
  PMX AM Stereo, 3.2-55—61
    broadcast signal equation, 3.2-55
    characteristics, 3.2-58
      bandwidth, 3.2-58
      compatibility, 3.2-58
      coverage, 3.2-58
    measurement, 3.2-58
    performance, 3.2-58
    sound field disturbances, 3.2-58
    system implementation, 3.2-55—56
    synchronous detection, 3.2-58
AM Transmitters, 3.1-1—36
  ampliphase, 3.1-9
  audio phase linearity, 3.1-20—21
  carrier amplitude regulation (carrier shift), 3.1-19—20
  carrier frequency generator/exciter, 3.1-13—14
  characteristics, 3.1-24—25
  Chireix modulation, 3.1-9
    diagram, 3.1-9
  circuitry, 3.1-13
  Class "B" level anode modulation, 3.1-5
    diagram, 3.1-6
  Doherty High Efficiency Linear Amplifier, 3.1-9—10
    diagram, 3.1-11
  factory tests, 3.1-18
  harmonic and spurious output, 3.1-22
  high level anode modulation, 3.1-5
  high voltage power supplies, 3.1-17
  hum and noise, 3.1-19
  incidental phase modulation(IPM), 3.1-19,24
  occupied bandwidth, 3.1-21—22
  operating efficiency and input power, 3.1-22—24
  outphasing, 3.1-9
  performance measurements, 3.1-18
  pulse width high level anode modulation, 3.1-7—9

diagram, 3.1-8
RF output networks, 3.1-14—16
RF power amplifier, 3.1-14
representative transmitters, 3.1-26—36
shortwave, 3.1-25—26
stereophonic base/gain equalizer, 3.1-25
transmitter control and monitoring, 3.1-17
Advanced Television Systems Committee (ATSC), 1.6-90
American National Standards Institute (ANSI), 1.6-93
American Radio Relay League (ARRL), 1.6-93
Amplitude Modulation (*See* AM)
Amplitude Measurement, 7.9-185—187
metering, 7.9-186—187
peak function, 7.9-186
peak program (PPM) meter, 7.9-186—187
true RMS detection, 7.9-186
volume indicator (VU) meter, 7.9-186—187
Anchors (*See* Towers)
Armstrong, Major Edwin H., 3.3-63
Association for Broadcast Engineering Standards (ABES), 1.6-93
Association of Federal Communications Consulting Engineers (AFCCE), 1.6-89
Association of Maximum Service Telecasters (MST), 1.6-90
Audio, 5.6-107—119
production, 5.6-118—119
Audio Console, 5.6-109—113
Audio Engineering Society (AES), 1.6-93—94
Audio Measurement, 7.9-185—200
amplitude measurement, 7.9-185—187
metering, 7.9-186—187
peak function, 7.9-186
peak program (PPM) meter, 7.9-186—187
true RMS detection, 7.9-186
volume indicator (VU) meter, 7.9-186—187
distortion measurement, 7.9-190
harmonic distortion, 7.9-190
intermodulation distortion, 7.9-190—196
total harmonic distortion (THD), 7.9-190
transient intermodulation distortion (TID), 7.9-190
wow and flutter, 7.9-193
frequency analysis, 7.9-187
real time analyzer (RTA), 7.9-189—190
fast Fourier transform analyzer, 7.9-190
parallel analysis, 7.9-189
swept frequency, 7.9-188—189
noise measurement, 7.9-196
CCIR/ARM method, 7.9-197
Fletcher and Munson, 7.9-197
NAB A weighting, 7.9-197
phase measurement, 7.9-198—199
phase monitoring, 7.9-198—199
relative program/loudness, 7.9-197—198
audio program analyzer 7.9-198
signal to noise ratio, 7.9-197
telephone noise, 7.9-197
Audio Processing, 5.6-117
Augmented Pattern Equation (*See* AM Directional Arrays)
Automatic Frequency Control (AFC), 3.3-77—78
phase locked loop AFC, 3.3-77—78
Automotive Road Information (ARI), 3.4-121

—B—

Base Radiation Resistance, 2.4-76
Belar AM Stereo (*See* AM Stereo Listing)
Bessel Function Analysis, 3.4-125
Bessel Nulls, 3.3-67—68
Bessel function, 3.3-66—67
Binary Coded Decimal (BCD), 3.7-200
Blondel-Ray Relationship, 2.1-7
Brewster Angle, 2.5-120—121
Broadcast Education Association (BEA), 1.6-94
Broadcast Facility, 5.1-1—27
acoustics, 5.1-8—12
economics, 5.1-9
examples, 5.1-13—27
reverb time, 5.1-11
studio, 5.1-8
construction, 5.1-2
economics, 5.1-1—3,9
budget (form), 5.1-3
codes, 5.1-2
planning, 5.1-1—2
electrical, 5.1-4—7
engineering, 5.1-2
mechanical, 5.1-7
site selection, 5.1-2
telephones, 5.1-5

—C—

C Band, 4.3-79
Cameras, television, 5.3-45—72
afterimage, 5.3-69
amplitude, 5.3-67
automatic beam optimization, 5.3-64
automatic set-up, 5.3-54
beam current, 5.3-64
camera tube preamplifier, 5.3-47
camera types, 5.3-55
electronic field production (EFP), 5.3-56—57
electronic news gathering (ENG), 5.3-56
portable, 5.3-56
remote control unit, 5.3-56
sports, 5.3-51
studio, 5.3-55
charge coupled device (CCD), 5.3-64
choice, 5.3-70—72
deflection system, 5.3-54
block diagram, 5.3-54
clock driver, 5.3-54
encoder, 5.3-52—53
synchronizing generator, 5.3-52—53
image enhancer, 5.3-50—52
image preamplifier, 5.3-47
imaging device, 5.3-46
lag, 5.3-68—69
lead-oxide camera tubes, 5.3-63
leadicon, 5.3-63
plumbicon, 5.3-63
saticon, 5.3-63
limiting resolution, 5.3-66—67
measurement, 5.3-66
Nyquist limit, solid state images, 5.3-65
optical system, 5.3-45—46, 57—62
beam splitter, 5.3-46
filters, 5.3-62—63
lens, 5.3-45—46
lens parameters, 5.3-57—60
angle of view, 5.3-57
field of view, 5.3-57
focal length, 5.3-57
geometric distortion, 5.3-59—60
longitudinal chromatic variations, 5.3-59
minimum object difference (MOD), 5.3-60
modulation transfer function (MTF), 5.3-57
ramping, 5.3-57
relative operation, 5.3-57
uniformity of field, 5.3-59
vignetting, 5.3-59
prismatic beam splitter, 5.3-62
relay type beam splitter, 5.3-62
performance, 5.3-69

pixels, 5.3-64
power, 5.3-54
sensitivity, 5.3-67—68
set-up evaluation, 5.3-69—70
signal current, 5.3-64
system parameters, 5.3-69
video processor, 5.3-47
x and y alignment, 5.3-63
Candella, definition, 2.1-7
Cardioid microphone, 5.6-116
Cavity Panel Antennas, 2.5-133
Chart Recorder, 2.7-211
Chireix modulation, 3.1-9
diagram, 3.1-9
Co-channel Interference, 2.9-247
Color Subcarrier, (*See* Color Television Systems, and Multichannel Television Sound)
Color Television Standards, 7.1-51—60
International Radio Consultative Committee (CCIR), 7.1-51—52
monochrome-compatible color television systems, 7.1-52—61
National Television System Committee (NTSC), 7.1-52
system, 7.1-54—58
Phase Alternation Line (PAL), 7.1-53, 58—60
Sequential Coleur Avec Memoire (SECAM), 7.1-53, 61—63
Color Television System, 7.1-1—60
bandwidth, 7.1-3
burst amplitude error, 7.1-26
burst phase error, 7.1-25
camera alignment, 7.1-40
aperture correction, 7.1-42
signal to noise, 7.1-41
three tube concept, 7.1-41
carrier unbalance, 7.1-26—27
color encoder, 7.1-37
aperture compensation, 7.1-38—40
block diagram, 7.1-40
functions, 7.1-37
waveforms, 7.1-38
color errors, 7.1-36—37
color fidelity, 7.1-16
color frequency standards, 7.1-13
color subcarrier, 7.1-8—12
color system, 7.1-13
block diagram, 7.1-13
color variables, 7.1-5
displaying colors, 7.1-5—6
generating colors, 7.1-5
primary colors, 7.1-5
compatibility, 7.1-1
demodulation, 7.1-25
differential phase, 7.1-34—35
distortion in transmission system, 7.1-27
electronic aspects, 7.1-6
band shaping, 7.1-8
matrixing, 7.1-7-8
envelope delay, 7.1-29—31
eye characteristics, 7.1-17—24
film chains, 7.1-44
frequency interlace, 7.1-12—13
fundamentals,7.1-1
gain characteristic, 7.1-27
gain stability, 7.1-25
incremental gain, 7.1-32—34
incremental phase, 7.1-34—35
linear transmission system, 7.1-27
matrix coefficients, 7.1-36
matrixing, 7.1-36
modulation, 7.1-25
monochrome television system, 7.1-4
radiated picture signal, 7.1-4
receiver, 7.1-4
nonlinearities of transmission systems, 7.1-31
phase accuracies, 7.1-36
phase characteristic, 7.1-28—29
receiver, 7.1-15
block diagram, 7.1-14—16
resolution, 7.1-3
scanning, 7.1-3
subcarrier frequency accuracies, 7.1-36
subcarrier frequency error, 7.1-27
synchronizing, 7.1-3
system colorimetry, 7.1-35—36
system exponent, 7.1-36
transmission characteristics, 7.1-36
video unbalance, 7.1-27
Color Test Equipment, 7.1-44—48
sine-squared pulse and bar, 7.1-45—46
stair-step generator, 7.1-45
vector scope, 7.1-46
vertical interval reference, 7.1-48
vertical interval test signal, 7.1-48
Communications Act of 1934, 1.1-1
Community Antenna Economics, 2.5-135—136
Compact Disc Players, 5.6-114
Computer Systems (for newsrooms), 7.6-123—157
centralized systems, 7.6-139
data communication, 7.6-134—138
interconnection, 7.6-138—139
modems, 7.6-138
distributed systems, 7.6-140
glossary, 7.6-148—157
hardware, 7.6-125
hybrid system, 7.6-141
installation, 7.6-144—145
languages, 7.6-127
local area network (LAN), 7.6-140
mainframes, 7.6-123—124
arithmetic/logic unit, 7.6-123
bits, 7.6-123
bitwidth, 7.6-124
bus, 7.6-124
memory, 7.6-124
maintenance, 7.6-145—147
newswire services, 7.6-137
planning, 7.6-141—144
programmable read-only memory, 7.6-126
security, 7.6-146—147
software, 7.6-126
terminals, 7.6-132—134
Condenser Microphone, 5.6-116
Consultant Service, 1.4-67—76
services, 1.4-67—70
Crossed Dipole Theory, 2.5-133—134

—D—

D layer, 2.9-236
Data Communication, 7.6-134—138
dBx™, 5.11-225
Department of Agriculture, 1.6-87
Department of Commerce 1.6-87
National Bureau of Standards, 1.6-87—88
Time and Frequency Division, 1.6-87—88
WWV, 1.6-87—88
WWVB, 1.6-87—88
WWVH, 1.6-87—88
National Telecommunications and Information Administration,1.6-88
Department of Labor, 1.6-88
Occupational Safety and Health Act, 1.6-88
Department of the Interior, 1.6-88
Bureau of Land Management, 1.6-88
Topographic Maps, 1.6-88
U.S. Geological Survey, 1.6-88

Department of Transportation, 1.6-88
Federal Aviation Administration (FAA), 1.6-88
Dielectrics, 2.5-148
Diplexers, 2.4-105—106
Direct Broadcast Satellites (DBS), 1.1-7
Directional Antennas (*See* AM or FM listing)
Directional Microphone, 5.6-116
Distortion Measurement, 7.9-190
harmonic distortion, 7.9-190
intermodulation distortion, 7.9-190—196
total harmonic distortion (THD), 7.9-190
transient intermodulation distortion (TID), 7.9-190
wow and flutter, 7.9-193
Distribution Amplifiers,Audio, 5.6-117
Distribution Amplifiers, Pulse, 5.4-79
Distribution Amplifiers, Video, 5.4-77—80
Doherty High Efficiency Linear Amplifier, 3.1-9—10
diagram, 3.1-11
Dolby A™, 5.11-225
Dolby B ™, 5.11-225
Dolby C ™, 5.11-225
Dolby Labs ™, 5.11-225
Dolby ™, 5.11-225
Dummy Loads, 2.5-153
Dynamic Microphone, 5.6-115

—E—

E layer, 2.9-236
Effective Radiated Power (ERP), 2.5-117, 2.6-160—161, 3.3-80—81
definition, 2.5-125
Electrical Systems, 7.3-77—91
efficient energy use, 7.3-91—93
lagging power factor, 7.3-78—79
leading power factor, 7.3-78—79
maintenance, 7.3-94
motor generator units (MGU), 7.3-85—86
problems, 7.3-80—84
assessment, 7.3-81
measurement, 7.3-81
suppression, 7.3-84
processing line filters, 7.3-86—87
standby power system, 7.3-87—91
protection, 7.3-88
transients, 7.3-80
uninterruptible power systems (UPS), 7.3-86
utility power system, 7.3-77
utility company interfacing, 7.3-79—80
Electromagnetic Interference (EMI), 4.4-94
Electronic Field Production (EFP), 5.3-56—57
Electronic Industries Association (EIA), 3.6-185—186, 1.6-90
Standards, 1.6-90—91
Electronic News Gathering (ENG), (*See* Video Tape Editing, 1.5-79—81, 6.1-1—8, 6.2-19—27, 6.3-39)
Electronically Erasable Programmable ROM (EEPROM), 3.7-200
Emergency Broadcasting System, 7.8-167—183
checklist, 7.8-172—179
local level, 7.8-172
station responsibility, 7.8-172
National Industry Advisory Committee, 7.8-181—183
operation, 7.8-169
organization, 7.8-168—169
state and local level instructions, 7.8-179
reception, 7.8-180—181
state level, 7.8-171
station responsibility, 7.8-171—172
station responsibility, 7.8-170
tests, 7.8-170—171
Environmental Protection Agency (EPA), 1.6-89
National Environmental Protection Act (NEPA), 1.6-89
Equalizers, 5.6-117

—F—

F1 layer, 2.9-237
F2 layer, 2.9-237
FM, (*See* Frequency Modulation, and FM Antennas)
FM Antennas, 2.5-117—153
antenna gain, 2.5-136—137
antenna gain, definition, 2.5-125
antenna site selection, 2.5-128
beam tilt, 2.5-125—126
blanketing, 2.5-125
cavity panel antennas, 2.5-133
class A station coverage, 2.5-126—127
class B station coverage, 2.5-127—128
commercially available antennas, 2.5-130—131
community antenna economics, 2.5-136
advantages, 2.5-136
crossed dipole theory, 2.5-133—134
directional antennas, 2.5-136
effective radiated power (ERP), 2.5-117
definition, 2.5-125
FCC service contours, 2.5-122
flat panel antennas, 2.5-133
transmitter power, 2.5-136—137
antenna installation on AM towers, 2.5-141—145
accessory antenna system equipment, 2.5-152
dummy loads, 2.5-153
electrical heaters, 2.5-149—150
FM SCA multiplexing, 2.5-151—152
FM tower guying, 2.5-141—142
break up insulators, 2.5-141—142
effects on antenna, 2.5-141—142
plastic guys, , 2.5-142 (Table) 2.5-143
plastic rope, 2.5-142
porcelain insulators, 2.5-142
harmonic filters, 2.5-152
installation procedures, 2.5-146—147
planning, 2.5-146
procedure, 2.5-146—147
receiving and unpacking, 2.5-146
interference, 2.5-152
isolation transformers, 2.5-141
diagram, 2.5-141
lighting 2.5-151 (*See* listing)
method, 2.5-145
pattern optimization, 2.5-143
pattern service, 2.5-145—146
diagram, 2.5-145
protection from icing, 2.5-149—150
RF switches, 2.5-153
radomes, 2.5-150—151
reflectometers, 2.5-153
spurious frequencies, 2.5-152
structural considerations, 2.5-147
antenna polemounting, 2.5-147
wind loading, 2.5-147
transmission lines, 2.5-147—148
diagram, 2.5-148
dielectrics, 2.5-148
rigid coax, 2.5-148
semiflexible coax, 2.5-148
diagram, 2.5-144
theory, 2.5-143—144
(*See* VSWR)
FM signal measurements, 2.5-124—125
requirements, 2.5-124—125
Fresnel zone clearance, 2.5-121—122
diagram, 2.5-121
formula, 2.5-121
graph, 2.5-121

general coverage standards, 2.5-123—124
high transmitter power ERP myth, 2.5-136
null fill 2.5-126
panel antennas, 2.5-132—134
polarization, 2.5-117—123
circular polarization-Cpol, 2.5-117,120,122—123
diagrams, 2.5-123
cross polarization, 2.5-117
elliptical polarization-Epol, 2.5-117
horizontal polarization-Hpol, 2.5-117,120
vertical polarization-Vpol, 2.5-117,120
recommended minimum antenna height, 2.5-122
ring stub antenna, 2.5-132
series fed antennas, 2.5-131
short helix, 2.5-132
short helix multi-arm, 2.5-131
shunt fed antennas, 2.5-131
slanted dipole FM antennas, 2.5-131
soil conductivity, 2.5-122
station diplexing, 2.5-137—140
branched starpoint, 2.5-139—140
cavity, 2.5-140
constant impedance type, 2.5-139
diagram, 2.5-138—139
diplexer, definition, 2.5-137—138
example, 2.5-140—141
twisted ring antenna, 2.5-132
wide-band antenna, 2.5-134—136
zones, 2.5-124
FM Propagation, 2.5-118—120
propagation loss, 2.5-118—119
multi-path problems, 2.5-119—120
diagram, 2.5-119
reflections, 2.5-119—120
ground reflections, 2.5-120
diagram-2.5-120
(*See* Brewster Angle)
FM SCA Multiplexing, 2.5-151—152
FM Translators (*See* translators)
Fan-Vee Antenna, 2.6-193
Far field (*See* Fraunhofer Region)
Federal Aviation Administration, 1.6-88
Federal Communications Commission (FCC), 1.1-1—21, 1.6-89
Code of Federal Regulations, 1.6-89
Communications Act of 1934, 1.1-1
licensing process, 1.1-5—7
application, 1.1-1
auxiliary and translator services, 1.1-7
direct broadcast satellites (DBS), 1.1-7
low power television (LPTV), 1.1-7
renewal, 1.1-6—7
sales/transfers, 1.1-7
steps, 1.1-6—7
types of facilities, 1.1-5—6
structure, 1.1-5
chart, 1.1-2
Common Carrier Bureau (CCB), 1.1-3
Field Operations Bureau (FOB), 1.1-3, 1.2-19—21
Enforcement Division, 1.2-19—20
Engineering Division, 1.2-19—20
field facilities, 1.2-20
field offices, 1.2-20
inspection, 1.2-20—21
actions, 1.2-21
appeals, 1.2-21
element, 1.2-20—21
off air monitoring, 1.2-21
violations, 1.2-21
monitoring stations 1.2-20
regional director, 1.2-20
Public Service Division, 1.2-19—20
Mass Media Bureau (MMB), 1.1-3
Audio Services Division, 1.1-3—4
AM branch, 1.1-4
Auxillary Services Branch, 1.1-4
FM Branch, 1.1-4
Enforcement Division, 1.1-4
Complaints and Investigations Branch, 1.1-4
Equal Employment Opportunity Branch, 1.1-4
Fairness/Political Broadcasting Branch, 1.1-4
Hearing Branch, 1.1-4
Policy and Rules Division, 1.1-4—5
Allocations Branch, 1.1-5
Legal Branch, 1.1-5
Policy Branch, 1.1-5
Technical and International Branch, 1.1-5
Video Services Division, 1.1-4
Cable Television Branch, 1.1-4
Distribution Service Branch, 1.1-4
Low Power Television Branch, 1.1-4
Television Branch, 1.1-4
Office of Administrative Law Judges (ALJ), 1.1-3
Office of General Counsel (OGC), 1.1-3
Office of Managing Director (OMD), 1.1-1
Office of Plans and Policy (OPP), 1.1-3
Office of Science and Technology, (OST), 1.1-3
Private Radio Bureau (PRB), 1.1-3
Review Board (RB), 1.1-3
FCC Service Contours, 2.5-122
Fiber Optics, 4.4-93—103
characteristics, 4.4-95—97
advantages, 4.4-93
attenuation or loss, 4.4-97
disadvantages, 4.4-94
dispersion, 4.4-96—97
index of refraction, 4.4-95
modes, 4.4-96
light and fiber characteristics, 4.4-94
multimode graded index, 4.4-96
multimode step index, 4.4-96
optical fibers, 4.4-95
single or mono modes step index, 4.4-96
types, 4.4-95—96
video link, 4.4-93—103
bandwidth, 4.4-93—94
digital multiplexing, 4.4-100
dimensions, 4.4-94
economics, 4.4-94
electromagnetic interference (EMI), 4.4-94
frequency modulation, 4.4-99
installation, 4.4-100—101
cable specifications, 4.4-101
intensity modulation, 4.4-96
loss, 4.4-94
modulation technique, 4.4-98
multiple video transmission, 4.4-99
optical device characteristics, 4.4-97
detectors, 4.4-97
sources, 4.4-97
pulse code modulation (digital), 4.4-99
system planning, 4.4-101
test equipment, 4.4-102—103
transmission techniques, 4.4-98
trouble shooting, 4.4-103
wavelength division multiplexing, 4.4-99—100
Field Strength, 2.7-203—216
AM Proof of Performance, 2.8-217—234
analysis of measurement to direct coverage, 2.7-212—213
antenna supporting mast, 2.7-211
attenuation, 2.4-64
chart recorder, 2.7-211
coverage measurement, 2.7-204—206
definition, 2.4-64
emergency procedures, 2.7-214—215
equipment principles, 2.7-207
FCC measurement method, 2.7-212

FM field strength, 2.7-203
Fresnel zone radius formula, 2.7-206
horizontal RMS field strength, 2.4-78
inverse distance field, 2.4-64
measurement procedures and techniques, 2.7-212—213
meters, 2.7-209—210
power supplies, 2.7-211
precautions, 2.7-215—216
propagation, 2.7-207
receiving antennas, 2.7-210—211
spurious emission, 2.7-207
surveys, 2.7-213
television field strength, 2.7-203
time variation, 2.7-213—214
transmitting system evaluation, 2.7-206
(*See* AM Directional Arrays, and FM Antennas)
Film, 5.8-137—157
audio, 5.8-146—148
film density to electronic output, 5.8-138—140
low contrast print films, 5.8-138
recommended practices, 5.8-149—154
scanner, 5.8-140—143
slides, 5.8-148—149
splicing, 5.8-154—155
storage, 5.8-155—157
telecines, 5.8-142—146
television pictures 5.8-140
Film Chains, 7.1-44
telecines, 5.8-142—146
Flat Panel Antennas, 2.5-133
Fraunhofer Region (far field), 2.6-157
Frequency Analysis, 7.9-187—190
real time analyzer (RTA), 7.9-189—190
fast Fourier transform analyzer, 7.9-190
parallel analysis, 7.9-189
swept frequency, 7.9-188—189
Frequency Coordination, 1.3-49—62, 4.3-87
satellite antenna site selection, 4.3-87
aural STL considerations, 1.3-57—59
benefits for microwave users, 1.3-61
committee formation, 1.3-53—55, 62—64
coordination considerations, 1.3-51—52
history, 1.3-49—51
interference, 1.3-62
propagation anomalies, 1.3-59—61
television microwave considerations, 1.3-59—61
terrain considerations, 1.3-51
user density, 1.3-51
Frequency Modulation (FM), 3.3-63—111
characteristics, 3.3-63—65
FCC transmission standards, 3.3-65
high fidelity, 3.3-64—65
occupied bandwidth, 3.3-64—68
reduced noise, 3.3-63—65
stereo transmission, 3.3-65
subcarrier transmission, 3.3-65
combined transmitters, 3.3-98—101
filterplexing, 3.3-101—103
hybrid combiners, 3.3-99—101
hybrid couplers, 3.3-98—99
hybrid splitting, 3.3-101
installation, 3.3-108
maintenance, 3.3-110—111
operational measurements, 3.3-103—107
asynchronous AM, 3.3-107
audio frequency response measurement, 3.3-105
audio performance measurement, 3.3-105
carrier frequency measurement, 3.3-104
FM modulation measurement, 3.3-103—104
exciter, 3.3-75-79—80
metering, 3.3-79
output stage, 3.3-80
packaging, 3.3-80
field strength, 2.7-203
history, 3.3-63
logging of transmitter operating parameters, 3.3-104—105
power amplifier output circuits, 3.3-88—91
folded-half-wavelength cavity, 3.3-89—90
output coupling, 3.3-90—91
power amplifier cavity, 3.3-88—89
power amplifier source impedance, 3.3-91
quarter-wavelength cavity, 3.3-89
power supplies, 3.3-91
polyphase power supplies, 3.3-92
single phase power supplies, 3.3-92
special power supplies, 3.3-92—93
step start, 3.3-93
RF intermodulation, 3.3-102—103
RF output low-pass filters, 3.3-95—96
notch filters, 3.3-96
RF power amplifiers, 3.3-80
bandwidth considerations, 3.3-81
Gysel, 3.3-84
intermediate power amplifies IPA, 3.3-81
"N-Way", 3.3-83—84
performance requirements, 3.3-81
power output requirements, 3.3-80—81
solid state IPA systems, 3.3-83
splitter combiner, 3.3-83—84
RF power output, 3.3-104
signal noise ratio, 3.3-106
harmonic distortion, 3.3-106
total harmonic distortion (THD), 3.3-106
solid state FM transmitters, 3.3-85
standing wave ratio-SWR, 3.3-96—97
synchronous AM, 3.3-107
theory, 3.3-65—68
angular modulation, 3.3-65—66
Bessel Nulls, 3.3-67—68
Bessel function, 3.3-66—67
FM sideband structure, 3.3-66—67
modulation index equation, 3.3-65
phase modulation (PM), 3.3-65
theory, 3.3-65—66
transmission line power, 3.3-96—98
transmitters, 3.3-63—111
direct FM, 3.3-75
limiting factors, 3.3-71
modulator linearity, 3.3-76
pre-emphasis, 3.3-72—73
RF path, 3.3-71
transmitter control systems, 3.3-93—95
automatic power control-APC, 3.3-94
controller back-up systems, 3.3-94
microprocessor control systems, 3.3-94
purpose, 3.3-93
remote control interfacing, 3.3-95
"Turn-Around Loss", 3.3-102—103
transmitter tuning, 3.3-107—108
vacuum tube power amplifier circuits, 3.3-85
cathode-driven triode amplifiers, 3.3-85
grid-driven tetrode and pentode amplifiers, 3.3-86—87
grounded grid versus grid-driven tetrode operation, 3.3-86
impedance matching into the grid, 3.3-87
neutralization, 3.3-88
Frequency Monitors, 3.8-211—215
Fresnel, 5.2-43
Fresnel Zone, 2.5-121—122
diagram, 2.5-121
formula, 2.5-121
graph, 2.5-121
Fresnel Zone radius Formula, 2.7-206

—G—

Genlock, 5.4-82—84
Geosynchronous orbit, 4.3-79
Ground Systems, 2.4-67,110
  grounding, 2.2-23
  (*See* lightning)

—H—

Harris Linear AM Stereo System (*See* AM Stereo)

—I—

Illumination Engineering Society of North America (IES), 1.6-44
Institute of Electrical and Electronic Engineers (IEEE), 1.6-91—92
  Broadcast Technology Society, 1.6-91—92
  standards, 1.6-92
Instructional Television Fixed Service (ITFS), 7.5-115—122
Insulated Tower Base Impedance, 2.4-64—65
Interference
  channel 6/FM antenna problem 2.5-128—129
    alternate locations, 2.5-129
    alternate polarization, 2.5-129
    collocation, 2.5-128—129
    rejection filters, 2.5-129
  FM, 2.5-152
  low power television, 7.4-100—104
  microwave, 4.2-71, 6.2-25—27
  translators, 7.4-100—104
  (*See* Federal Communications Commission, Frequency Coordination, and satellite systems)
Interstage Coupling Circuits, 3.3-81—83
Inverse Distance Field (*See* Field Strength)
Ionosphere, 2.9-236

—K—

Kahn-Hazeltine Independent Sideband System (*See* AM Stereo)
Klystrons, 3.5-155—162
  cavity tuning, 3.5-157
  efficiency, 3.5-158
  external cavity Klystron tuning, 3.5-158—159
  incidental phase, 3.5-162
  linearity correction, 3.5-162
  magnetic field, 3.5-157
  mod anode, 3.5-156—157
  mod anode pulsing, 3.5-160
  perveance, 3.5-156
  power calibration, 3.5-158
  pulsing, 3.5-160
  RF drive power, 3.5-157—158
  S Klystron visual, 3.5-161—162
  transmission line coupling, 3.5-157
  tuning, 3.5-158
  variable coupler for integral cavity, 3.5-161
Ku Band, 4.3-79

—L—

Leadicon, 5.3-63
Lightning protection, 2.3-23—31
  lightning conductor voltage drop (with formula), 2.2-23
  sideflash, definition, 2.2-23—24
  touch voltages, definition, 2.2-23
  step voltages, definition, 2.2-23
  surge suppression, 2.2-24—31
    balance line suppressor, 2.2-30
    balance pairs-2.2-30
    components, 2.2-26—27
      gas tubes, 2.2-26
      metal oxide varistors (MOV), 2.2-26—27
      silicon avalanche devices, 2.2-27
      spark gaps, 2.2-26
    criteria, 2.2-26
    equipment suppressor, 2.2-28—29
      diagram, 2.2-28
    low level audio circuits, 2.2-30
    primary suppressor, 2.2-28
    RF circuit protection, 2.2-30
      shielding, 2.2-30—31
    secondary suppressor, 2.2-28
      diagram, 2.2-29
    surge protection, 2.2-29
      single (non-paired) conductors, 2.2-29
        diagram, 2.2-29
    video circuit protection, 2.2-30
    video surge protection, 2.2-30
Local Area Network (LAN), 7.6-140
Low Power Television Systems (LPTV), 1.1-7
  (*See* translators)

—M—

Magnetic Recording, 5.7-121—136, 5.11-217
  (*See* video tape recording and editing)
  AC bias 5.11-219—221
    optimum bias, 5.11-220—221
    penetration, 5.11-221
  alignment, 5.11-223
    azimuth, 5.11-223
    height, 5.11-223
    meridian, 5.11-223
    mono sum loss, 5.11-225
    speed, 5.11-225
    tape format, 5.11-225
    zenith, 5.11-223
  cleaning, 5.7-122—125
  equalization, 5.11-222—223
  head contour effects, 5.11-223
    history, 5.11-217—218
  maintenance, 5.11-233
    alignment, 5.11-237
    azimuth, 5.11-236
    cleaning, 5.11-236
    demagnetization, 5.11-235
    distortion, 5.11-236
    frequency response, 5.11-236
    head cleaning, 5.11-234
    noise, 5.11-236
    path cleaning, 5.11-235
    performance check, 5.11-236
    phase response, 5.11-236
    test tapes, 5.11-237
    torque, 5.11-236
    wow and flutter, 5.11-236
  operation, 5.7-122—125
  playback process, 5.11-221—222
    gap loss, 5.11-221
    recorded wavelength, 5.11-221
    speed, 5.11-222
  practice, 5.7-122—125
  principles, 5.7-127—136
  self erasure, 5.11-221
  storage, 5.7-125

system performance, 5.11-225
encode-decode system, 5.11-225
Dolby A™, 5.11-225
Dolby B™, 5.11-225
Dolby C™, 5.11-225
Dolby Labs™, 5.11-225
Dolby™, 5.11-225
dBx™, 5.11-225
fluxivity, 5.11-225
high coecivity, 5.11-225
remenance, 5.11-225
single-ended noise reduction systems, 5.11-225
DNR, 5.11-226
Dynafex, 5.11-226
modulation noise, 5.11-226
tape, 5.11-218—219
composition, 5.11-218—219
type, 5.11-218—219
tape machine electronics, 5.11-226
bias, 5.11-226
control, 5.11-228—230
equalization, 5.11-226—228
flux level, 5.11-233
interfacing, 5.11-230
audio, 5.11-230
remote control, 5.11-230
performance, 5.11-231
reference level, 5.11-233
Maintenance
towers (*See* tower maintenance), transmitters (*See* individual listing)
Matching networks, 2.4-95—97
L networks, 2.4-95—97
diagram, 2.4-96—97
power divider, 2.4-97—99
diagrams, 2.4-98
ohms-law divider, 2.4-97
simplification, 2.4-99
tank-type divider, 2.4-97
T networks, 2.4-95
Metal Oxide Varistors (MOV), 2.2-26—27
Medium Wave (*See* AM amplitude modulation)
Microphones, 5.6-115—116, 5.12-239
cardioid microphone, 5.6-116
care, 5.12-260
condenser microphone, 5.6-116
directional microphone, 5.6-116
distance, 5.12-249—250
acoustic gain devices, 5.12-249—250
distant miking, 5.12-250
frequency response, 5.12-250
shotgun, 5.12-249
durability, 5.12-252—253
dynamic microphone, 5.6-115
dynamic range, 5.12-252
frequency response, 5.12-243—244
noise problem, 5.12-253—258
AC hum, 5.12-255
acoustic phase interference, 5.12-255—258
acoustic phase cancellation, 5.12-258
high-pass filter, 5.12-253
popfilter, 5.12-253
radio frequency interference (RFI), 5.12-253
omnidirectional microphone, 5.6-116
output impedance, 5.12-252
phantom power, 5.12-242—243
polar patterns, 5.12-244
bidirectional, 5.12-244
cardioid, 5.12-244—248
dynamic range, 5.12-244—245
headset microphones, 5.12-249
inverse square law, 5.12-248—249
omnidirectional, 5.12-244—248
polar scaling, 5.12-244—245
supercardioid, 5.12-244
polarity reversal, 5.12-258—259
reliability, 5.12-252—253
ribbon microphone, 5.6-115
sensitivity rating, 5.12-250
EIA sensitivity rating, 5.12-251
line-level microphones, 5.12-252
open circuit output voltage, 5.12-250
power level, 5.12-251
stereo miking, 5.12-259—260
Blumfein technique, 5.12-260
mid-side coincident technique (M-S), 5.12-259
transducer, 5.12-239
carbon, 5.12-239
condenser, 5.12-242
electret, 5.12-242
dynamic microphones, small size, 5.12-241
dynamic moving coil, 5.12-240—241
dynamic ribbon, 5.12-239—240
wireless microphone, 6.1-17
Microwave EFP, 6.2-19
airborne considerations, 6.2-25—27
frequency considerations, 6.2-19—20
receive site, 6.2-20, 24—25
remote control, 6.2-25
tower, 6.2-20
van, 6.2-21—24, 25
(*See* Frequency Coordination)
Microwave ENG, 6.2-19—27
van, 6.2-21—24, 25
(*See* Frequency Coordination)
Microwave Systems, 4.2-59—77
antenna and wave guide considerations, 4.2-64
antenna feeders, 4.2-67
antenna systems, 4.2-64—65
horns, 4.2-66
isotropic antenna, 4.2-65—67
omni, 4.2-66
parabolas, 4.2-66
passive reflectors, 4.2-66
FCC licensing, 4.2-77
(*See* Frequency Coordination)
frequency planning, 4.2-76
heterodyne television microwave, 4.2-73
passive repeaters, 4.2-68—69
repeaters, 4.2-64
power, 4.2-75
power supplies, 4.2-73
receivers, 4.2-71
subcarriers, 4.2-74
transmitters, 4.2-70
K factor, 4.2-61—64
clearance requirements, 4.2-61
path profiles, 4.2-64
path performance, 4.2-59—61
free space path loss, 4.2-59—60
source of path loss, 4.2-60
MOV (*See* Metal Oxide Varistor)
Modems, 7.6-138
Modulation Monitors, 3.8-211—215
calibration, 3.8-215
features, 3.8-212—214
FCC rules, 3.8-211—212
maintenance, 3.8-215
monitoring techniques, 3.8-214—215
Monochrome Television System, 7.1-4
Motorola C-Quam AM Stereo System (*See* AM Stereo)
Multichannel Television Sound (BTSC System), 3.6-185
Broadcast Television Systems Committee (BTSC), 3.6-185—186
objective, 3.6-186
companding system, 3.6-189

amplitude compression, 3.6-190
fixed preemphasis, 3.6-190
noise reduction, 3.6-189—190
separate audio program channel (S.A.P.), 3.6-190
spectral compression, 3.6-190
compatibility, 3.6-194
Electronic Industries Association, 3.6-185—186
operation, 3.6-194—196
stereo subcarrier, 3.6-187—188
monophonic channel, 3.6-187
pilot carrier, 3.6-188
subcarriers, 3.6-191
"Common Mode" phase modulation, 3.6-193
incidental carrier phase modulation (ICPM), 3.6-193
intercarrier sound receivers, 3.6-193
performance specifications, 3.6-191—193
Multiplexers, 2.4-105—106
Multiplication Of Two Tower Patterns (*See* AM Directional Arrays)
Multipoint Distribution Service (MDS), 7.5-115—122
antenna, 7.5-120
amplifiers, 7.5-120
block diagram, 7.5-117
down converter/receiver, 7.5-119—121
multichannel MDS, 7.5-115
RF system, 7.5-115—117
repeater, 7.5-119—120
response channels, 7.5-121—122
transmitters, 7.5-117—118
Mutual Impedance Curves (AM directional antenna), 2.4-76—77

—N—

National Association of Broadcasters (NAB), 1.6-91
phone list, 1.6-91
publications, 1.6-91
National Bureau of Standards, 1.6-87—88
Time and Frequency Division, 1.6-87—88
WWV, 1.6-87—88
WWVB, 1.6-87—88
WWVH, 1.6-87—88
National Cable Television Association (NCTA), 1.6-91
National Industry Advisory Committee, 7.8-181—183
National Labor Relations Board, 1.6-89
National Labor Relations Act, 1.6-89
National Telecommunications and Information Administration (NTIA) 1.6-88
National Television System Committee system (NTSC), 7.1-52, 54—58
Nondirectional AM Antennas, 2.4-64—67
current and voltage distribution, 2.4-64—65
chart and formula, 2.4-64
folded conical monopole, 2.4-65—66
chart, 2.4-66
ground systems, 2.4-67
ground towers, shunt fed and folded monopole 2.4-65
insulated tower base impedance, 2.4-64—65
chart, 2.4-65
sectionalized towers, 2.4-66
top loading, 2.4-66
vertical radiation characteristics, 2.4-64
Nonionizing Radiation (design consideration), 2.6-157, 163
charts, 2.6-164, 2.8-218

—O—

Occupational Safety and Health Act (OSHA), 1.6-88
Omnidirectional Microphone, 5.6-116
Operational Amplifiers, 7.2-69—75
active filters, 7.2-73
equalizers, 7.2-73
Optical Fibers, 4.4-95

—P—

PMX AM Stereo (*See* AM Stereo)
Partial Proof, 2.8-220—221
Phase Locked Loop AFC, 3.3-77—78
Phase Modulation (PM), 3.3-65
Plumbicon, 5.3-63
Power Systems, (*See* Electrical Systems)
Propagation, 2.9-235
above thirty megahertz, 2.9-241
smooth earth conditions, 2.9-241
K factor, 2.9-242
allocations, 2.9-236
beyond line-of-sight conditions, 2.9-242—243
coverage areas, 2.9-248—249
electromagnetic spectrum, 2.9-235
FM, 2.5-118—120
propagation loss, 2.5-118—119
multi-path problems, 2.5-119—120
diagram, 2.5-119
reflections, 2.5-119—120
ground reflections, 2.5-120
diagram-2.5-120
(*See* Brewster Angle)
free space propagation, 2.9-237—240
earth surface, 2.9-238—239
plane earth, 2.9-239—240
antenna heights, 2.9-239
dielectric constants, 2.9-240
effects, 2.9-239
ground conductivity, 2.9-240
horizontal polarization, 2.9-240
vertical colorization, 2.9-239
medium frequency (AM), 2.9-240
ground waves, 2.9-240
interference, 2.9-241
sky waves, 2.9-240—241
ionosphere, 2.9-240
solar activity, 2.9-241
obstacles, 2.9-243
atmospheric refraction, 2.9-247
refractive index, 2.9-247
buildings, 2.9-246
co-channel interference, 2.9-247
ducting, 2.9-247
hills, 2.9-244—246
vegetation, 2.9-246
quantifying propagation, 2.9-236
D layer, 2.9-236
E layer, 2.9-236
F1 layer, 2.9-237
F2 layer, 2.9-237
ionosphere, 2.9-236
stratosphere, 2.9-236
troposphere, 2.9-236
rain attenuation, 2.9-248
absorption, 2.9-248
(*See* VHF, UHF, AM, FM, Microwave, Satellite, and Frequency Coordination)
Pulse Code Modulation (digital), 4.4-99

—Q—

Quadruplex recorders, 5.5-90—91
Quadruplex Video Tape Recorders, (*See* Video Systems)

—R—

Radar (Weather), 7.7-159
Radio Electronic News Gathering (RENG), 6.1-1—10
  antenna, 6.1-10
  planning, 6.1-1
  remote pickup unit (RPU), 6.1-5
  wireless microphone, 6.1-17
  wireless systems, 6.1-2—4
    equipment, 6.1-3—4
RF Circuit Protection (lightning), 2.2-30
RF Switching, 2.10-251
  diplexers, 2.10-258—261
    Tee diplexer, 2.10-258
  filters, 2.10-253
    band pass filters, 2.10-254—258
    band stop filters, 2.10-254—258
    harmonic filters, 2.10-254
  multiplexer, 2.10-258—261
  patch panels, 2.10-251
    coaxial, 2.10-251
    waveguide, 2.10-251—252
  switches, 2.10-252—253
    manual coaxial switches, 2.10-252
    motorized coaxial switches, 2.10-252—253
    open wire switches, 2.10-253
    waveguide switches, 2.10-253
  transmitter systems, 2.10-261
    alternate main, 2.10-261
    parallel, 2.10-261
      AM, 2.10-262—263
      multi-transmitter different frequencies, 2.10-276—278
        coax system, 2.10-276—278
      shortwave, 2.10-262—263
      UHF, 2.10-271—275
        phaseshifters, 2.10-273—275
        switchless, 2.10-273—275
      VHF, 2.10-263—271
        switchless, 2.10-266—271
    single main, 2.10-261
Random Access Memory (RAM), 3.7-200
Read Only Memory (ROM), 3.7-200
Rectangular Waveguide, 2.3-52—59
  charts and graphs, 2.3-53—58
Remote Pickup Unit (RPU), 1.3-55—57, 61, 65, 1.5-79—81, 6.1-5
Ribbon Microphone, 5.6-115
RS170, 5.4-75

—S—

Safety, 2.1-5—6
  access facilities, 2.1-5—6
    elevator, 2.1-5—6
    ladder, 2.1-5
    stairways, 2.1-6
    transmission line bridges, 2.1-6
  (*See* lightning protection)
Sampling loops, 2.4-101
Satellite Systems, 4.3-79—91
  C Band, 4.3-79
  channeling, 4.3-79—80
  data on blanking interval, 4.3-84
  digital radio, 4.3-84
  earth station components, 4.3-84—87
    antenna, 4.3-84—85
      cassegrain antenna, 4.3-85
      horn antenna, 4.3-85
      multiple beam antenna, 4.3-85
      prime focus antenna, 4.3-84—85
    orthogonal mode transducer (OMT), 4.3-85
      low noise amplifier (LNA), 4.3-86
      low noise converter, 4.3-86
    site selection, 4.3-86
      coordination contour, 4.3-87
      frequency coordination, 4.3-87
      interference, 4.3-87—88
        equation, 4.3-87
  FCC licensing, 4.3-88
    installation, 4.3-88—90
    maintenance, 4.3-90—91
    operation, 4.3-90
  frequencies, 4.3-79—80
  frequency division multiplexed/FM (FDM/FM), 4.3-84
  geosynchronous orbit, 4.3-79
  Ku band, 4.3-79
  polarization, 4.3-79—80
  satellite link analysis, 4.3-80
  signal types, 4.3-83
    audio subcarrier, 4.3-83
    data, 4.3-84
    full transponder/FM video, 4.3-83
    half transponder/FM video, 4.3-83
    slow scan video, 4.3-84
    teletext, 4.3-84
  single channel per carrier (SCPC), 4.3-84
  system description, 4.3-79—84
  time division multiplexing (TDM), 4.3-84
  (*See* Frequency Coordination)
Saticon, 5.3-63
Scanner, film, 5.8-142—143
Scanning, Helical, (*See* Video Tape Recording)
Second Audio Program Channel (S.A.P.), 3.6-190
Security, Transmitter Site, 2.8-218
Sequential Coleur Avec Memoire (SECAM), 7.1-53, 61—63
Series Fed Antennas, 2.5-131
Shortwave, 3.1-25—26
Shunt Fed Antennas, 2.5-131
Single sideband AM subcarriers, 3.4-130
Slanted Dipole FM Antennas, 2.5-131
Slides, 5.8-148—149
Slow Scan Video, 4.3-84
Society of Broadcast Engineers, Inc. (SBE), 1.6-92
  certification program 1.6-92
Society of Motion Picture and Television Engineers (SMPTE),1.6-92—93
  Recommended Practice RP113-1983 Supervisory Protocol for Digital Control Interface, 5.10-198—216
  SMPTE time code, 5.5-104
Soil Conductivity, 2.4-113, 2.5-122
Stand-by power systems, (*See* electrical systems)
Standing Wave Ratio (SWR), 3.3-96—97 (*See* Voltage Standing Wave Ratio)
Stereophonic FM, 3.4-113—134
  baseband signal, 3.4-116—122
  frequency decoder circuits, 3.4-121
    phase locked loop, 3.4-121
  generators, 3.4-116—122
  performance, 3.4-128—130
  SCA to stereo interference, 3.4-131—134
  time division multiplex (TDM), 3.4-117, 119—121
  transmission standard, 3.4-116
Stratosphere, 2.9-236
Studio Lighting, 5.2-29—44
  architectural antenna, 5.2-36—38
    air conditioning, 5.2-37
    distribution, 5.2-37—38
    electrical, 5.2-36—38
    fixtures, 5.2-44
    Fresnel, 5.2-43
    lighting control, 5.2-38—44
    scoops, 5.2-43
  cyclorama, 5.2-34—36
  studio dimensions, 5.2-30
  suspension, 5.2-30—34

battens, 5.2-32
catwalks, 5.2-32
fixed grid, 5.2-30—31
modular grid, 5.2-34
winches, 5.2-32
Studio Transmitter Link (STL), 3.7-205
Subcarrier, color, 7.1-27—36
subcarrier frequency accuracies, 7.1-36
subcarrier frequency error, 7.1-27
(*See* Multichannel Television Sound)
Subcarrier, FM, 3.4-113—134
Bessel function analysis, 3.4-125
composite baseband, 3.4-113—115
frequency spectrum, 3.4-115
glossary of terms, 3.4-113—114
history, 3.4-122—133
interference, 3.4-123—124
modulation limits, 3.4-115
operation, 3.4-124—126
subsidiary communication authorization (SCA), 3.4-122—133
requirements for operation, 3.4-123
types, 3.4-124—135
automotive road information (ARI), 3.4-121
data systems, 3.4-126—128
autofrequency shift keying (AFSK), 3.4-126
crosstalk, 3.4-134—135
data multiplexing, 3.4-128
direct data modulation, 3.4-127—128
frequency division multiplexing (FDM), 3.4-128
frequency shift keying (FSK), 3.4-127
guard bands, 3.4-128
indirect data modulation, 3.4-126—127
interference, 3.4-131—134
performance, 3.4-128—130
Subsidiary Communication Authorization (SCA), 3.4-122—133
Surge Suppression, 2.2-24—31
(*See* lightning)
Synchronizing Generator, 5.4-82—85, 7.1-3
Synchronizing Waveform, 5.4-75

—T—

Tape, 5.11-218—219
composition, 5.11-218—219
type, 5.11-218—219
(*See* Magnetic Recording)
Telco (*See* Telephone Systems)
Telecine, (*See* film chain)
Telemetry, 3.7-207 (*See* Transmitter Control Systems)
Telemetry Return Link (TRL), 3.7-205
Telephone Systems, 6.4-41
access, 6.4-58
audio interfacing, 6.4-44—48, 55
hybrid, 6.4-45—48
QKT, 6.4-44—45
voice coupler, 6.4-44—45
cellular telephone, 6.4-52
digital telephone, 6.4-52
frequency shifting, 6.4-50—52
line test, 6.4-53—54
quality, 6.4-48—50
bandwidth, 6.4-49—50
processing, 6.4-41
satellites, 6.4-57
specification, 6.4-56
studio-transmitter link (STL), 6.4-53
switched network, 6.4-41—42
CODEC's, 6.4-41
frequency response, 6.4-41
phone pairs, 6.4-41
regulations, 6.4-42
signal to noise ratio, 6.4-42
C message weight, 6.4-42
subscriber loops, 6.4-41
switching circuit, 6.4-43—44
"A" leads, 6.4-43
HOLD, 6.4-43
lamp leads, 6.4-43
25 pair color code, 6.4-44
tip/ring, 6.4-43
terminal equipment, 6.4-42
key systems, 6.4-42—43
PBX, 6.4-42—43
types of lines, 6.4-56—57
Teletext, 4.3-84
Television Antennas, 2.6-155—201
antenna assembly, 2.6-200
antenna design, 2.6-172—173
half-wave dipole, 2.6-172—173
loop, 2.6-173
panels, 2.6-174—176
charts, 2.6-174—175
slot antenna, 2.6-173—174
traveling wave antenna, 2.6-176
antenna gain, 2.6-157, 180, 181
antenna test, 2.6-198—199
azimuth pattern (horizontal plane), 2.6-156—159, 176—180
beam tilt, 2.6-162
bridge diplexing, 2.6-182
charts, 2.6-164
circular polarization, 2.6-161—162
constant impedance notch diplexer, 2.6-182—184
deflection and wind load, 2.6-171
economics, 2.6-157—160
effective radiated power (ERP), 2.6-160—161
elevation pattern, 2.6-158—159
feed systems, 2.6-181
branching, 2.6-181
standing wave feed systems, 2.6-181—182
traveling wave, 2.6-182
Fraunhofer region (far field), 2.6-157
frequency of rotation (formula), 2.6-170
graphs, 2.6-165—167
horizontal pattern (formula), 2.6-167—168
input impedance, 2.6-157, 180—181
installation, 2.6-199—200
maintenance, 2.6-200—201
multichannel television sound diplexer, 2.6-184—186
multiple antennas, 2.6-186
multiple cavities, 2.6-186
nonionizing radiation (design consideration), 2.6-157, 163
charts, 2.6-164
null fill, 2.6-166
pattern, 2.6-164—168, 176—186
pattern tests, 2.6-198
power capability, 2.6-162—163
radiating characteristics, 2.6-158—160
refectometer test, 2.6-199
systems planning, 2.6-187—188
antenna mounting methods, 2.6-186
emergency provisions, 2.6-187
antenna, 2.6-187
RF switching feature, 2.6-187—188
standby provisions, 2.6-187
transmission lines, 2.6-187
layout of transmission lines, 2.6-186—188
load location, 2.6-187
RF filter networks, 2.6-187
transmission line run, 2.6-186—187
propagation study, 2.6-186
system tests, 2.6-169
time domain reflectometers (TDR), 2.6-169
transmission line and components, 2.6-169
transmitter power, 2.6-157

types, 2.6-188
cloverleaf panel, 2.6-195
CPV antenna, 2.6-193—194
delta dipole antenna, 2.6-189—190
Fan-Vee antenna, 2.6-193
pylon circular polarized, 2.6-197
pylon-UHF, 2.6-195—196
rhombic/butterfly panels, 2.6-193
ring panel, 2.6-195
slot-director antenna, 2.6-197
spiral antenna, 2.6-194
TDM antenna, 2.6-194
trasar-circular polarized, 2.6-197—198
travelling wave antenna, 2.6-190—193
UHF antenna linear polarized, 2.6-195
VHF circular polarized antenna, 2.6-193
VHF super turnstile/batwing, 2.6-188—189
wave star (omni), 2.6-196
zig-zag, 2.6-196
uniform field distribution (formula), 2.6-164
vertical alignment, 2.6-200
vertical pattern (elevation model), 2.6-157
vertical patterns, 2.6-164—166
Voltage Standing Wave Ratio (VSWR), 2.6-168—170
Television Field Production, 6.3-29—40
electronic field production, 6.3-39
electronic news gathering, 6.3-39
equipment, 6.3-32
cameras, 6.3-32—34
recorders, 6.3-34—35
switching, 6.3-35—38
operation, 6.3-38—40
microwave considerations, 1.3-59—61
(*See* microwave systems)
Television Signal Transmission Standards, 4.1-1—50
amplitude versus frequency response, 4.1-49
audio-video time differential, 4.1-51
chrominance-luminance delay in equality, 4.1-18—19
chrominance-luminance gain in equality, 4.1-16—17
chrominance non-linear gain in distortion, 4.1-24—25
chrominance non linear phase distortion, 4.1-26—27
chrominance to luminance intermodulation, 4.1-36—37
continuity of audio service, 4.1-50
crosstalk noise, 4.1-44
differential gain, 4.1-32—33
differential phase, 4.1-34—35
dynamic gain, 4.1-30—31
field time wave form distortion, 4.1-10—11
gain frequency distortion, 4.1-20—21
harmonic distortion, 4.1-49
impulsive noise, 4.1-41
insertion gain, 4.1-8—9, 50
interconnection requirements, 4.1-95
line time wave form distortion, 4.1-12—13
luminance nonlinear distortion, 4.1-22—23
measuring techniques, 4.1-5—7
parameters, 4.1-5—7
performance, 4.1-5-7
performance standards for relay facilities, 4.1-2—3
periodic noise, 4.1-42-4-3
random noise weighted, 4.1-38—40
relative burst gain error, 4.1-47
relative burst phase error, 4.1-47
short time wave form distortion, 4.1-14—15
signal to noise ratio, 4.1-49—50
Television Transmitters, 3.5-137—183
aural exciter, 3.5-149—155
BTSC Multichannel Sound System, 3.5-149—150
companding, 3.5-151
maskings, 3.5-151—152
noise, 3.5-151
preemphasis, 3.5-152
spectral companding, 3.5-152
transient protection, 3.5-153
transmitter requirements, 3.5-153—155
wideband amplitude companding, 3.5-153
combining circuits, 3.5-173—177
frequency control, 3.5-177—180
modulator, 3.5-142—149
active group delay equalizer, 3.5-145—146
delay compensators, 3.5-143—145
IF linearity precorrection, 3.5-147—149
passive group delay equalizer, 3.5-145
vestigal sideband filter, 3.5-146—147
performance measurements, 3.5-180—182
principles, 3.5-138—141
fields, 3.5-138
frames, 3.5-138
horizontal interval, 3.5-138—139
measurement units, 3.5-138
NTSC color transmission system, 3.5-141
picture, 3.5-138
vertical interval, 3.5-139—140
test signals (VITS), 3.5-140
RF generator, 3.5-149
tetrodes, 3.5-162—173
triodes, 3.5-162—173
UHF Klystrons, 3.5-155—162
cavity tuning, 3.5-157
efficiency, 3.5-158
external cavity Klystron tuning, 3.5-158—159
incidental phase, 3.5-162
linearity correction, 3.5-162
magnetic field, 3.5-157
mod anode, 3.5-156—157
mod anode pulsing, 3.5-160
perveance, 3.5-156
power calibration, 3.5-158
pulsing, 3.5-160
RF drive power, 3.5-157—158
S Klystron visual, 3.5-161—162
transmission line coupling, 3.5-157
tuning, 3.5-158
variable coupler for integral cavity, 3.5-161
video processing, 3.5-141—142
clamp circuit, 3.5-141—142
video precorrection, 3.5-142
visual exciter, 3.5-137
Time Division Multiplex (TDM), 3.4-117, 119—121
time division multiplexing, 4.3-84
Total Harmonic Distortion (THD), 3.3-106
Towers, 2.1-1—20
access facilities, 2.1-5—6
elevator, 2.1-5—6
ladder, 2.1-5
stairways, 2.1-6
transmission line bridges, 2.1-6
aircraft marking, 2.1-5
design standards, 2.1-8—9
industry, 2.1-8
statutory, 2.1-9
finishes 2.1-5
corrosion protection, 2.1-1
electroplating, 2.1-5
flamespraying, 2.1-5
hot-dip galvanizing, 2.1-5
zinc rich paint, 2.1-5
FM antenna installation on AM towers, 2.5-141—145
grounded towers, 2.4-65
guyed, 2.1-2—3
diagram, 2.1-3
ice prevention, 2.1-5—6
insulated tower base impedance, 2.4-64—65
insulators, 2.1-4—5
base insulators, 2.1-4
guy insulators 2.1-4—5

sectionalizing insulators, 2.1-4
materials, 2.1-3—5
guys, 2.1-4
self-supporting towers, 2.1-1—2
chart, 2.1-2
structures, 2.1-3—4,9—15
allowable stresses, 2.1-12—13
ice load, 2.1-9—10
safety factors, 2.1-12—13
seismic loads, 2.1-11
temperature changes, 2.1-10—11
width restrictions, 2.1-13—15
antenna mounting, 2.1-13—14
foundation and anchors, 2.1-14—15
construction, 2.1-15
guy anchors, 2.1-15
guyed tower base foundations, 2.1-15
self-supporting tower foundations, 2.1-15
soil investigation, 2.1-15
wind load, 2.1-9
chart-2.1-10
Tower Construction, 2.1-15—17
assembly, 2.1-16
chart, 2.1-16
guy installation, 2.1-17
preparation, 2.1-16
access, 2.1-16
clearing, 2.1-16
electrical power, 2.1-16
permits, 2.1-16
stacking, 2.1-16—17
Tower Lighting, 2.1-6
Blondel-Ray relationship, 2.1-7
candella, definition, 2.1-7
FAA requirement, 2.1-6—7
medium intensity electronic lights, 2.1-7
red lights with orange and white paint, 2.1-6—7
Tower Maintenance, 2.1-17—20
structure
alignment, 2.1-17—18
base insulator, 2.1-19—20
condition of paint, 2.1-17
connections, 2.1-17
corrosion, 2.1-17
damage or deformed member, 2.1-17
elevator system, 2.1-20
lighting system, 2.1-20
safety device, 2.1-20
Translators, 7.4-95—114
coverage, 7.4-101—104
input signal considerations, 7.4-104
antenna stacking, 7.4-105
filtering 7.4-105
preamplification, 7.4-104—105
installation, 7.4-111—113
power, 7.4-111—113
protection, 7.4-112
security, 7.4-112
shelter, 7.4-111—112
multiple outputs, 7.4-95
offset operation, 7.4-114
regulatory requirements, 7.4-100—101, 110
FM, 7.4-100—101
low power television (LPTV) application, 7.4-110
television, 7.4-100—101
site selection, 7.4-95
block diagrams, 7.4-95—99
stereo television (BTSC system), 7.4-113
Surface Acoustic Wave (SAW), 7.4-113
SAW filters, 7.4-113—114
transmitting systems, 7.4-105—108
antennas 7.4-106
combiners 7.4-107—108
isolators, 7.4-107—108
noise, 7.4-108
towers, 7.4-107
transmission lines, 7.4-106—107
air dielectric, 7.4-106—107
foam dielectric, 7.4-107
voltage standing wave ratio, 7.4-107—108
UHF translator, 7.4-108—111
amplifier stages, 7.4-110
mixing process, 7.4-110
output circuitry, 7.4-110
specifications, 7.4-111
UHF input, 7.4-108
VHF input, 7.4-108—110
Transmission Lines, 2.3-33—62, 2.4-100—101, 110
characteristic impedance, 2.4-100
coaxial transmission lines, 2.3-33—36
graphs, 2.3-34—35
dead load, 2.1-13
indoor installation considerations, 2.3-51
installation-run considerations, 2.3-50—52
dimensions, 2.3-52
horizontal, 2.3-51
vertical, 2.3-50—51
jacketing, 2.4-100
line losses, 2.4-100
line mismatch, 2.4-101
moisture (from new line), 2.3-51
phase-stabilized line, 2.4-100—101
rigid coaxial transmission line, 2.3-40—52
features, 2.3-40
transmission line section length, 2.3-40
charts and graphs, 2.3-41—50
formula, 2.3-40
reflection, 2.3-40
semi-rigid transmission line, 2.3-36
chart, 2.3-36—39
diagram, 2.3-37—38
installation, 2.3-36—40
preparation, 2.3-36
hanger installation, 2.3-36—39
horizontal runs, 2.3-39
ice loading, 2.3-36—40
ice shields, 2.3-36—40
power handling of semi-rigid transmission lines, 2.3-40
pressurization, 2.3-40
transmission line fittings, 2.4-101
wave guides (*See* listing)
wind load, 2.1-13
Transmitter Control Systems, 3.7-197—210
AM base currents, 3.7-208
analog block diagram, 3.7-199
control terminal, 3.7-202—204
FCC regulations, 3.7-198—199
filament voltage, 3.7-209
line voltage, 3.7-209
modulation monitors, 3.7-210
power supply, 3.7-208
RF power input, 3.7-208
remote control, 3.7-200—202
digital, 3.7-201
remote terminal, 3.7-204—205
status input, 3.7-209
studio transmitter link (STL), 3.7-205
telemetry return link (TRL), 3.7-205
television monitoring equipment, 3.7-209
temperature, 3.7-209
terminal communication, 3.7-205—206
theory, 3.7-199—200
binary coded decimal (BCD), 3.7-200
electronically erasable programmable ROM (EEPROM), 3.7-200
random access memory (RAM), 3.7-200

read only memory (ROM), 3.7-200
tower lights, 3.7-208
transmitter facility interfacing, 3.7-206—208
command, 3.7-207
control, 3.7-207
metering, 3.7-207
plate current, 3.7-207—208
plate voltage, 3.7-207
telemetry, 3.7-207
transmitter to studio link (TSL), 3.7-205
types, 3.7-197—198
wireless communications, 3.7-206—207
Transmitter to Studio Link (TSL), 3.7-205
Troposphere, 2.9-236
"Turn-Around Loss," 3.3-102—103
Turntables, 5.6-113—115

—U—

U-format, (*See* Video Systems)
U-matic, (*See* Video Systems)
UHF, (*See* Klystron)
Underwriters Laboratories (UL), 1.6-94

—V—

Vacuum Tube Power Amplifier Circuits, 3.3-85
cathode-driven triode amplifiers, 3.3-85
grid-driven tetrode and pentode amplifiers, 3.3-86—87
grounded grid versus grid-driven tetrode operation, 3.3-86
impedance matching into the grid, 3.3-87
neutralization, 3.3-88
Video, 5.4-73
Video Signal Switching, 5.4-80—82
multiple bus switching, 5.4-80—82
single bus switchers, 5.4-80
switching system control, 5.4-82
Video Signal Timing, 5.4-82—83
genlock, 5.4-83—84
timing, 5.4-85—88
Video Systems
editing, (*See* Video Tape Editing)
half-inch format, 5.9-165—172
features, 5.9-168—170
control track, 5.9-168
editing features, 5.9-169
noise reduction, 5.9-169
recorders, 5.9-169
time code generator, 5.9-169
fundamentals, 5.9-165—166
Betacam format, 5.9-165
chrominance (C), 5.9-165, 168
component recording, 5.9-165—166
luminance (Y), 5.9-165, 168
MII-format, 5.9-165
M format, 5.9-165
maintenance, 5.9-170—171
cleaning, 5.9-170
head degaussing, 5.9-170
head drum slip rings, 5.9-170
pinchroller, 5.9-170
tape path, 5.9-170
video heads, 5.9-170
head optimization, 5.9-170
head replacement, 5.9-170
operational check, 5.9-170
tension check, 5.9-170
test equipment, 5.9-171
tools, 5.9-171
solder stations, 5.9-171
principles, 5.9-166—168
trouble shooting, 5.9-171—172
alignment tape, 5.9-172
audio system, 5.9-172
control system, 5.9-171
power supply, 5.9-172
servo system, 5.9-172
tape runs, 5.9-171—172
tension, 5.9-171
threading, 5.9-171
video system, 5.9-172
U-format, 5.9-159—163
color, 5.9-159—160
chrominance (C), 5.9-159—160
luminance (Y), 5.9-159—160
NTSC composite video signal, 5.9-160
drum, 5.9-159
effective drum diameter, 5.9-159
electronic switching, 5.9-162
helical-scan, 5.9-160—162
helix angle, 5.9-159
lower drum, 5.9-159
maintenance, 5.9-163
alignment tape, 5.9-164
audio system, 5.9-165
cleaning, 5.9-163
head degaussing, 5.9-163
head drum slip rings, 5.9-163
pinch roller, 5.9-163
tape path, 5.9-163
video heads, 5.9-163
control system, 5.9-164
head optimization, 5.9-163—164
head replacement, 5.9-163—164
operational check, 5.9-163
power supply, 5.9-165
servo system, 5.9-164
tape run, 5.9-164
tension, 5.9-164
tension detector adjustment, 5.9-163
threading, 5.9-164
troubleshooting, 5.9-164
video system, 5.9-165
scanner, 5.9-159—160
specifications, 5.9-162
features, 5.9-162
drop-out compensation, 5.9-162
dubbing, 5.9-162
editing, 5.9-162
search, 5.9-162
time base correctors, 5.9-162
time code generator, 5.9-162
SMPTE time code, 5.9-162
tracking, 5.9-162
track angle, 5.9-159
video heads, 5.9-160—162
wrap angle, 5.9-159
Video Tape Editing, 5.10-175
decision list, 5.10-184
design considerations, 5.10-194—195
disc technology, 5.10-176—178
edit commands, 5.10-178-1
edit timing, 5.10-178
editor control, 5.10-181—184
external devices, 5.10-195—197
hardware systems, 5.10-184—186
interfaces, 5.10-186—194
audio mixer, 5.10-192—193
audio tape recorder, 5.10-188
digital control interface, 5.10-198—215
digital video effects, 5.10-191—192
tape speed override (TSO), 5.10-187
video switcher, 5.10-188—191
preview system, 5.10-193—194

time code editing controller, 5.10-179—181
dialogue, 5.10-181
SMPTE time-code, 5.10-180, 187—188
sync error, 5.10-180
Video Tape Recording, 5.5-89—106
C-format helical recorder, 5.5-91—100
servo systems, 5.5-96
capstan, 5.5-96
tape tension, 5.5-96
tape transport, 5.5-91—95
control systems, 5.5-103—104
disc recorders, 5.5-106
formats, 5.5-106
history, 5.5-89—90
quadruplex recorders, 5.5-90—91
signal system, 5.5-100—101
modulation, 5.5-101
playback, 5.5-101
SMPTE time code, 5.5-104
time base correction, 5.5-102—103
digital time correctors, 5.5-102—103
video heads, 5.5-96—100
position, 5.6-96—98
video tape editing, 5.5-104
(*See* Magnetic Recording)
Voltage Standing Wave Ratio (VSWR), 2.6-168—170, 3.3-97
waveguides, 2.3-61—62
bandwidth, 2.5-129—130
intermodulation and AM distortion, 2.5-129—130

—W—

WWV, 1.6-87—88
WWVB, 1.6-87—88
WWVH, 1.6-87—88
Waveguides, 2.3-51—62
circular waveguide, 2.3-51—52
rectangular waveguide, 2.3-52—59
charts and graphs, 2.3-53—58
waveguide installation, 2.3-59—62
hangers, 2.3-59—61
horizontal, 2.3-59
installation, 2.3-60
vertical, 2.3-59
lateral braces, 2.3-59
materials, 2.3-59
pressurization systems, 2.3-61
storage, 2.3-60
Teflon probe, 2.3-61—62
tower top, 2.3-59
tuners, 2.3-60
tuning, 2.3-61—62
VSWR, 2.3-61—62
Weather Radar Systems, 7.7-159—165
colorizers, 7.7-161
conventional (noncoherent) Radar, 7.7-160
dial-up weather Radar data, 7.7-1—65
Doppler (coherent) Radar, 7.7-160
Radar (Radio Detection and Ranging), 7.7-159
history, 7.7-159
Naval Research Laboratory (NRL), 7.7-159
principles, 7.7-159
Radar displays, 7.7-160—161
digital video integration processor (DVIP), 7.7-160
plan position indicator (PPI scope), 7.7-160
range height indicator (RHI scope), 7.7-160
remoting, 7.7-161
typical applications, 7.7-162—165
Wide Band Antenna, 2.5-134—136
Wireless Microphone, 6.1-17