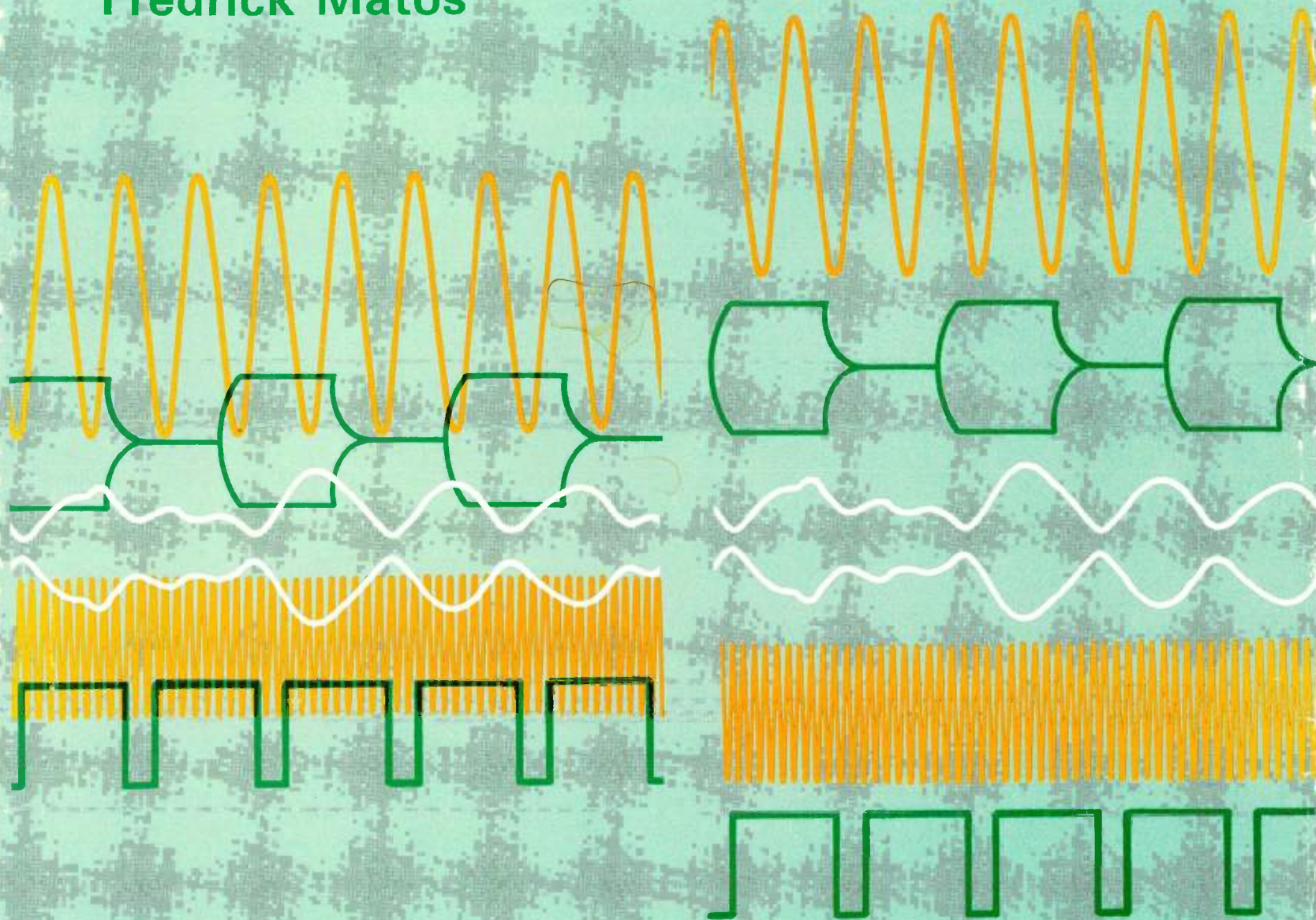


Spectrum Management and Engineering

Edited by
Fredrick Matos



**IEEE
PRESS**

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Spectrum Management and Engineering

Accelerated growth in the telecommunications field has placed increasing demands on the radio spectrum. Now, more than ever, there is need for a comprehensive book to aid professionals dealing with spectrum management and engineering. This book is meant to fill the void in the literature with its 51 papers from a variety of sources, some of which are very obscure and difficult to find. This collection will be current for years to come, making it an excellent resource for both the novice and the expert connected with any aspect of spectrum management and engineering.

The Editor has geared the contents to meet the needs of a diverse number of professionals concerned with spectrum management and engineering, i.e., communications engineers and managers, frequency engineers and managers, system planners, propagation scientists, radar and aerospace engineers, space law scholars, and telecommunications executives and attorneys. These professionals can easily locate their job-related topic in one of the following parts:

Part I: Legal and Regulatory

Part II: Management Tools and Methods

Part III: Spectrum Engineering

In addition to these parts, the Appendix includes "Terms and Definitions" and "Frequency Allocations" reprinted from *Radio Regulations*, Geneva, 1982. If this information is not enough, the Editor includes an extensive bibliography: "Part I: Space Services" and "Part II: Propagation".

Thus we have an up-to-date, comprehensive source that will aid in the management of the increasingly complex telecommunications growth, placing potential-crises demands on the radio spectrum.

Fredrick Matos

is with the National Telecommunications and Information Administration (NTIA), Washington, DC, where he has been working in spectrum management. His responsibilities include the preparations for and participation in international conferences concerning the radio spectrum. He has leading roles in the U.S. preparations for the 1986 Regional Broadcasting Conference and the 1987 Mobile Services Conference.

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**National Telecommunications and
Information Administration
U.S. Department of Commerce**

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Contents

Preface	ix
Introduction	1
Part I: Legal and Regulatory	5
Section I-A. International	11
The International Telecommunication Union and Development of Worldwide Telecommunications, <i>W. H. Bellchambers, J. Francis, E. Hummel, and R. L. Nickelson (IEEE Communications Magazine, May 1984)</i>	11
The International Telecommunication Convention from Madrid (1932) to Nairobi (1982): Half a Century in the Life of the Union, <i>F. M. Negro and J. -M.ª Novillo-Fertrell y Paredes (Telecommunication Journal, December 1982)</i>	22
ITU Plenipotentiary Conference—1982, <i>J. J. O'Neill, Jr. (Telecommunications January 1983)</i>	27
The International Radio Consultative Committee (CCIR): Part 1, <i>E. K. Smith and R. C. Kirby (Communications Society, July 1974)</i>	31
International Frequency Registration Board (IFRB) Assistance to Member Countries of the ITU in Matters Relating to Frequency Management, <i>M. K. Khabiri (IEEE Transactions on Electromagnetic Compatibility, August 1977)</i>	39
Regulating International Airwaves: The 1979 WARC, <i>G. O. Robinson (Virginia Journal of International Law, Fall 1980)</i>	43
The Post-WARC Frequency Situation in Central Europe, <i>K. Olms (IEEE Transactions on Electromagnetic Compatibility, August 1981)</i>	70
WARC Allocations and Some of their Impacts on Japan and in Asia, <i>S. Tanaka (IEEE Transactions on Electromagnetic Compatibility, August 1981)</i>	74
The WARC-79 and Papua New Guinea, <i>G. H. Railton (IEEE Transactions on Electromagnetic Compatibility, August 1981)</i>	81
Impact of WARC-79 on the Studies of the International Radio Consultative Committee (CCIR), <i>R. C. Kirby (IEEE Transactions on Electromagnetic Compatibility, August 1981)</i>	85
WARC-79 Changes to the Technical Radio Regulations, <i>R. D. Parlow (IEEE Transactions on Electromagnetic Compatibility, August 1981)</i>	90
The Impact of the 1979 World Administrative Radio Conference on the Fixed-Satellite, Inter-Satellite, and Mobile-Satellite Services, <i>E. E. Reinhart (IEEE Transactions on Electromagnetic Compatibility, August 1981)</i>	94
The Effect of WARC-79 on Efficient Use of the Geostationary Satellite Orbit, <i>D. Withers (IEEE Transactions on Electromagnetic Compatibility, August 1981)</i>	105
Mobile-Services—The Impact of the 1979 World Administrative Radio Conference, <i>W. M. Borman, C. Dorian, R. Johnson, and J. E. Miller (IEEE Transactions on Electromagnetic Compatibility, August 1981)</i>	111
CISPR Plenary Assembly, <i>J. Rutkowski (Telecommunication Journal, December 1980)</i>	121
Section I-B. United States	124
United States National Spectrum Management, <i>L. A. Buss and R. L. Cutts (Telecommunication Journal, June 1980)</i>	124
Federal Systems Review Process, <i>W. D. Gamble and R. D. Porter (IEEE International Symposium on Electromagnetic Compatibility, 1980)</i>	139
NABER Frequency Coordination: The Hows and Whys of this Process, <i>M. Gianessi (Communications, March 1981)</i>	144
International and U.S. Preparations for the 1979 World Administrative Radio Conference, <i>S. E. Probst (IEEE Transactions on Electromagnetic Compatibility, August 1977)</i>	147

Part II: Management Tools and Methods	153
Spectrum Utilization Problems, S. S. Sviridenko (<i>IEEE Transactions on Electromagnetic Compatibility</i> , August 1977)	159
On Efficient Spectrum Utilization from the Standpoint of Communication Theory, C. P. Tou and D. A. Roy (<i>Proceedings of the IEEE</i> , December 1980)	165
Spectrum Metrics and Spectrum Efficiency: Proposed Definitions, L. A. Berry (<i>IEEE Transactions on Electromagnetic Compatibility</i> , August 1977)	171
Definition of a Measurement Capability for Spectrum Managers, G. H. Hagn, D. M. Jansky, and T. I. Dayharsh (<i>IEEE Transactions on Electromagnetic Compatibility</i> , August 1977)	177
On the Definition and Estimation of Spectrum Occupancy, A. D. Spaulding and G. H. Hagn (<i>IEEE Transactions on Electromagnetic Compatibility</i> , August 1977)	186
A Radio Spectrum Measurement System for Frequency Management Data, R. J. Matheson (<i>IEEE Transactions on Electromagnetic Compatibility</i> , August 1977)	198
Frequency Assignment: Theory and Applications, W. K. Hale (<i>Proceedings of the IEEE</i> , December 1980)	204
Frequency Assignment Games and Strategies, J. A. Zoellner (<i>IEEE Transactions on Electromagnetic Compatibility</i> , November 1973)	222
Optimum Frequency Planning: A New Concept, R. G. Stružak (<i>Telecommunication Journal</i> , January 1982)	228
FAA Remote Terminal System Frequency Assignment Model, C. Cram and T. Hensler (<i>IEEE International Symposium on Electromagnetic Compatibility</i> , 1978)	236
Frequency Planning for Broadcast Services in Europe, J.- F. Arnaud (<i>Proceedings of the IEEE</i> , December 1980)	240
Spectrum Management Data Bases, G. W. Garber (<i>IEEE Transactions on Electromagnetic Compatibility</i> , August 1977)	248
The Use of Computerized Analytical Techniques in Spectrum Management, D. Cohen and R. Mayher (<i>Third Symposium and Technical Exhibition on Electromagnetic Compatibility</i> , 1979)	257
Microcomputers for Spectrum Management, J. de Mercado, J. da Silva, G. Chan, and G. Overtveld (<i>Telecommunication Journal</i> , April 1982)	263
Classification and Designation of Emissions, W. A. Luther (<i>IEEE Transactions on Electromagnetic Compatibility</i> , August 1981)	271
The Value of Frequency Spectrum Allocated to Specific Uses, D. W. Webbink (<i>IEEE Transactions on Electromagnetic Compatibility</i> , August 1977)	277
FCC Controls Digital Equipment, A. Wall and R. Bromery (<i>IEEE International Symposium on Electromagnetic Compatibility</i> , 1980)	286
Part III: Spectrum Engineering	295
Techniques for Implementing a Frequency Spectrum Engineering System, W. I. Harada (<i>Telebras Revista</i> , December 1982)	303
Objective EMC Criteria for Radio Systems: Do They Exist?, A. Wojnar (<i>Fifth International Wroclaw Symposium on Electromagnetic Compatibility</i> , 1980)	327
Measures of Voice Transmission Performance Applicable for Electromagnetic Compatibility Analysis, CCIR (<i>Spectrum Utilization and Monitoring</i> , Volume I, Geneva, 1982)	334
PPI Interference Prediction, L. Katz (<i>IEEE Transactions on Electromagnetic Compatibility</i> , June 1965)	342
Radiodetermination Spectrum Utilization/Conservation, R. L. Hinkle, R. M. Pratt, and J. S. Levy (<i>IEEE National Telecommunications Conference</i> , 1979)	348
Modulation Methods and Channel Separation in the Land Mobile Service, R. T. Buesing (<i>IEEE Transactions on Vehicular Technology</i> , May 1970)	355
A Method for Calculating Adjacent Band Interference, CCIR (<i>Spectrum Utilization and Monitoring</i> , Volume I, Geneva, 1982)	375
Interference and Propagation Formulas and Tables Used in the Federal Communications Commission Spectrum Management Task Force Land Mobile Frequency Assignment Model, J. H. McMahon (<i>IEEE Transactions on Vehicular Technology</i> , November 1974)	383
Aids for the Gross Design of Satellite Communication Systems, G. M. Northrop (<i>IEEE Transactions on Communication Technology</i> , February 1966)	389
Radio Propagation at Frequencies Above 30 Megacycles, K. Bullington (<i>Proceedings of the IRE</i> , October 1947)	400
Radio Propagation Above 40 MC Over Irregular Terrain, J. J. Egli (<i>Proceedings of the IRE</i> , October 1957)	415
Computer Prediction of Service Areas for VHF and UHF Land Mobile Radio Services, J. Durkin (<i>IEEE Transactions on Vehicular Technology</i> , November 1977)	424

An Approach to Estimating Land Mobile Radio Coverage, <i>E. A. Neham (IEEE Transactions on Vehicular Technology, November 1974)</i>	429
Selection of Intermodulation-Free Frequencies for Multiple-Channel Mobile Radio Systems, <i>R. Edwards, J. Durkin, and D. H. Green (Proceedings of the IEE, August 1969)</i>	433
Examples of Signals and Noise in the Radio-Frequency Spectrum, <i>W. R. Vincent (IEEE Transactions on Electromagnetic Compatibility, August 1977)</i>	441
Appendix	455
Introduction	455
Terms and Definitions (<i>Radio Regulations, Geneva, 1982</i>).....	457
Frequency Allocations (<i>Radio Regulations, Geneva, 1982</i>).....	471
Bibliography	477
Space Services	477
Propagation	481
Author Index	487
Subject Index	489
Editor's Biography	493

Preface

THIS volume is a collection of reprints of original papers on spectrum management and engineering with comments and bibliographies prepared by the Editor. The IEEE Electromagnetic Compatibility Society is the sponsor of this book.

The Editor is employed in spectrum management by the National Telecommunications and Information Administration, U.S. Department of Commerce. The papers presented and the views expressed herein are not those of the Department of Commerce or any other government agency or international organization.

The Editor expresses his deep gratitude to Richard Kirby, Donald Jansky, Bob Eldridge, Richard Schultz, Dr. John Durkin, Paul Roosa, Bruce Kraselsky, Martin Rothblatt, Fred Friel, and Jack Kelleher for their advice and assistance; to the IEEE Electromagnetic Compatibility Society for their sponsorship; and to Teresa Abiuso and Reed Crone of the IEEE for their infinite patience.

FRED MATOS
Editor

*Annapolis, Maryland
August 1984*

Introduction

BACKGROUND

THIS collection of reprints is intended to be useful not only to the professional spectrum management and engineering community and those entering it, but also to those involved in other aspects of telecommunications who have only a tangential interest in the spectrum management process. Professional spectrum managers and engineers will find some of the individual papers to be of interest. Secondly, the papers were selected to provide a broad and comprehensive treatment of the subject matter, and the bibliographies were compiled so that the professional could be aided in researching a specific problem or interest. The collection was also developed for those entering the spectrum management and related engineering professions with only a limited knowledge of the subject matter.

This book is also intended for the telecommunications managers, system planners, and equipment designers who have only a slight interest in the spectrum management process. Such groups should be aware that the spectrum is not an infinite resource and that the spectrum management process is a complex one. Indeed, if such groups had more understanding of the spectrum management process, it could help alleviate some of the problems facing spectrum managers and engineers.

The spectrum management process is a dynamic one, particularly in this era of new communications techniques, broadcasting satellites, microcomputers, etc., but many papers are being outdated by changing events and evolving technologies. This collection was selected to be current for years to come. A second selection criteria employed was to choose papers of historical significance.

A megahertz is a megahertz, be it in Lagos, Detroit, or Heard Island. The spectrum should be judiciously used and managed regardless of the location. Some aspects of the spectrum management process are appropriate universally. On the other hand, some aspects need to be tailored to the requirements of specific nations. This collection of papers and bibliographies was assembled with those requirements in mind.

TELECOMMUNICATIONS GROWTH

We have seen a tremendous growth in telecommunications over the years since 1960, and it appears that such growth may be even more accelerated in the future. Some of the factors contributing to the growth are technological such as the invention and development of the transistor and other solid state devices, the development of digital communications, the devel-

opment of communications satellites, and the widespread use of computers. Other factors spurring telecommunications growth are increasing requirements for rapid information transfer caused by increasing commerce and trade, and a desire from many peoples for social growth in which modern telecommunications plays an important role. Needless to say, the growth in telecommunications places increasing demands on the radio spectrum.

The management of the radio spectrum is becoming increasingly complex. The telecommunications demands have been met without serious spectrum crises only because of the resourcefulness and ingenuity of the spectrum managers and engineers. The accelerated telecommunications growth in the future will require even more resourcefulness and ingenuity.

The consequences of paying inadequate attention to spectrum management can be very serious: 1) electronic systems may be built that may not perform properly due to interference, necessitating equipment redesign or new system engineering; 2) missions of the groups employing the telecommunications systems, whether they be fire departments, military, or international communications satellite organizations, may not be accomplished because of interference problems; and 3) requests for the radio service may be denied [1]. Spectrum requirements must be considered at all stages of the evolution of a telecommunications system. For example, planning the design, development, and production of a radio communications product should consider the radio frequency management aspects as early as possible in the evolution of the product. The decision process in purchasing already developed and readily available radio communications products must also take into consideration the radio frequency management aspects lest the purchased equipment not be able to fulfill the communication requirements.

SOME DEFINITIONS

A concise definition of management is the judicious allocation of resources. Prefacing the term by "spectrum" naturally evolves into "a judicious allocation of spectrum resources," with the term "allocation" used in the general sense, not specifically referring to the term "frequency allocation" as in "Table of Frequency Allocations".

Generally, spectrum management is the function whereby

- 1) requirements for the use of the radio frequency spectrum are presented, reviewed, and satisfied; and

2) control of the use of the spectrum is exercised. Portions of the process whereby spectrum requirements are presented, reviewed, and satisfied are often technical in nature and can be so complex that unique specialists or spectrum engineers are needed to solve the problems.

After directing activities and otherwise observing the U.S. national and international spectrum management processes, Vice Admiral Jon Boyes developed a definition for the process and the individuals participating therein [2]:

Radio frequency management is done by experts who meld years of experience with a curious blend of regulations, electronics, politics and not just a little bit of larceny. They justify requirements, horse-trade, coerce, bluff and gamble with an intuition that cannot be taught other than by long experience.

The term "electromagnetic compatibility" or "EMC" is also frequently used in spectrum management and related engineering processes. The following is a widely accepted definition:

Electromagnetic Compatibility—the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to that environment or to other equipment therein.

Other definitions of similar text and length also exist and are preferred by some groups. A very concise definition that is easily recalled was developed by Richard Kirby and Jerzy Rutkowski of the CCIR [3]:

EMC = Coexistence.

The terms spectrum management, spectrum engineering, and electromagnetic compatibility are often used interchangeably by some members of the profession. However, the management function is of greater hierarchy, but electromagnetic compatibility (when applied to intentionally generated emissions) and spectrum engineering are synonymous terms, both largely technical in nature. Indeed, the sponsor of this work is the Electromagnetic Compatibility Society of the IEEE.

HISTORY—UNITED STATES

Spectrum management has been a necessity since the very early days of radio. In the United States, interference among government, commercial, and amateur stations continued to increase rapidly despite early attempts to establish regulations. This situation received attention at the highest government level in 1906 when the yacht of President Theodore Roosevelt was unable to receive radio messages due to interference, making it necessary to dispatch a torpedo boat to deliver messages. As a direct result, President Roosevelt ordered a memorandum on radiotelegraphy and recommendations as to its control [4]. The resulting memorandum recommended that all coast wireless stations be under the control of the Navy Department

and that no private wireless stations be permitted inland that could send messages to the coast.

One significant early application of radio was ship-to-shore or ship-to-ship communications, and radio played a major role in assistance during ship disasters of various kinds. One of the earliest laws was the Radio Ship Act of 1910 that required installation of wireless apparatus and operators on large sea-going passenger vessels [5]. Enforcement of the act was the responsibility of the Secretary of Commerce and Labor, who at that time administered the domestic maritime navigation laws.

The Radio Act of 1912 extended government control to domestic radio communications in general as well as to wireless telegraph, particularly in maritime use [6]. It also provided for the protection of government operations, gave the President special authority over radio communication in an emergency, and placed licensing of stations and operators in the hands of the Secretary of Commerce and Labor. The Interdepartment Advisory Committee was organized upon the invitation of Herbert C. Hoover, then Secretary of Commerce, to assist and advise in carrying out the President's responsibilities under the Radio Act of 1912 [7]. The Interdepartment Advisory Committee was a United States Government interagency committee with the purpose of finding means for making the most effective use of radio then being used for U.S. Government broadcasting. Originally named the Interdepartment Advisory Committee on Government Broadcasting, it soon recognized the need to consider other telecommunications matters of interest to the departments, and in 1923 changed its name to the Interdepartment Radio Advisory Committee (IRAC) [8].

The Radio Act of 1927 created a five-member Federal Radio Commission (FRC) to regulate certain aspects of radio, including the allocation of bands of frequencies to radio services, assignment of specific power, and issuance of station licenses [9]. This act gave the Secretary of Commerce authority to assign call signs, inspect radio stations, and examine and license radio operators. These duties were absorbed by the FRC in 1932. Chaos in the rapidly developing radio broadcast service was the prime reason for the Radio Act of 1927.

Enactment of the Communications Act of 1934 placed the regulation of radio, wire, and ocean cable communications under a single body. The Communications Act of 1934 created a seven-member Federal Communications Commission (FCC) as an independent agency to regulate interstate and foreign commerce in communication by wire and radio, including radio broadcasting and radio operations of state and local governments [10]. It also continued the President's authority to assign radio frequencies to stations belonging to and operated by the U.S., and to control communications in an emergency. The Communications Act of 1934 still stands today, albeit in a somewhat amended form. However, it results in the

United States being the only nation in the world with two regulatory bodies in the spectrum management process: the FCC, which is the frequency assignment authority for the private sector including state and local governments, and the President, who regulates and has the frequency assignment authority for the various Federal Government agencies.

Over the years, the importance of telecommunications and spectrum management have been recognized and have received high-level attention in the U.S. Government. In 1950, President Truman established the President's Communications Policy Board [11]. Among other things the President's letter constituting the Board emphasized the problem of radio frequencies:

I feel that the problem of radio frequencies will be one of the most important areas for the Board's investigations. I hope that, as a result of its studies, the Board will be able to recommend possible means for conserving frequencies, as well as standards for determining the relative priority of competing claims for frequencies, and possible administrative arrangements within the Government for assuring, on a continuing basis, a sound and equitable allocation of the limited frequency supply.[11]

The resulting final report gave significant attention to frequency management. It recommended that a three-man Telecommunications Advisory Board be established in the Executive Office of the President to advise and assist the President on telecommunication matters. The report recommended that the Advisory Board should

...establish and monitor a system of adequate initial justification and periodic rejustification and reassignment of frequencies assigned to Federal Government users, and, in cooperation with the Federal Communications Commission, supervise the division of frequency spectrum space between Government and non-Government users. [12]

President Lyndon Johnson appointed a task force in 1967 to make a comprehensive study of communications policies [13]. Among other things, he directed the task force to examine the major question "are we making the best use of the electro-magnetic frequency spectrum?"[13]. The task force produced a report that had a chapter on the use and management of the electromagnetic spectrum that concluded that [14]:

- 1) National "block" allocation procedures lack adequate flexibility.
- 2) Existing criteria for apportioning spectrum resources among competing uses are unsatisfactory.
- 3) The division of spectrum resources and management responsibilities between Government and non-Government uses is a source of inefficiency.
- 4) Spectrum waste is a significant problem.

- 5) Present levels of staff and funding devoted to spectrum management are inadequate.

Some of these conclusions resulted in changes in spectrum management, thus improving the efficiency of spectrum usage.

An important and comprehensive study of needed technical programs related to spectrum management was conducted in March 1968 by the Joint Technical Advisory Committee (JTAC), a joint committee of the Institute of Electrical and Electronics Engineers and the Electronics Industries Association. The study was undertaken at the direction of the Special Assistant to the President for Telecommunications who recognized that "there is a need for consolidation and clarification of the technical programs leading to the enhancement of electromagnetic compatibility, and for leadership in developing national policy and adequate official recognition and support of this work in the United States," [15]. The JTAC was comprised of 230 members from the Federal Government, state and city governments, and private industry, and represented the spectrum management and engineering community and various telecommunications users.

The JTAC approach was largely technical, and its final report covers such topics as frequency selection, spectrum engineering planning, equipment standards, interference reduction, analytical capabilities, mathematical models, spectrum monitoring, data bases, and unintended radiation [16]. The final report was well received and some regard it as a classic fifteen years after it was published.

The JTAC report recommended the adoption of spectrum engineering in the form of new analytical capabilities, improved spectrum monitoring, improvement and standardization of data base capabilities, and the review of existing standards and the development of new ones. Some of these recommendations eventually came into fruition but such cannot be attributed to the JTAC in all cases.

The IEEE continues to provide a forum for spectrum engineering and management. The IEEE Electromagnetic Compatibility Group (later to become a Society) published a special issue on spectrum management in August, 1977 [17]. The issue contained 33 papers, some of which are reprinted herein. The other IEEE Groups and Societies publish TRANSACTIONS and Magazines that occasionally contain papers or articles on U.S. and international spectrum engineering and management topics.

HISTORY—INTERNATIONAL

The history of international spectrum management and engineering is contained in works by Smith and Kirby [18], and Coddington [19]. The paper by Smith and Kirby is reprinted in Part I.

RECENT WORKS OF GENERAL INTEREST

There is only one book that covers spectrum management as a whole: *Spectrum Management Tech-*

niques by Jansky published in 1977 [20]. Since spectrum management is an ever-changing process, parts of the Jansky book have become outdated. Nevertheless, the book contains much useful information on spectrum management and engineering procedures.

The CCIR has recently published a handbook on spectrum management and computer-aided techniques [21]. The handbook contains a great deal of information on spectrum management techniques, frequency coordination, spectrum engineering techniques, spectrum engineering models, and computer techniques, including a catalog of data files and computer programs and where they can be obtained.

REFERENCES

- [1] W. Dean, Jr., "Overview reflections on the spectrum management process," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, part 2, Aug. 1977.
- [2] Vice Admiral Jon Boyes, U.S. Navy, circa 1974, used with permission.
- [3] R. C. Kirby and J. T. Rutkowski, "Electromagnetic compatibility guidelines for the next 20 years: Impact of WARC 79," presented at Fifth Int. Wroclaw Symp. Electromagn. Compatibility, Sept. 17-19, 1980, Wroclaw, Poland.
- [4] Capt. L. S. Howeth, USN (Ret.), *History of Communications—Electronics in the United States Navy*. Washington, DC: U.S. Government Printing Office, 1963.
- [5] Public Law 262 (Frye Bill), "The Radio Ship Act of 1910," 60th Congress, Effective July 1, 1911.
- [6] Public Law 264, "The Radio Act of 1912," U.S. Congress, 1912.
- [7] Executive Office of the President, Office of Emergency Planning, "Chronological resume of some significant incidents in U.S. telecommunications from 1866," Washington, DC, Jan. 1962.
- [8] Executive Office of the President, Office of Telecommunications Policy, "The Interdepartment Radio Advisory Committee—50 years of service," TEL-IRAC-72-30, Washington, DC, June 1972.
- [9] Radio Act of 1927, U.S. Congress, 1927.
- [10] Communications Act of 1934, U.S. Congress, 1934.
- [11] "Telecommunications: A program for progress, a report by the President's Communications Policy Board," U.S. Government Printing Office, Washington, DC, Mar. 1951.
- [12] "Telecommunications: A program for progress, a report by the President's Communications Policy Board," U.S. Government Printing Office, Washington, DC, Mar. 1951, p. 19.
- [13] "Global communications system, message from the President of the United States transmitting recommendations relative to world communications," House of Representatives, 90th Congress, 1st Session, Document 157, Aug. 14, 1967.
- [14] "Final report—President's Task Force on Communications Policy," U.S. Government Printing Office, Dec. 7, 1968. (Note: this note also contains Note 13 in an appendix.)
- [15] Jerome B. Weisner, Acting Special Assistant to the President for Telecommunications, Letter to the Joint Technical Advisory Committee, Dec. 6, 1963.
- [16] The Joint Technical Advisory Committee, "Spectrum engi-

neering—The key to progress," Published by the IEEE, New York, NY, 1968.

- [17] *IEEE Trans. Electromagn. Compat.*, Special Issue on Spectrum Management, vol. EMC-19, no. 3, part 2, Aug. 1977.
- [18] E. K. Smith and R. C. Kirby, "The International Radio Consultative Committee (CCIR): Part 1," *Communications Society (IEEE)*, vol. 12, no. 4, July 1974.
- [19] G. A. Coddington, Jr., *The International Telecommunication Union—An Experiment in International Cooperation*. New York, NY: Arno Press, 1972.
- [20] D. M. Jansky, *Spectrum Management Techniques*. Germantown, MD: Don White Consultants, 1977.
- [21] *Handbook—Spectrum Management and Computer-Aided Techniques*. Geneva: CCIR, 1983.

BIBLIOGRAPHY

- [1] "A summary of the Federal Government's use of the radio frequency spectrum," U.S. Department of Commerce, National Telecommunications and Information Administration, issued annually.
- [2] R. E. Beery, "A renewal of EMC Policy in the Department of Defense," *IEEE Int. EMC Symp.*, 1977.
- [3] "Electromagnetic spectrum utilization—The silent crisis," Telecommunications Science Panel of the Commerce Technical Advisory Board, Washington, DC, 1966.
- [4] "Frequency management principles—Spectrum engineering measurements," Rep. 6050.23, Federal Aviation Administration, Washington, DC, May 29, 1969.
- [5] K. G. Heisler and H. J. Hewitt, *Interference Notebook*, U.S. Air Force, Rome Air Development Center, Rome NY, June 1966.
- [6] "Information on management and use of the radio frequency spectrum—A little understood resource," General Accounting Office, Washington, DC, 1975.
- [7] C. L. Jackson, "The allocation of the radio spectrum," *Sci. Amer.*, vol. 242, no. 2, Feb. 1980.
- [8] H. J. Levin, "Foreign and domestic U.S. policies—Spectrum reservations and media balance," *Telecommunications Policy*, vol. 6, no. 2, June 1982.
- [9] —, *The Invisible Resource: Use and Regulation of the Radio Spectrum*. Baltimore, MD: Johns Hopkins, 1971.
- [10] D. M. Jansky, "The nature of the problem," Conference Record, IEEE EASCON, Washington, DC, Oct. 1974.
- [11] M.N. Lustgarten, "Some thoughts on the philosophy of spectrum management," *IEEE Trans. Electromagn. Compat.*, vol. EMC-15, no. 2, May 1973.
- [12] *Manual of Regulations and Procedures for Federal Radio Frequency Management*. Washington, DC: National Telecommunications and Information Administration, latest ed.
- [13] W. P. McLauchlan and R. M. Westerberg, "Allocating broadcast spectrum—models and proposals," *Telecommunications Policy*, vol. 6, no. 2, June 1982.
- [14] R. D. Parlow, "Management techniques for improved spectrum utilization," presented at 5th Symp. Electromagnetic Compatibility, Wroclaw, Poland, Sept. 1980.
- [15] "Radio Regulations—Edition of 1982," International Telecommunication Union, Geneva, 1982.
- [16] L. P. Petak, "Planning in support of spectrum management," 32nd IEEE Vehicular Techn. Conf., San Diego, May 1982.
- [17] R. E. Taylor, "Radio frequency interference handbook," Report NASA SP-3067, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, MD, 1971.
- [18] "The Radio Frequency Spectrum—United States Use and Management," Executive Office of the President, Office of Telecommunications Policy.

Part I

Legal and Regulatory

INTERNATIONAL

INTERNATIONAL regulation of the spectrum would be greatly simplified if radio waves would remain within a country and not cross its borders. If such were the case, international regulations of the spectrum would be necessary only for international communications or for broadcasting from country to country, or for communications involving aircraft or ships traveling from country to country. But radio waves do not observe borders, and it is therefore necessary to have a set of rules by which nations will abide. International rules, laws, or regulations are developed by international bodies with all member nations having the opportunity to participate. In radio frequency spectrum management, the organization that develops the laws and regulations is the International Telecommunication Union or the ITU, a specialized agency of the United Nations [1].

The basic set of laws governing the ITU is the International Telecommunication Convention, which was revised most recently in 1982 in Nairobi [2]. The Convention has full treaty status and requires ratification by the member nations. The Convention is revised periodically, at and only at, a meeting called a Plenipotentiary Conference, which is often referred to as the supreme organ of the ITU. The next Plenipotentiary Conference is scheduled to be held in France in 1989 for six weeks. The first Plenipotentiary Conference was held in Madrid in 1932, followed by Atlantic City in 1947, Buenos Aires in 1952, Geneva in 1959, Montreaux in 1965, Malaga-Torremolinos in 1973 and Nairobi in 1982. Molina Negro and Novillo-Fertrell Y Paredes discuss the significant results of each of the Conferences from Madrid through Nairobi [3]. The O'Neill paper included herein presents his views of the Nairobi Plenipotentiary Conference including discussions of political controversies, elections, schedule of future conferences, technical cooperation, and other significant results [4]. Other excellent papers on the Nairobi Conference have been written by Codding [5] and Segal [6].

The Nairobi Convention consists of two parts. Part one contains the Basic Provisions consisting of the Composition, Purposes, and Structure of the Union; General Provisions relating to Telecommunications; Special Provisions for Radio; Relations with the United Nations and with International Organizations; Application of the Convention and the Regula-

tions; Definitions; and Final Provisions. Part two contains the General Regulations consisting of the Functioning of the Union; General Provisions regarding Conferences; General Provisions regarding International Consultative Committees; Rules of Procedure of Conferences and other Meetings; Other Provisions; and Administrative Regulations. The Convention also consists of Final Protocol (statements from various countries), Resolutions, Recommendations, and Opinions, some of which are discussed in the papers by Molina Negro and Novillo-Fertrell Y Paredes; and O'Neill. The Resolutions, Recommendations, and Opinions are not ratified and, hence, do not have treaty status.

Rapidly growing technologies, together with ever-changing telecommunications needs and associated changing operational procedures, necessitate a separate set of regulations that are amended more frequently than the convention, and contain much more detailed information including technical matters and operational procedures. Article 42 of the Nairobi Convention presents the legal basis of the Radio Regulations: "the provisions of the Convention are supplemented by the Administrative Regulations which regulate the use of telecommunication and shall be binding on all Members." Thus, the Radio Regulations also have treaty status. The Radio Regulations—Edition of 1982, including resolutions and recommendations, contain over 2000 pages and include such diverse items as a Table of Frequency Allocations, channel plans, satellite coordination procedures, and call-sign prefixes for member countries [7]. The Appendix presented herein contains the definitions of radio services and a page taken from the Table of Frequency Allocations from the Radio Regulations to illustrate typical allocations and their hierarchy.

The Radio Regulations are very important because of their international status and also because many nations adopt major portions of them as their own national regulations, particularly when international coordination procedures or international communications are involved. The Radio Regulations contain coordination procedures that establish a dialogue between nations such that interference situations are precluded before serious problems occur.

The Radio Regulations are amended at a meeting called an Administrative Radio Conference. A major conference was held in 1979 called the 1979 World Administrative Radio Conference or WARC-79, at

which the Radio Regulations—Edition of 1982 (actually effective January 1, 1982) were developed. The WARC-79 set the foundations of the regulations for the next 20 years. The IEEE published a joint special issue on the results of the WARC-79 containing 26 papers [8]. The papers on WARC-79 by Olms [9], Tanaka [10], Railton [11], Kirby [12], Parlow [13], Reinhart [14], Withers [15], and Borman [16] were selected for inclusion herein. The papers by Olms, Tanaka, and Railton not only review the WARC-79 from the perspective of some of these nations of central Europe, Japan, and Papua New Guinea, but also provide some insight into spectrum management procedures and interests in the countries. The paper by Robinson provides a comprehensive treatment of the conference including negotiation activities [17]. A thorough review of WARC-79 and the impact on the United States was made by the Office of Technology Assessment of the U.S. Congress [18]. In addition to these and the papers of the special edition of the IEEE TRANSACTIONS, other reviews of WARC-79 results can be found in Bowie [19], A. Rutkowski [20], Ackerman and Weinberger [21], the Federal Communications Commission General Docket 80-739 [22], Robinson [23], and Kirby [24].

The parts of the ITU that are important with respect to spectrum management are the General Secretariat, the International Frequency Registration Board (IFRB), the International Radio Consultative Committee (CCIR), and the Administrative Council. The paper by Bellchambers, Francis, Hummel, and Nickelson presents an excellent treatment of the purposes, structure, and activities of the ITU [1]. The paper by Smith and Kirby [25] is included herein and provides a brief history of the ITU and the CCIR, while the Khabiri paper expands on the role of the IFRB in assisting member countries in frequency management matters [26]. Codding and A. Rutkowski have developed a comprehensive book on the ITU [27], an updated version of the earlier book by Codding [28]. Although out of date in some parts, the book by Leive is useful [29]. In addition to the works by Codding and Leive, additional historical information pertaining to the ITU can be found in Michaelis [30], Smith [31], Kirby [32], and occasional articles in the *Telecommunication Journal*, a monthly publication of the ITU. Indeed, the *Telecommunication Journal* should also be followed for current information concerning the ITU and international spectrum management activities.

International disputes and the role of the ITU are the subjects of works by Ickowitz [33], Gregg [34], and Wallenstein [35]. The role and function of the ITU is the subject of works by A. Rutkowski [36] and McWhinney [37], with different ideas explored in Gross [38], [39], Chayes [40], and Rothblatt [41].

The International Electrotechnical Commission (IEC) is an organization conducting international standardization in the electrical and electronics

fields. The International Special Committee on Radio Interference (C.I.S.P.R.) is a special committee of the IEC [42]. The C.I.S.P.R. is mainly concerned with methods of measuring radio frequency signals and the radiations from electrical devices. The C.I.S.P.R. cooperates very closely with the CCIR. J. Rutkowski presents the results of the 1980 C.I.S.P.R. Plenary Assembly held in Tokyo [43].

The various treaties and agreements concerning outer space and the systems using it are a significant portion of the legal framework. These are presented separately in Space Services, Part I of the Bibliography.

In addition to the ITU Radio Regulations and Convention, nations may have separate agreements of formal or informal status. The formal agreements may be regional involving numbers of nations or bilateral treaties between two nations. Informal arrangements are usually bilateral involving neighboring countries and consist of coordination of radio frequency assignments.

UNITED STATES

In the United States, the Communications Act of 1934 divides the frequency management authority into two parts: the Federal Communications Commission (FCC) which regulates the private users including state and local governments; and the President who will assign frequencies to Federal Government users [44]. The FCC also derives authority from the Communications Satellite Act of 1962 [45], [46]. The FCC rulemaking and other procedures must also adhere to the Administrative Procedures Act of 1946 [47], [48], [49]. Major new legislation was drafted in 1977–1979 in the form of the Communications Act of 1979 (H.R. 3333) that would restructure the entire spectrum management administrative structure and processes in the United States [50]. The new legislation, H.R. 3333, was not adopted, but other amendments have been made that affect the spectrum management process. For example, S.3033 by Senator Barry Goldwater amended Section 302 of the Communications Act to authorize the FCC to prescribe regulations with respect to certain electronic equipment that is susceptible to radio frequency energy interferences [51].

By Executive Order 12046, “the authority of the President to assign frequencies to radio stations or to classes of radio stations belonging to and operated by the United States, including the authority to amend, modify, or revoke such assignments, was transferred to the Secretary of Commerce,” [52]. As discussed by Buss and Cutts, the responsibility is exercised by the Administrator of the National Telecommunications and Information Administration (NTIA) [53]. The NTIA was created in 1978 in a reorganization of the Executive Branch [54]. The NTIA Administrator is the President’s principal tele-

communications advisor and is responsible for the regulation of the radio spectrum used by all Federal Government agencies. Advice and assistance is provided to the NTIA by the Interdepartment Radio Advisory Committee (IRAC) in all areas related to spectrum management [52], [53], [54], [55], [56], [57].

The National Telecommunications and Information Administration and the Federal Communications Commission each publish their own rules and regulations [58], [59]. Both the NTIA "Manual of Regulations and Procedures for Federal Radio Frequency Management" and the FCC Rules and Regulations contain tables of frequency allocations, channel plans, assignment procedures, and technical standards. The NTIA Manual is self-contained in a single volume, whereas the FCC Rules and Regulations are contained in 43 noncontiguous parts numbered up to 100 in four volumes in the CFR (Code of Federal Regulations) version. For the most part, the FCC Rules and Regulations are divided into administrative and telecommunications services, e.g., Part 1 is "Practice and Procedure," Part 87 is "Aviation Services" and Part 90 is "Private Land Mobile Services." The paper by Buss and Cutts contained herein presents a brief but comprehensive treatment of both the FCC and NTIA organizations and procedures.

The paper by Gamble and Porter presents an expanded view of the Federal Government system review process and that of the Spectrum Planning Subcommittee of the IRAC [60]. The Federal Government agencies develop and/or purchase many different types of telecommunications equipment and it is necessary to ensure that new proposed uses of the spectrum take into consideration each existing and planned use so that interference will not be caused or received by the new systems. The process assists the short- and long-term spectrum planning activities. Further information on the system review process can be obtained by referring to the NTIA Manual [58] or to Watson [61].

The frequency assignment and licensing procedures of the FCC differ depending on the service involved. For example, the procedure differs considerably between a satellite earth station operating in the fixed satellite service, a radio broadcasting station, and a land mobile station in the business radio service. The land mobile area is one of high growth and spectrum congestion in some geographical areas. The article by Gianessi [62] presents the frequency coordination procedures of the business radio service as conducted by the National Association of Business and Educational Radio, a "frequency coordinating committee" recognized by the FCC as an advisory body following Section 90.175(a)(2) of the FCC Rules and Regulations [63].

The ITU Conferences can have a significant impact on the national spectrum management process. Thus, it is appropriate to review the U.S. conference

preparation process. Probst presents an excellent overview of the preparations for WARC-79 [64], including committee organizations in the Federal Government and FCC areas. (It should be noted that the Office of Telecommunications Policy referred to in the Probst paper is the predecessor of the NTIA. A government reorganization in 1978 created the NTIA.) The WARC-79 was considered to be of such importance that considerable congressional review and scrutiny was initiated [65], [66], [67], [68].

The United States role and goals in the ITU are examined from time to time. Lee suggested a possible withdrawal and alternative arrangements in 1974 in his famous "Crosswinds of Change" speech [69]. In-depth studies have focused on the increasing politicization of the ITU and other trends, and various recommendations have been made [18], [70], [71].

OTHER ADMINISTRATIONS

The papers by Olms [9], Tanaka [10], and Railton [11] provide some insight into the spectrum management activities in Central Europe, Japan, and Papua New Guinea. Occasional articles on the administrative aspects of telecommunications in various countries appear in the *Telecommunication Journal* and other publications [72], [73], [74].

REFERENCES

- [1] W. H. Bellchambers, J. Francis, E. Hummel, and R. L. Nickelson, "The International Telecommunication Union and development of worldwide telecommunications," *IEEE Communications Magazine*, vol. 22, no. 5, May 1984.
- [2] *International Telecommunication Convention*, (Nairobi 1982), International Telecommunication Union, Geneva, Switzerland, 1982.
- [3] F. Molina Negro and J. M. Novillo-Fertrell Y Paredes, "The International Telecommunication Convention from Madrid (1932) to Nairobi (1982): Half a century in the life of the union," *Telecommun. J.*, vol. 49, no. 12, Dec. 1982.
- [4] J. J. O'Neill, Jr., "ITU Plenipotentiary Conference—1982," *Telecommunications*, vol. 17, no. 1, Jan. 1983.
- [5] G. A. Coddington, Jr., "The changing nature of the ITU Plenipotentiary," *Telecommunications Policy*, vol. 7, no. 4, Dec. 1983.
- [6] B. Segal, "ITU Plenipotentiary and beyond: A case for serious foreign policy," *Telecommunications Policy*, vol. 7, no. 4, Dec. 1983.
- [7] "Radio Regulations—Edition of 1982," International Telecommunication Union, Geneva, Switzerland, 1982.
- [8] D. Bodson, R. G. Gould, G. H. Hagn, and W. F. Utlaut, Eds., Joint Special Issue on the 1979 World Administrative Radio Conference (WARC-79), *IEEE Trans. Commun.*, vol. COM-29, no. 8, Aug. 1981; also published as *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, no. 3, Aug. 1981.

The following eight references were taken from the IEEE TRANSACTIONS listed in Reference [8].

- [9] K. Olms, "The post-WARC frequency situation in Central Europe."
- [10] S. Tanaka, "WARC allocations and some of their impacts on Japan and in Asia."
- [11] G. H. Railton, "The WARC-79 and Papua New Guinea."

- [12] R. C. Kirby, "Impact of WARC-79 on the studies of the International Radio Consultative Committee (CCIR)."
- [13] R. D. Parlow, "WARC-79 changes to the Technical Radio Regulations."
- [14] E. E. Reinhart, "The impact of the 1979 World Administrative Radio Conference on the fixed-satellite, inter-satellite, and mobile-satellite services."
- [15] D. Withers, "The effect of WARC-79 on efficient use of the geostationary orbit."
- [16] W. M. Borman, C. Dorian, R. Johnson, and J. E. Miller, "Mobile services—the impact of the 1979 World Administrative Radio Conference."
- [17] G. O. Robinson, "Regulating International Airwaves: The 1979 WARC," *Virginia J. Int. Law*, vol. 21, no. 1, Fall 1980.
- [18] "Radiofrequency use and management: Impacts from the World Administrative Radio Conference of 1979," Congress of the United States, Office of Technology Assessment, undated but circa 1982.
- [19] N. A. Bowie, "Third world Countries at WARC: Positions and achievements," Conference on World Communications: Decisions for the Eighties, Annenberg School of Communications, University of Pennsylvania, Philadelphia, PA, May 1980.
- [20] A. M. Rutkowski, "Six ad-hoc Two: The Third World speaks its mind," *Satellite Commun.*, vol. 4, no. 3, Mar. 1980.
- [21] P. G. Ackerman and H. L. Weinberger, "Satellite systems for industrialized nations—After WARC '79," presented at the 8th AIAA Conference, Orlando, FL, Apr. 1980.
- [22] "Amendment of Part 2 of the Commission's rules regarding implementation of the final acts of the World Administrative Radio Conference, Geneva, 1979," Second Report and Order, General Docket 80-739, Federal Communications Commission, Dec. 8, 1983.
- [23] G. O. Robinson, "Report of the chairman of the United States Delegation to the World Administrative Radio Conference of the International Telecommunication Union, Sept. 24–Dec. 6, 1979," U.S. Department of State, Office of International Communications Policy, TD Serial No. 116, 74, (1979).
- [24] R. C. Kirby, "WARC plots spectrum use," *Spectrum*, vol. 17, no. 2, Feb. 1980.
- [25] E. K. Smith and R. C. Kirby, "The International Radio Consultative Committee (CCIR): Part 1," *Commun. Soc.*, IEEE, vol. 12, no. 4, July 1974.
- [26] M. K. Khabiri, "International Frequency Registration Board (IFRB) assistance to member countries of the ITU in matters relating to frequency management," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Aug. 1977.
- [27] G. A. Coddington, Jr., and A. M. Rutkowski, *The International Telecommunication Union in a Changing World*. Dedham, MA: Artech House, 1982.
- [28] —, *The International Telecommunication Union: An Experiment in International Cooperation*. New York: Arno Press, 1972.
- [29] D. M. Leive, *International Telecommunications and International Law: The Regulation of the Radio Spectrum*. Dobbs Ferry, NY: Oceana Publications, 1970.
- [30] A. R. Michaelis, *From Semaphore to Satellite*. Geneva, Switzerland: International Telecommunication Union, 1965.
- [31] E. K. Smith, "The history of the ITU, with particular attention to the CCITT and the CCIR, and the latter's relations with URSL," *Radio Sci.*, vol. 11, no. 6, June 1976.
- [32] R. C. Kirby, "CCIR 50th anniversary," *Telecommun. J.*, Parts 1 and 2 respectively in vol. 45, nos. 6 and 7, June and July 1978.
- [33] A. H. Ickowitz, "The Role of the International Telecommunication Union in the settlement of harmful interference disputes," *Columbia J. Transnational Law*, vol. 13, no. 1, 1974.
- [34] D. C. Gregg, "Capitalizing on national self interest: The management of international telecommunication conflict by the International Telecommunication Union," *Law and Contemporary Problems*, vol. 45, Winter 1982.
- [35] G. D. Wallenstein, *International Telecommunication Agreements*. Dobbs Ferry, NY: Oceana, Looseleaf Service updated to Dec. 1982.
- [36] A. M. Rutkowski, "The International Telecommunication Union and the United States," *Telecommunications*, vol. 17, no. 10, Oct. 1983.
- [37] E. McWhinney, "The antinomy of policy and function in the law of international telecommunications," *Columbia J. Transnational Law*, vol. 13, no. 1, 1974.
- [38] G. C. Gross, "The new ITU—A Plan for reorganization of the union," *Telecommun. J.*, vol. 30, no. 3, Mar. 1963.
- [39] —, "Towards the streamlining of the ITU Convention," *Telecommun. J.*, vol. 32, no. 1, Jan. 1965.
- [40] B. Chayes, "Reforming ITU?" in *Twentieth Century Fund, Global Communication in the Space Age* (1972). John and Mary Markle Foundation, 1973.
- [41] M. A. Rothblatt, "Rapid Evolution in Satellite Network Facilities—Legal Implications and the 1985 Space WARC," presented at *4th World Telecommunication Forum, Part III, Legal Symp.*, International Telecommunication Union, Geneva, Oct. 28–29, 1983.
- [42] "Organization, rules and procedures of the C.I.S.P.R.," C.I.S.P.R. Document 10, International Electrotechnical Commission, Geneva, Switzerland, 1981 with Amendment No. 1 in 1983.
- [43] J. Rutkowski, "CISPR Plenary Assembly (Tokyo, July 1980), *Telecommun. J.*, vol. 47, no. 12, Dec. 1982.
- [44] "Communications Act of 1934, as amended," U.S. Code 1976 Title 47, U.S. Government Printing Office, Washington, DC. (See also amendments in 1952, 1960, 1978, and 1983.)
- [45] "Communications Satellite Act of 1962," Public Law 87-624, 87th Congress, 2nd Session, H.R. 11040, 1962.
- [46] M. Kinsley, *Outer Space and Inner Sanctums: Government, Business, and Satellite Communication*. New York: Wiley, 1976.
- [47] Administrative Procedures Act, as amended.
- [48] K. C. Davis, *Administrative Law Treatises*. San Diego: K. C. Davis Pu. Co., 1978—(volumes).
- [49] G. O. Robinson and E. Gellhorn, *The Administrative Process*. St. Paul, MN: West Publishing Co., 1974.
- [50] "The Communications Act of 1979," H.R. 3333, 96th Congress, Hearings before the Subcommittee on Communications of the Committee on Interstate and Foreign Commerce, House of Representatives, Serial No. 96-121, Apr. 24–May 8, 1979. (See also statement of Stanley I. Cohn on spectrum management matters.)
- [51] "To amend Section 302 of the Communications Act of 1934 to authorize the Federal Communications Commission to prescribe regulations with respect to certain electronic equipment that is susceptible to radio frequency energy interference," S.3033, 94th Congress, Committee on Commerce, United States Senate, Senator Barry Goldwater, Feb. 25, 1976.
- [52] Jimmy Carter, Executive Order 12046, Relating to the Transfer of Telecommunications Functions, March 27, 1978, Code of Federal Regulations, Part 3, 1978.
- [53] L. A. Buss and R. L. Cutts, "United States national spectrum management," *Telecommun. J.*, vol. 47, no. 6, June 1980.
- [54] M. K. Sidel and V. Mosco, "U.S. communications policy making: The results of executive branch reorganization," *Telecommunications Policy*, vol. 2, no. 3, September 1978.
- [55] R. H. Coase, "The Interdepartment Radio Advisory Committee," *J. Law and Economics*, vol. 5, Oct. 1962.
- [56] "The Interdepartment Radio Advisory Committee—Fifty years of service," TEL-IRAC-72-30, Office of Telecommunications Policy, Washington, DC, June 1972.

- [57] "Report of the Interdepartment Radio Advisory Committee," issued semi-annually by E. Dinkle, Executive Secretary, IRAC, National Telecommunications and Information Administration, Washington, DC, latest edition.
- [58] *Manual of Regulations and Procedures for Federal Radio Frequency Management*. Washington, DC: National Telecommunications and Information Administration, latest edition.
- [59] Code of Federal Regulations, Title 47, Telecommunications, Chapter I—Federal Communications Commission, Office of the Federal Register, Washington, DC, latest edition.
- [60] W. D. Gamble and R. D. Porter, "Federal systems review process," presented at the 1980 IEEE International Symposium on Electromagnetic Compatibility, Baltimore, MD, 1980.
- [61] R. T. Watson, "Planning guide for the review of telecommunications systems for frequency availability and electromagnetic compatibility," NTIA Report 84-141, National Telecommunications and Information Administration, Washington, DC, Jan. 1984.
- [62] M. Gianessi, "NABER frequency coordination: The hows and whys of this process," *Communications*, vol. 18, no. 3, Mar. 1981.
- [63] See Note 59 at Part 90.
- [64] S. E. Probst, "International and U.S. preparations for the 1979 World Administrative Radio Conference," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Aug. 1977.
- [65] S. E. Probst, J. J. O'Neill, Jr., R. S. Black, and R. E. Simonds, Separate Prepared Statements, Hearing Before the Subcommittee on Communications of the Committee on Commerce, Science, and Transportation, United States Senate, 95th Congress, First Session on Oversight on International Telecommunications Policies, serial No. 95-54, July 13, 1977.
- [66] Congressional Research Service, "The World Administrative Conference of 1979: U.S. preparations and proposals," Congressional Record—Senate, S9313-9315, July 12, 1979.
- [67] Arthur D. Little, Inc., "An analysis of probable worldwide reactions to United States proposals to the 1979 World Administrative Radio Conference," prepared for the Senate Committee on Commerce, Science, and Transportation, Sept. 1979, Congressional Record, Sept. 6, 1979, S12113.
- [68] Senator Harrison Schmitt, "Keynote luncheon speech," presented at the 1978 Convention of the Armed Forces Communications and Electronics Association, reprinted in *Signal*, vol. 32, no. 8, Aug. 1978.
- [69] Robert E. Lee, "The ITU—Crosswinds of change," remarks before the International Radio and Television Society, Inc., New York, NY, Nov. 13, 1974.
- [70] "Long-range goals in international telecommunications and information—An outline for United States policy," printed at the direction of Hon. Bob Packwood, Chairman, Senate Committee on Commerce, Science, and Transportation, Committee Print 98-22, Mar. 11, 1983.
- [71] L. Milk and A. Weinstein, "United States participation in the International Telecommunication Union: A study of policy alternatives," Georgetown Center for Strategic and International Studies, Washington, DC, July 1984.
- [72] "Telecommunications in Canada," *Telecommun. J.*, vol. 44, no. 3, Mar. 1977.
- [73] "Telecommunications in the Federal Republic of Germany," *Telecommun. J.*, vol. 49, no. 9, Sept. 1982.
- [74] G. A. Wagner, "Telecommunications Policy making in New Zealand during the last two decades," *Telecommunications Policy*, vol. 8, no. 2, June 1984.

The International Telecommunication Union and Development of Worldwide Telecommunications

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A historical perspective of the ITU's structure and purposes

FROM THE early dawn of civilization until a little over 100 years ago, man did not get much further in his efforts to communicate across long distances than the written message, the drum, the beacon, the smoke signal, and the optical telegraph. With the development of electricity in the first half of the 19th century, man's capacity for practical achievement in the field of communicating at a distance was suddenly enlarged a hundred-fold. On May 24, 1844, the first public link using Morse telegraph apparatus was inaugurated between Washington, DC and Baltimore, MD.

The electric telegraph was made available to the general public in Europe about 1848. At first the lines stopped short at national frontiers, and telegrams were taken by hand across borders for further transmission. But the popularity of this useful and marvelous means of communications was such that States soon felt the need to regulate, by intergovernmental agreements, the use of particular types of transmission lines and apparatus, the application of uniform operating instructions, the collection of charges, and the mutual settlement of accounts.

In Paris, on May 17, 1865, the first International Telegraph Convention thus came to be signed by 20 States, founders of the International Telegraphic Union; in 1932, this became the International Telecommunication Union.

The history of the ITU is a mirror of the history of telecommunications. For example, after having regulated electrical telegraphy in 1855, it began legislating internationally for the telephone launched by Alexander Graham Bell in 1876. In 1895 and 1896, the first successful wireless transmissions, which crowned decades of research and

experiment, brought about what is still the greatest revolution in the history of telecommunications.

At first regarded purely as a radically advanced form of telegraphy, radio spread across the international scene even more rapidly than the parent invention, for the first time bringing ships at sea within the reach of telecommunications. It became clear with equal rapidity that international regulations were needed in this field as well. A Preliminary Radio Conference was held in Berlin in 1903, which paved the way for the Berlin Radio Conference of 1906. The 1906 Conference drew up the first international Radio Regulations.

Development of modern techniques and their complicated nature was, during the 1920's, to lead to the successive creation of three International Consultative Committees:

- the International Telephone Consultative Committee (CCIF, 1924),
- the International Telegraph Consultative Committee (CCIT, 1925), and
- the International Radio Consultative Committee (CCIR, 1927).

The 13th International Telegraph Conference and the 3rd International Radiotelegraph Conference met simultaneously in Madrid in 1932. As the two conferences were different legal entities, they had to resolve, by compromise, a number of disagreements concerning the questions of voting, conference language, and a new name for their combined union. The name selected was International Telecommunication Union, which drew upon a term first used at the turn of the century by Edouard Estaunie, Director of the Ecole Supérieure des Postes et Télégraphes of France.

After the Second World War, two ITU Conferences met in Atlantic City, NJ in 1947 with the aims of further developing and strengthening the activities of the Union. Under an agreement with the United Nations, the ITU became a specialized agency and its headquarters were transferred from Bern to the traditionally international atmosphere of Geneva. Furthermore, an International Frequency Registration Board (IFRB) was created.

The development of technical cooperation for developing countries and the advent of the space age have presented the ITU with new challenges. World and regional conferences and meetings of Consultative Committees throughout the ITU's history have permitted the creation and updating of international regulations and standards which enable the harmonious operations and development of telecommunications worldwide.

The last Plenipotentiary Conference, held in Nairobi at the end of 1982, revised the International Telecommunication Convention, the basic instrument of the Union, and set up a program of conferences for the next seven years. Among other decisions, it also adapted the technical cooperation activities of the Union to the need for accelerated development in developing countries.

Purposes of the Union

The ITU has 158 Member countries. The purposes of the Union are stated in the International Telecommunication Convention as:

- To maintain and extend international cooperation between all Members of the Union for the improvement and rational use of telecommunications of all kinds, as well as to promote and offer technical assistance to developing countries in the field of telecommunications;
- To promote the development of technical facilities and their most efficient operation with a view to improving the efficiency of telecommunication services, increasing their usefulness, and making them, as far as possible, generally available to the public;
- To harmonize the actions of nations in the attainment of these ends. To this end, the Union shall in particular:
- Effect allocation of the radio frequency spectrum and registration of radio frequency assignments in order to avoid harmful interference between radio stations of different countries;
- Coordinate efforts to eliminate harmful interference between radio stations of different countries and to improve the use made of the radio frequency spectrum;
- Foster international cooperation in the delivery of technical assistance to developing countries and the creation, development, and improvement of telecommunication equipment and networks in developing countries by every means at its disposal, including the relevant programs of the United Nations and the use of its own resources, as appropriate;
- Coordinate efforts with a view to harmonize the development of telecommunication facilities, notably those using space techniques, with a view to full advantage being taken of their possibilities;
- Foster collaboration among its Members with a view to the establishment of rates at levels as low as possible, consistent with an efficient service and taking into

account the necessity for maintaining independent financial administration of telecommunications on a sound basis;

- Promote the adoption of measures for ensuring the safety of life through the cooperation of telecommunications services;
- Undertake and make regulations, adopt resolutions, formulate recommendations and opinions, and collect and publish information concerning telecommunication matters.

In brief, the ITU regulates, standardizes, coordinates, and plans international telecommunications. It also participates as an executing agency in the United Nations Development Program.

Structure of the Union

The Union comprises the following organs:

- the Plenipotentiary Conference, which is the supreme organ of the Union;
- World or Regional Administrative Conferences, which regulate international telecommunications and the use of the frequency spectrum;
- the Administrative Council, composed of 41 members, which supervises the administrative functions and coordinates the activities of the ITU Headquarters and examines and approves the budget;
- the four permanent organs: the General Secretariat, the International Frequency Registration Board (IFRB), the International Radio Consultative Committee (CCIR), and the International Telegraph and Telephone Consultative Committee' (CCITT). The General Secretariat is directed by a Secretary-General, who is assisted by a Deputy Secretary-General. The IFRB consists of five independent members, elected by the Plenipotentiary Conference and assisted by a specialized secretariat. Each of the CCIs works through the media of its Plenary Assembly, study groups, and a Director, who is assisted by a specialized secretariat. Their activities are described in the sections which follow.

The administrations of the members of the Union are major participants in Union activities, as are recognized private operating agencies and scientific and industrial organizations, especially in the work of the CCIs.

World and Regional Conferences

One of the most important functions of the Union is the conduct of World and Regional Conferences. Except for the conferences held in 1959 and 1979 in Geneva to review the entire Radio Regulations, and that held in 1973 to review the telegraph and telephone regulations, each conference in the past couple of decades has confined its work to specific subjects such as MF broadcasting, VHF sound broadcasting, satellite broadcasting, space services, aeronautical services and mobile services.

The most recent such conferences have included:

¹In 1956, the CCIF and the CCIT were merged to become the CCITT.

- the Special Regional Conference, 1960;
- the European VHF/UHF Broadcasting Conference, Stockholm, 1961;
- the African VHF/UHF Broadcasting Conference, 1963;
- the Extraordinary Administrative Radio Conference to allocate frequencies for space telecommunications, 1963;
- the Extraordinary Administrative Radio Conference to allocate frequencies for the aeronautical mobile service, 1966;
- the World Administrative Radio Conference for maritime mobile services, 1967;
- the World Administrative Radio Conference for aeronautical mobile services, 1968;
- the World Administrative Radio Conference for space telecommunications, 1971;
- the World Administrative Maritime Radio Conference, 1974;
- the Regional Administrative Radio Conference for LF/MF broadcasting in Regions 1 and 3, 1975;
- the World Administrative Radio Conference for planning the broadcasting satellite service in the 12-GHz band, 1977;
- the World Administrative Radio Conference, 1979;
- the Region 2 Administrative MF Broadcasting Conference, Rio de Janeiro, 1981;
- the Regional Administrative Radio Conference for FM sound broadcasting in the VHF band (Region 1 and certain countries in Region 3), 1982;
- the World Administrative Radio Conference for mobile telecommunications, 1983; and
- the Regional Administrative Radio Conference for planning (in Region 2) the broadcasting-satellite service in the 12-GHz band and associated feeder links, 1983.

All of these conferences took place in Geneva, unless otherwise stated.

An average of one World and one Regional Administrative Radio Conference are scheduled every year for the period 1983–1988, in accordance with the timetable of future conferences established at the Nairobi Plenipotentiary Conference, 1982.

These conferences include: the World Administrative Radio Conference for: Mobile Services (1987), High-Frequency Broadcasting Service (1st Session in 1984, 2nd Session in 1986); Space Services (1st Session in 1985, 2nd Session in 1988); the Regional Administrative Radio Conferences for VHF FM Broadcasting Service in Region 1 (2nd Session in 1984); MF Broadcasting Services, Region 2, to plan the additional band 1605–1705 kHz (1986); African VHF/UHF Broadcasting Conference (1987); and the Region 3 VHF/UHF Conference (1988).

General Secretariat

History

The historic 1865 Telegraph Conference was followed in 1868 by one in Vienna which made an important decision for the history of the Union and future international organizations. It set up a headquarters with a secretariat. The headquarters, established in Bern as the "Bureau of the Union," started with a staff of three. Modest though this beginning may have been, it established the principle of a permanent secretariat for intergovernmental organizations.

Structure and Functions

The General Secretariat is directed by the Secretary-General and assisted by the Deputy Secretary-General, both of whom are elected by the Plenipotentiary Conference. The Secretary-General takes all actions required to ensure economic use of the Union's resources, and is responsible to the Administrative Council for all the administrative and financial aspects of the Union's activities including technical cooperation programs, dissemination of information, and secretarial support for conferences and coordination of work with other organizations. The Secretary-General also acts as the legal representative of the Union.

A Coordination Committee ensures coordination at Headquarters among the permanent organs of the Union. In addition to the Secretary-General, who presides over the Committee, it consists of the Deputy Secretary-General, the Directors of the International Consultative Committees, and the Chairman and (from 1984) Vice-Chairman of the International Frequency Registration Board.

The Coordination Committee advises and gives the Secretary-General practical assistance on all administrative, financial, and technical cooperation matters affecting more than one permanent organ, and on external relations and public information. In its consideration, the Committee keeps fully in view the provisions of the Convention, the decisions of the Administrative Council, and the interests of the Union as a whole.

Activities

In addition to handling all the administrative and financial aspects of the Union's activities, including provision of computer services, the work of the General Secretariat covers a wide range of technical cooperation activities in support of telecommunication development; actions connected with the implementation of the provisions of the Administrative Regulations of the Union on operational questions; dissemination of information on telecommunication matters for operational and other purposes; provision of secretarial support to the Union's conferences; and coordination of the work of the Union with other international organizations. The work of information dissemination includes the coordination of data (and its publication) which the Members and their telecommunication operating agencies need to exchange through the Union to ensure the efficient day-to-day operation of telecommunication services of all kinds including communications with ships at sea.

In the area of technical cooperation, the orientation of action is towards the development of networks and human resources, with emphasis given to the latter. In pursuance of this policy, the Union has been associated with the establishment of a number of national and regional training institutions all over the world. The Union's activities in this field are directed towards the standardization of training and the development of courses. In this connection, the Union continues to actively pursue a project on course development in telecommunications (CODEVTEL) which is a modular approach. Teaching aids such as printed documents, and audio-visual aids such as slides, transparencies, and sound and video tapes, are prepared for each module in association

with subject-matter specialists. The modules thus prepared are in a standardized form permitting the widest possible exchange among developing countries. For the present, courses intended for the training of middle-level technicians have been given priority.

As far as networks are concerned, the Union is involved in the planning and development of regional networks such as those for Africa (PANAFTEL), the Mediterranean and Arab countries (MEDRABTEL), the Americas, Asia, and the Pacific; as well as in the planning (including preparation of specifications), operation, and maintenance of national networks. For this purpose, in addition to experts recruited for service in the region or country concerned, a Group of Engineers in the General Secretariat—made up of specialists in such fields as telephone switching, satellite communications, and broadcasting—is available at headquarters to undertake short-term consultancy missions at the request of administrations. The services of the Group of Engineers complement activities carried out by the Union's participation in the United Nations Development Program (UNDP) and programs financed from trust funds placed at the disposal of the Union by Member States and other entities and managed by the Secretary-General.

The development of networks involves the use of appropriate technologies. In this regard, studies concerning the application of satellite communications for regional and domestic networks are carried out from time to time. One such study involves the global use of high-powered satellites or transponders of satellites for domestic rural and remote-area communications. The system the study recommends is one that would be available to all developing countries, to provide intracountry connections over which thin-route communications to rural areas could be established. With high sensitivity and transfer-gain, and steerable-spot or area beams, the satellite design would permit the use of earth stations with 3-m antennas including power supplies suitable for installation in unelectrified rural areas.

The above study forms part of a project concerning the contribution of telecommunications to economic and social development carried out cooperatively with the Organization for Economic Cooperation and Development.

The report of this project² focuses on a number of issues concerning the relationship between telecommunications and socioeconomic development. It establishes the importance of indirect benefits that flow from telecommunications and underlines the need to give higher priority to investment in this sector. It questions the conventional wisdom of reaching investment decisions related to telecommunications on the basis of direct returns only.

In proclaiming 1983 as "World Communications Year: Development of Communications Infrastructure," with the ITU as the lead agency for coordinating the activities of the Year at the international level, the General Assembly of the United Nations recognized the fundamental importance of communication infrastructures as an essential element in the economic and social development of all countries. The Year was to provide the opportunity for countries to conduct an in-depth review and analysis of their policies on communications development and to stimulate accelerated

growth of communications infrastructures. In addition to a number of projects in different countries on the use of new techniques such as digital switching and transmission, several seminars have been organized in different regions of the world on the role of telecommunications in development and the choice of appropriate technology.

A highlight of the Year was the world telecommunication exhibition TELECOM '83, which included the World Telecommunication Forum at which the policy, economic, financial, technical, and legal aspects of telecommunications were discussed by a large number of national policy makers, leaders of industry, telecommunication specialists, and legal experts.

Another important event of the Year was the commencement of work by the Independent International Voluntary Commission for Worldwide Telecommunication Development, set up by the ITU's Plenipotentiary Conference in Nairobi in the autumn of 1982. With a membership of 17 eminent personalities drawn from the highest decision-making levels and representing various disciplines, the Commission will identify the best methods of transfer of resources and recommend a range of methods calculated to accelerate telecommunications development. The recommendations of the Commission are expected to have a major impact on the technical cooperation activities of the Union.

The Union collects, analyzes, and publishes—in a readily usable form—data on a wide variety of subjects for the task of disseminating administrative and operational information on telecommunications. These data include lists like those on ship stations and telegraph offices, which fall into the category of service documents, the contents of which are specified in the Administrative Regulations of the Union and are indispensable for the efficient operation of the concerned telecommunication services. The publication of these service documents responds in part to one of the basic purposes of the Union: ensurance of the smooth operation of international telecommunication service of all kinds.

Information of a statistical nature is also published periodically. Such information is of considerable use to administrations in their planning activities. Other publications include notifications, operational bulletins, and circulars which keep administrations posted with up-to-date information on various matters of importance in domestic and international telecommunications, and in actions concerned with the relations between member countries in terms of the provisions of the International Telecommunication Convention and the Administrative Regulations which form a part thereof. Notifications appear once a month, whereas operational bulletins are published every fortnight, and circulars are issued as and when necessary.

A monthly *Telecommunication Journal* is also published from the Union's headquarters. In this journal, information is included on the activities of the various permanent organs of the Union as well as articles on telecommunication subjects of topical interest to administrations.

It is Members who basically furnish all relevant material to conferences by way of direct proposals or through proposals formulated in a CCI Plenary Assembly. It is also the Members who finally agree on regulatory provisions to be adopted in regard to the various agenda items concerned. In these processes, the General Secretariat provides considerable material support in the way of conference facilities, documentation, translation, interpretation, preparation of the

²ITU/OECD report, "Telecommunications for development," ITU, Geneva, June 1983.

meeting minutes, and publication of the Final Acts, which eventually become part of the Administrative Regulations and have international treaty force.

In order to carry out its mandate as the specialized agency in the United Nations system responsible for telecommunications, the Union maintains liaison with other United Nations agencies to ensure that telecommunications activities are adequately coordinated. In addition to the United Nations and the UNDP, the organizations with which the Union collaborates include: UNESCO, for matters concerning communications in general, and for the International Program for the Development of Communications (IPDC) in particular; the Universal Postal Union (UPU), for studies involving the introduction of the electronic mail service, and other matters having a commonality of postal and telecommunications interests; the International Maritime Organization (IMO), for questions concerning radio-communications services for maritime applications; the International Civil Aviation Organization (ICAO), for similar questions in the aeronautical field; the World Meteorological Organization (WMO), for studies related to telecommunications networks and services for meteorological applications; and the Office of the United Nations Disaster and Relief Coordinator (UNDRC) for disaster relief communications.

The Union also maintains working relationships with other international organizations with an interest in telecommunications, including those involved in satellite communications, and regional broadcasting and telecommunications organizations.

Furthermore, the Union maintains close liaison with the United Nations Committee on the Peaceful Uses of Outer Space and its two subcommittees, one legal and the other scientific and technical. In this context, the Union publishes an annual report entitled "Telecommunications and the Peaceful Uses of Outer Space." This report is of major use not only to the above-mentioned Committee and subcommittees, but also to others among all national telecommunications administrations.

The International Frequency Registration Board (IFRB)

In the mid 1940's, immediately following the end of WWII, the use of the radio-frequency spectrum was growing at a rate beyond the means for multilateral coordination of each assignment, particularly in the high-frequency bands (3-30 MHz), which provided the only means for transoceanic radio communications at the time and were therefore heavily used for intercontinental radio communications, as well as for national fixed services, mobile services, and international broadcasting.

Technical progress had accelerated during the war years and many new services had been introduced, with the result that the Madrid Convention (1932) and the Cairo Radio Regulations (1938), although still in effect, were largely out-of-date.

Since 1928, the Bureau of the Union at Bern had been engaged in compiling the ITU List of Frequencies which contained the characteristics and date of notification of all frequencies in use throughout the world, together with the notified date of going into service. However, due to the circumstances prevailing during the war years, many frequencies in use had not been notified and many frequencies listed were no longer used. Further, in compiling this

List of Frequencies, the Bureau simply recorded the frequency notified by an administration regardless of whether or not its use would conflict with an existing listing.

The need for an international administrative body through which administrations could regulate the use of frequencies to avoid harmful interference was recognized at the Atlantic City Conferences (1947), which expanded and made obligatory the Table of Frequency Allocations for the various radio services. Accordingly, the Atlantic City Plenipotentiary Conference established the International Frequency Registration Board (IFRB). The Board held its first meeting on September 28, 1947 under the auspices of the Atlantic City Radio Conference.

The International Frequency Registration Board currently consists of five independent members elected by the Plenipotentiary Conference (Nairobi, 1982) who serve not as representing their respective countries or regions, but as custodians of an international public trust.

Objectives and Functions of the IFRB

The mandate of the Board contained in the Convention and in Article 10 of the Radio Regulations is essentially that adopted by the Atlantic City Conferences in 1947, to which further provisions have been added in 1959, 1971, 1973, 1979, and 1982. These additional provisions cover (a) extensive studies on the use of the radio frequency spectrum, (b) new duties relating to radio services using space techniques and the geostationary satellite orbit, and (c) special assistance to developing countries.

The concise texts from the Convention which govern the objectives of the Board follow:

764. The essential duties of the International Frequency Registration Board shall be:

77a) to effect an orderly recording and registration of frequency assignments made by the different countries in accordance with the procedure provided for in the Radio Regulations and in accordance with any decision which may be taken by competent conferences of the Union, with a view to ensuring formal international recognition thereof;

78b) to effect, in the same conditions and for the same purpose, an orderly recording of the positions assigned by countries to geostationary satellites;

79c) to furnish advice to Members with a view to the operation of the maximum practical number of radio channels in those portions of the spectrum where harmful interference may occur, and with a view to the equitable, effective, and economical use of the geostationary satellite orbit, taking into account the needs of Members requiring assistance, the specific needs of developing countries, as well as the special geographical situation of particular countries.

80d) to perform any additional duties, concerned with the assignment and utilization of frequencies and with the equitable utilization of the geostationary satellite orbit, in accordance with the procedures provided for in the Radio Regulations, and as prescribed by a competent conference of the Union, or by the Administrative Council with the consent of a majority of the Members of the Union, in preparation for or in pursuance of the decisions of such a conference;

81e) to provide technical assistance in making preparations for and organizing radio conferences in consultation, as appropriate, with the other permanent organs of the Union, and with due regard for the relevant directives of the Administrative Council in carrying out these preparations; the Board shall also provide assistance to the developing countries in their preparation for these conferences.

82 f) to maintain such essential records as may be related to the performance of its duties.

The Board's original terms of reference have not needed any major change since its constitution in 1947; however its field of activities has broadened and its order of priorities has evolved.

This evolution of priorities can be seen in three main phases:

(i) in the 1950's, the Board's principal and most urgent task was to assist administrations in bringing the Table of Frequency Allocations into effect by the elimination of out-of-band assignments, the establishment of the Master International Frequency Register, and the implementation of the appropriate notification, examination, and registration procedures;

(ii) in the 1960's, while continuing to keep the Master Register up-to-date and to apply the related procedures, the Board was required to take an increasingly active part in the various stages of coordinating frequency utilization among administrations before new stations were brought into service—especially in Broadcasting and Mobile Services and in services using space techniques. It was also responsible for ensuring that administrations observed the procedural time limits, failing which they could, in certain cases, lose previously acquired rights; and

(iii) since the late 1960's, while continuing to carry out its duties in connection with the coordination, notification, examination and registration of frequency assignments, the Board has been required to develop its activities in connection with the technical preparation of world and regional administrative radio conferences, as required by RR 1003 to enable conferences to complete their work successfully within the time limits laid down by the Administrative Council. Moreover, realizing the growing complexity of the decisions of these conferences, the Board has, on its own initiative, undertaken studies and developed circular-letters addressed to all Members of the Union aimed at facilitating the implementation of conference decisions.

Present Activities of the IFRB

The present activities of the IFRB in relation to frequency matters above include:

a) examination of notices of new frequency assignments and of changes to frequency assignments received from administrations, and their entry in the Master Register as well as the application of coordination procedures between Members of the Union in accordance with the provisions of the Radio Regulations as established by the Radio Conference 1959 and reviewed by subsequent World Conferences;

b) special on-going tasks assigned to the IFRB by the above conferences as well as by subsequent Regional or other World Conferences;

c) technical assistance in the preparation for and organization of future planned administrative radio conferences;

d) preparatory work for and participation in CCIR meetings;

e) review of entries in the Master Register;

f) investigation of harmful interference cases;

g) assistance to administrations;

h) courses and seminars, etc.;

i) preparation of publications related to the above.

Regulatory

Procedures governing notification and registration of frequency assignments in the Master International Frequency Register may be broadly subdivided into the acts of coordination, notification, examination, and registration.

In 1947, with the rapidly expanding use of radio communications, the administrations found it necessary to develop more sophisticated and mandatory procedures governing the use of the spectrum. The intent of these procedures was in effect to permit a more coordinated use of the spectrum prior to the actual use of frequencies by administrations, thus reducing the probability of harmful interference. In the late 1950's and 1960's, with the widespread use of more advanced terrestrial systems (radio relay links) and with the advent of space radio communications, there was a need to develop procedures for increased prior coordination of the use of frequencies and even more complex technical criteria. Accordingly, this has been a major preoccupation of the radio conferences convened by the Union since 1963.

As for the problem of harmful interference, each administration wishing to put into service a new station that is likely to cause interference outside the territory of the country in which it is located, is under obligation to send a notice of its intentions to the IFRB, giving the technical characteristics of the station concerned. The Board examines the notice for its conformity with the Table of Frequency Allocations and the other provisions of the Radio Regulations and then assesses the extent to which the use of the frequency, under the notified conditions, could cause interference to stations of any other administrations recorded in the Master International Frequency Register. If the Board finds that there is a probability of such interference, the notice is returned to the notifying administration, which then, normally, searches for an alternative frequency or modifies the characteristics of the station in such a way as to obviate the probable harmful interference. If the Board finds that there is little or no probability of harmful interference with existing entries of other administrations in the Master Register, the notices would normally receive a favorable finding. The particulars of the assignment are entered in the Master Register, accompanied by all relevant remarks, which establishes the legal status of the assignment together with other existing and future assignments.

In summary, it may be said that the notification and registration procedures were initially developed as a means of ensuring that the agreed-upon rules for the use of the spectrum were being respected by all administrations. With the arrival of space techniques, insofar as the frequency bands shared between space and terrestrial radio communications are concerned, these procedures were confirmed and further developed to include the *obligatory coordination* of the use of frequencies *prior* to the notification and registration procedures which apply for stations being put into service.

Future Activities of the IFRB

The World Administrative Radio Conference 1979 (WARC-79)—in the provisions of the Radio Regulations and in the

Resolutions and Recommendations of the Geneva 1979 Conference—entrusted the IFRB with the responsibility of providing assistance in preparation for and in the implementation of the decisions of World or Regional Administrative Radio Conferences planned for the period until 1988; this assistance is to be provided either individually to any telecommunications administration of a Member of the ITU or collectively to the entire membership of the ITU.

Some future additional activities of the IFRB which arise from the decisions of WARC-79 are already in hand and will be of a continuing nature. Among these are:

- (i) development of the internal procedures for the application of the new provisions of Article 12 of the Radio Regulations (RR 1218 procedure for choice of frequencies, RR 1255 enquiry procedure);
- (ii) preparation and maintenance of a handbook on procedures (Resolution No. 6 of the WARC-79); and
- (iii) organization of and participation in the activities of the development of the national frequency management units in developing countries, in accordance with Resolution No. 7 of the WARC-79 and Resolution No. 12 of the Plenipotentiary Conference, 1982.

Many modified or new provisions of Articles 11, 12, 13, 14, 15 (Appendix 30 to the Radio Regulations), and 16, as adopted by the WARC-79, emphasize the need for the IFRB to provide assistance to administrations in the application of the procedures contained in these articles.

The provisions of several Resolutions of the WARC-79 relating to procedures of a nature similar to the articles cited above, together with decisions of regional administrative radio conferences, also require the IFRB to provide assistance to administrations, particularly those of developing countries, in application of the relevant procedures.

In order to be able to provide such assistance on short notice and within a reasonable period of time in response to any request from administrations, either individually or collectively, and in carrying out its day-to-day tasks, the Board is presently engaged in improving its working methods by means of the extended use of the computer. In particular, the initial improvements are in connection with receipt and examination of frequency assignment notices with a view to recording them in the Master International Frequency Register, which is maintained by the IFRB, along with related communications concerning coordination of the use of the radio frequency spectrum and geostationary-satellite orbit. Due to the financial implications of such a large-scale automation in the complex tasks of the IFRB, this work will be spread over about the same period, namely up to 1989.

These activities will be further augmented by the decisions taken by the World and the Regional Administrative Radio Conferences to be held between 1983 and 1988, which undoubtedly will require the IFRB to carry out additional tasks related to its present mandate.

International Radio Consultative Committee (CCIR)

Terms of Reference

Article 11 of the International Telecommunication Convention (Nairobi, 1982) states that the duties of the CCIR shall

be to study technical and operating questions relating specifically to radio communications without limit of frequency range, and to issue recommendations on them. Such studies shall not generally address economic questions; where they involve comparison of technical alternatives, however, economic factors may be taken into consideration.

The Members of the CCIR include the administrations of all Members of the ITU and a number of recognized private operating agencies, each of which participates with the approval of the Member which has recognized it. In addition, scientific or industrial organizations that are engaged in the study of telecommunication problems, or in the design or manufacture of equipment intended for telecommunication services, participate in an advisory capacity in the work of the study groups, with the approval of the administrations of the countries concerned. Some international organizations and regional telecommunication organizations are also recognized as participants.

Organization and Working Methods

The CCIR works through its Plenary Assembly, which sets up study groups to deal with questions to be examined and elects a Director (who is provided with a specialized secretariat to assist him in carrying out his duties). (Starting with the next ITU Plenipotentiary Conference, the Directors of the CCIRs will be elected by the Plenipotentiary Conference, instead of by their Plenary Assemblies.)

The results of the work of the study groups are mainly presented in the form of Reports and Recommendations, which are continuously under review. The questions studied are mostly those decided upon by the study groups themselves and subsequently adopted by a CCIR Plenary Assembly. In the 4-year interval (approximately) between plenary assemblies, new questions can be introduced when requested or approved by correspondence from at least 20 members of the ITU. Questions may also be referred to the CCIR by an ITU Plenipotentiary Conference, by an administrative conference (such as the WARC 1979), by the ITU Administrative Council, by the CCITT, or by the IFRB. Eleven CCIR Study Groups and two joint CCIR/CCITT Study Groups administered by the CCIR carry out technical studies in accordance with the decisions of the most recent Plenary Assembly:

Study Group and Descriptive Title

- 1—Spectrum Utilization and Monitoring
- 2—Space Research and Radioastronomy Services
- 3—Fixed Service at Frequencies below about 30 MHz
- 4—Fixed-Satellite Service
- 5—Propagation in Nonionized Media
- 6—Propagation in Ionized Media
- 7—Standard Frequencies and Time Signals
- 8—Mobile, Radiodetermination, and Amateur Services
- 9—Fixed Service using Radio-Relay Systems
- 10—Broadcasting Service (Sound)
- 11—Broadcasting Service (Television)
- CMTT—CCIR/CCITT Joint Study Group for Television and Sound Transmission
- CMV—CCIR/CCITT Joint Study Group for Vocabulary and Related Subjects

Technical Substance

In its 55-year history, the CCIR has established technical standards and signal parameters for a wide variety of radio-communication services ranging from the fixed and mobile services to the fixed-satellite service and satellite broadcasting, thereby facilitating international operation. Quality and performance standards have been set in many areas, and new techniques and systems have been introduced with appropriate international compatibility for interworking and use of the spectrum.

In addition to the various radio-communication services, the CCIR work involves general disciplines such as propagation, space research, vocabulary, and spectrum utilization.

Specialists from the various radio-communication disciplines participate in the work of the CCIR Study Groups. The interaction of these specialists from many countries and varying backgrounds enables them to exchange ideas and to gain insight into technical viewpoints that are sometimes diametrically opposed, but more often are improved as a result of exposure to a broad base of critical, creative examination. The harmonization of technical ideas is a major function of the CCIR.

In addition to the contributions received from administrations, participating international organizations, and regional telecommunication organizations, contributions to the work of the CCIR come from recognized private operating agencies and scientific and industrial organizations. It is through these channels that the CCIR has benefited from the work of members of the IEEE and its predecessors.

Results

Even a partial list of the Reports and Recommendations of the CCIR in its 55-year lifetime would fill several pages. It is nevertheless worthwhile to list a few presently in effect:

- Selection of frequencies for space telecommunications;
- Radiation diagrams of earth-station antennas;
- Technical factors affecting the efficient use of the geostationary-satellite orbit;
- Hypothetical reference circuit and hypothetical reference digital path for the fixed-satellite service;
- Technical and operating characteristics for maritime-mobile satellite systems (in cooperation with INMARSAT);
- Standards and operational procedures for maritime-mobile radio communications;
- Digital selective calling for the international maritime mobile service;
- Basic spectrum utilization and monitoring using the computer;
- Technical characteristics of broadcasting satellites and associated earth stations;
- Standards for the international exchange and relay of television programs over long distances;
- Channeling arrangements and transmission standards for international radio-relay systems;
- Performance criteria and measurement methods for analog and digital radio-relay systems;
- Standards for interchange of television programs;
- International standards for color television;
- Standards in sound broadcasting for frequency modulation and stereophonic transmission;

- Standards for audio and video tape recording for the international exchange of programs on film and tape;
- Promulgation of ground-wave propagation curves;
- Basic solar indices for ionospheric propagation predictions;
- Computational method for HF skywave field-strength and transmission loss;
- Prediction methods for MF and LF field strengths;
- Standard groundwave propagation curves (10 kHz to 10 MHz);
- Tropospheric propagation calculation methods;
- Rainfall climatological classification for propagation calculations;
- Coordinated Universal Time (UTC);
- ARQ error-correcting system and Lincompex system, for HF radiotelegraphy and HF radiotelephony, respectively;
- Protection criteria for radio astronomy and related sciences;
- Radio-communication requirements for systems to search for extraterrestrial intelligence;
- Radio communications for meteorological satellite systems; and
- Radio communications for earth exploration satellites.

The most significant result of the latest CCIR Plenary Assembly was the adoption of a single extensible family of compatible digital coding standards of digital television for studios, based on component coding.

Trends

The rapid changes taking place in the very structure and nature of the worldwide telecommunication network are reflected in the contributions to the work of the CCIR in the 1982-86 study period.

Satellite communications remains at the forefront of CCIR activity, but there are also developments in the more traditional transmission means. The effective and efficient use of the geostationary orbit is one of the major areas of concern to a number of CCIR Study Groups. Antenna patterns for earth stations and satellites, modulation and coding techniques, and interference criteria are primary topics of interest.

The emphasis of work in the fixed-satellite service has gradually shifted from the adaptation of technology based on terrestrial systems to the development of new standards, particularly for the introduction of digital transmission and for the use of frequencies above 10 GHz. Present contributions place heavy emphasis on the use of frequencies above 15 GHz, digital systems, frequency reuse techniques, and improved antenna characteristics to increase the capacity of the geostationary orbit.

This latter emphasis is heavily influenced by the evolution towards an Integrated Services Digital Network (ISDN), which provides an impetus towards the use of digital signal processing and digital transmission.

A scarcity of data on the effects of rain in areas of high rainfall and high rainfall rates in tropical climates has resulted in increased emphasis on this aspect in the work of the CCIR.

Dissemination of standard frequencies and time signals by satellite will hopefully circumvent many of the difficulties

and limitations which have attended the various ground-based services. At the present state of development in the space segment there are a number of competing system designs which are under consideration by the CCIR and which may provide a basis for this service.

There is increased interest in the use of data relay satellites and also in the use of both active and passive sensors. Recent discoveries on the nature of galaxies and the universe by means of radio astronomy have underscored the importance of work in this field.

Strides being made in the design and manufacture of simple, inexpensive earth stations for accessing information from Earth-exploration and meteorology satellites are of primary importance.

Presently, the most important work on maritime satellite communications (in collaboration with IMO and INMARSAT) is in preparing a coordinated trials program for various satellite emergency position-indicating radio beacons (EPIRBs) which will lead to operating tests and the ultimate preparation of recommendations for a satellite EPIRB system.

Studies for an aeronautical satellite system started under the auspices of the International Civil Aviation Organization (ICAO) have been followed closely by the CCIR, which has provided an ICAO panel with technical and operational bases for an aeronautical satellite system which could serve to improve the safe operation of aircraft, especially on transoceanic flights.

There is also considerable interest at present in land-mobile satellite systems and the radio-determination and radio-navigation satellite services.

The development of standards for enhanced-quality and high-definition television systems will continue towards the goal of a single international standard for television transmission, perhaps based on the standards developed for the single extensible family of compatible digital coding for television.

By its nature, the work of the CCIR is of benefit to all participants. Recently, special emphasis has been given to make the Reports and Recommendations more useful to developing countries in particular. Seminars on satellite communications and propagation have been organized and special publications have been prepared in handbook form on subjects of special interest to these countries. Topics include satellite broadcasting, fixed-satellite service, and computer-aided spectrum management and monitoring.

Radio Conferences

Through the years, one of the most important activities of the CCIR has been to support radio conferences by providing the technical bases for decision making. There is a long list of such conferences, both past and future, as given elsewhere.

The CCIR has prepared extensive technical reports for each of these conferences. In view of the ever-increasing work load and complexity of such conferences, the XVth Plenary Assembly of the CCIR (1982) decided that the CCIR could call special joint meetings of concerned study groups to prepare conference reports. The first such Conference Preparatory Meeting (CPM) was held in June 1982 and produced a detailed technical report for the 1983 Regional Administrative Radio Conference (RARC) for satellite broadcasting in Region 2.

There is a heavy schedule of ITU radio conferences for the remainder of this decade. The CCIR is now preparing for a CPM to be held in June/July 1984 that will produce a technical report for the first session (1985) of the World Administrative Radio Conference on the use of the geostationary-satellite orbit and the planning of the space services using it.

The CCITT

History of the CCITT

The roots of CCITT, one of the standardizing arms of ITU, go back to the creation of CCIT and CCIF by a number of European countries in the 1920's to advise member countries on harmonizing their activities in building and running telecommunications networks: CCIT for telegraphy and CCIF for telephony. A couple of years later, AT&T—as the *de facto* standards maker in the American arena—joined in to contribute their immense knowledge on the various aspects of telecommunications.

Thus, CCIT and CCIF changed in this manner from a regional organization to an international organization, representative of a considerable portion of the world. Evolution to the global dimension was accomplished by the CCI's joining the International Telecommunication Union in 1932 and the merger of CCIT and CCIF into a single organization, the CCITT, in 1956.

Although the ITU, together with the CCITT, is an inter-governmental organization, the principle has been established that its meetings are not held behind closed doors, accessible only to representatives of countries or operating agencies. On the contrary, it has always been recognized that without the assistance of industry and scientific organizations, the work of CCITT would lose contact with the newest developments and technological trends, and that without user representation one of the most important factors would be excluded: the customer who will use the services. This in-principle tri-partite representation in the CCI's is perhaps unique in the world of international standardization. Although, legally speaking, the output of CCITT does not bind the members, the texts in the form of Recommendations are based on international consensus and they carry the power of common acceptability and common sense.

Objectives of the CCITT

The primary objectives of the CCITT are to standardize, to the extent necessary, techniques and operations in telecommunications to achieve end-to-end compatibility of international telecommunication connections, regardless of the countries of origin and destination. In the beginning of CCITT this meant to standardize the international portion of public telecommunication networks, but over the years it has become apparent that CCITT standards are useful also for national applications, for example, to avoid costly signal conversions at the international gateway or to cut down the number of proprietary interfaces of terminals to a small number of international multipurpose interfaces. This potential of CCITT Recommendations to be used also for national portions of the networks has certainly been the reason for

many purchasers of telecommunication equipment to request from their suppliers that their national and even local equipment comply with CCITT standards, wherever they exist. One example of this is the now-famous Recommendation X.25 to interface a customer with a packet-switched public data network. Quite a number of manufacturers of data equipment are now offering this interface while a couple of years ago there was a multitude of proprietary interfaces, not compatible with each other.

Another example is the International Signaling System No. 7 (Recommendation Q.701-Q.741), a common-channel signaling system for various applications (telephony, circuit switched data) which may also be considered a powerful national system for a great number of applications.

Working Procedures of the CCITT

The main principles of the working procedures of the CCITT are set out in the International Telecommunication Convention, whereas the detailed procedures are contained in various Resolutions of the CCITT Plenary Assemblies.

The work program of the CCITT in the various domains—such as telephone switching, transmission, or optical fiber technology—is established at every Plenary Assembly in the form of Questions submitted by the various Study Groups based on requests made to the Study Groups by their members. The Plenary Assembly assesses the various Study Questions, reviews the scope of the Study Groups, creates new or abolishes existing Study Groups, and allocates Questions to them. The Plenary Assembly also appoints the chairmen and vice-chairmen of all Study Groups for the new study period.

Based on these decisions and their list of Questions, the Study Groups organize their work (that is, which Questions are to be dealt with by the Plenary of the Study Group, by a Working Party, a Special Rapporteurs' group, or an *ad hoc* group) and appoint the Working Party Chairmen, Special Rapporteurs, etc.

At the beginning of each new study period, immediately after a Plenary Assembly, the CCITT Secretariat sends a circular letter to all members (administrations, carriers, manufacturers, scientific organizations, international organizations) which contains the complete work program of CCITT so that members can decide in which Study Group(s) they want to participate. During the course of a study period it is always possible for newcomers to become members and join in the work of CCITT. A similar procedure is followed in the CCIR.

Work on a CCITT Study Question should normally lead to one (or several) draft Recommendations to be submitted for approval to the next Plenary Assembly. All Recommendations, new or amended, will be printed in the various volumes of the CCITT Book after approval. A CCITT study period is in the order of four years. If a certain draft Recommendation is very urgent (for example, as happened during the present period with a Recommendation on teletext-interworking rules), a Study Group may apply the letter ballot procedure. The draft Recommendation has to be approved unanimously by the Study Group and then circulated to all Administrations for approval by correspondence. If adopted, the draft Recommendation becomes a Provisional Recommendation. The next CCITT Plenary As-

sembly is required to consider final approval of the Provisional Recommendation.

The work of CCITT in the field of public data networks illustrates the evolution of CCITT standards. Work in this field started with the decision of the IVth Plenary Assembly (1968) to form a Joint Working Party, reporting to several Study Groups (services, data transmission, switching) on "New Networks for Data Transmission." There was only one, albeit very broad, study point: a new telegraph-type network for message and data transmission.

The main factor which triggered these new studies was the perception that data transmission over switched voice channels was bound to certain characteristics of this network which were not favorable for some specific applications.

As a result of studies by this Joint Working Party, the *CCITT Green Book* (1972) already contained 11 Recommendations dealing with subjects such as user classes of services and facilities offered by public data networks, terminal interfaces, transmission multiplex schemes, and signaling systems between anisochronous circuit-switched data networks. The study program for 1972-76 expanded to 25 work items, including the notion of packet services and value-added features, sponsored by the early implementation in the United States of private packet networks like the ARPANET. It was recognized by CCITT that data network techniques have few similarities with telegraphy techniques. Thus, the Joint Working Party became a full-fledged Study Group.

At the VIth Plenary Assembly (1976), 24 Recommendations were approved, ranging from packet services to transmission, signaling and switching between circuit-switched data networks. This was also the first appearance of the now-famous X.25 for packet-mode terminal interfaces. The study program for the period 1976-80 comprised 34 Questions; the main thrusts were on the international interface between public packet-switched data networks, numbering and routing plans, and quality of service.

The VIIth Plenary Assembly (1980) had before it a total of 39 new or amended Recommendations on public data networks which consolidated the work so-far achieved. However, the work still increased with 41 Questions concentrating on the problem of interconnecting dissimilar data networks (for example, circuit switched to packet switched), on interconnecting with other public networks carrying data (for example, the analog telephone network or the maritime-mobile satellite service), on the use of the rapidly emerging ISDN for data transmission, and on value-added features such as message-handling facilities provided by public data networks. By the time of the VIIIth Plenary Assembly (autumn 1984) CCITT Study Group VII will have sifted through some 42 000 pages of Contributions in 4 years and produced more than 22 new Recommendations.

Trends and tendencies in the digital world indicate that in the coming years the standards on public data networks will be further consolidated and revised, taking into account new data-transmission applications and in particular the requirements of new telematic services. At the same time, the appropriate features of ISDNs will have to be scrutinized very thoroughly as to what extent they lend themselves to high-quality data transmission (as offered by dedicated public data networks). Interconnection procedures will have to be devised and multipurpose terminal interfaces developed to take full advantage of the inherent capabilities of ISDNs.

Range of CCITT Recommendations

CCITT Recommendations cover all important aspects of international public telecommunications, be they technical, operating, or tariff principles. It is firm CCITT policy to strive for one single standard for a given application and to avoid the ambiguity of double- or multi-standards, an aim which of course requires worldwide consensus among telecommunication administrations.

The following list illustrates the application of CCITT Recommendations:

- Series A Recommendations (A.1–A.21): Organization of the work of CCITT
- Series B Recommendations (B.1–B.12): Means of expression
- Series C Recommendation (C.1): General telecommunication statistics
- Series D Recommendations (D.1–D.401): General tariff principles
- Series E Recommendations (E.100–E.543): International telephone service operation
- Series F Recommendations (F.1–F.300): Telegraph and telematic service operations and tariffs
- Series G Recommendations (G.100–G.171): General characteristics of international telephone connections and circuits
 - (G.211–G.651): International analogue carrier systems
 - (G.701–G.941): Digital networks-transmission systems and multiplexing equipment
- Series H Recommendations (H.11–H.61): Line transmission of non-telephone signals
- Series J Recommendations (J.11–J.77): Sound program and television transmissions
- Series K Recommendations (K.1–K.19): Protection against interference
- Series L Recommendations (L.1–L.8): Protection of cable sheaths and poles
- Series M Recommendations (M.10–M.761): General maintenance principles, maintenance of international carrier systems, and telephone circuits
 - (M.800–M.1235): Maintenance of international VFT, facsimile, international leased circuits
- Series N Recommendations (N.1–N.67): Maintenance of international sound program and TV transmission circuits
- Series O Recommendations (O.11–O.171): Specifications of measuring equipment
- Series P Recommendations (P.10–P.79): Telephone transmission quality
- Series Q Recommendations (Q.1–Q.118): General recommendations on telephone switching and signaling, interface with the maritime service
 - (Q.120–Q.180): Specifications of Signaling Systems Nos. 4 and 5
 - (Q.251–Q.300): Signaling System No. 6
 - (Q.310–Q.490): Signaling Systems R.1 and R.2
 - (Q.501–Q.507): Digital transit exchanges
 - (Q.601–Q.685): Interworking of signaling systems
 - (Q.701–Q.741): Specification of Signaling System No. 7
- Series R Recommendations (R.2–R.140): Telegraph transmission
- Series S Recommendations (S.3–S.100): Alphabetical telegraph and telematic services terminal equipment

Series T Recommendations (T.0–T.35): Terminal equipment and transmission for facsimile services

Series U Recommendations (U.1–U.61): Telegraph switching

Series V Recommendations (V.1–V.57): Data communications over the telephone network

Series X Recommendations (X.1–X.29): Data communication networks: services and facilities terminal equipment, interfaces

(X.40–X.180): Data communication networks:

transmission, signaling and switching, maintenance

Series Z Recommendations (Z.101–Z.104): Functional specification and descriptive language (SDL)

(Z.200): CCITT high-level language (CHILL)

(Z.311–Z.341): Man-machine language (MML)

This list currently contains several thousand CCITT standards, and the 1984 CCITT Plenary Assembly will add more than a hundred new Recommendations covering various telecommunication subjects.

Recent Developments and Trends

There are a number of recent developments which will bring about benefits and innovations in their respective fields, but it is not possible to quote them all. However, there is no doubt that one development will have an enormous impact on all the telecommunication services on our globe, be they telephony, telex, data, facsimile, or telematics; that development is the ISDN. As its name implies, it offers to support any public telecommunications service on the basis of digital transmission and switching with clusters of various terminal or multifunctional terminals working over the same subscriber line.

The inherent potential of ISDN will open up new services and opportunities hitherto unknown or technically too expensive and will, at the same time, dramatically cut the cost of classical services.

Conclusions

The International Telecommunication Union, in its 109-year history, has evolved as the focal point of world telecommunications. Its contributions to the development of the worldwide network are substantial. As the twenty-first century approaches, the ITU will be faced with increasingly complex problems relative to the ever-expanding occupancy of the frequency spectrum and the geostationary orbit. Solutions will have to be found.

As the ITU has adjusted in the past to the introduction of new technologies—radio transmission, long-distance cables, satellites—so it will also have to adjust to the restructuring of the worldwide telecommunication network that is expected to result from the introduction of the ISDN and from the widespread adoption of fiber-optic transmission means.

As the recognized international forum for the regulation and development of telecommunications, the ITU will be called upon to resolve many different issues. But, as long experience has shown, the conference processes and technical cooperation responsibilities entrusted to the General Secretariat, when coupled with the technical capabilities of the CCI and the regulatory expertise of the IFRB, provide tried and proven ways of arriving at solutions.

The International Telecommunication Convention from Madrid (1932) to Nairobi (1982): half a century in the life of the Union

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THE Plenipotentiary Conference at Nairobi coincided with the 50th anniversary of the one held at Madrid in 1932, which ended with the signing on 9 December of that year of the first "new style" Convention of the International Telecommunication Union.

These fifty years have been marked, moreover, by spectacular telecommunications development and the introduction of new services, matched throughout by the standardization of systems and equipment and international co-operation in the sector.

But what about the basic instrument? How did it develop during this half century? Now that the Nairobi Conference has ended, the time seems ripe to consider the more significant aspects of its development as reflected in the successive Conventions from Madrid to Nairobi.

To start with, let us recall that the term "telecommunication" was defined for the first time in the Madrid Convention as: "Any telegraphic and telephonic communication of signs, signals, writing, facsimiles and sounds of any kind, by wire, wireless or other systems or processes of electric signalling or visual signalling (semaphores)".

Concentrating on the basic principles which shape the Union, its objectives, governing bodies and essential activities, let us consider, as a sort of preliminary "annotated edition", the succession of changes and the more significant innovations that have emerged.

Preamble to the Convention

The preamble to the Madrid Convention (1932) described the Convention as

a treaty between States, affirming that "the... plenipotentiaries of the Governments named above, being assembled in conference in Madrid, have, by common consent and subject to ratification, concluded the following Convention".

The Convention of Atlantic City (1947) expressly recognized "the sovereign right of each country to regulate its telecommunication" and specified that the purpose of the Convention was to ensure "the effectiveness of telecommunication".

The Buenos Aires Convention (1952) added the objective of "facilitating relations between the peoples" by means of telecommunications.

In the Nairobi Convention (1982), the preamble was improved in that it recognizes "the growing importance of telecommunication for the preservation of peace and the social and economic development of all countries" and includes "facilitating... economic and social development among peoples" as one of the purposes of efficient telecommunication services.

Composition, purposes and structure of the Union

When the International Telegraph and Radiocommunication Regulations were incorporated in the Madrid Convention, the International Telegraph Union and the International Radio Union were merged to form the present International Telecommunication Union (ITU) and countries which belonged to either of the former Unions became Members of the ITU.

The Atlantic City Convention defined Members and Associate Members under *Composition of the Union*.

In the Malaga-Torremolinos Convention (1973), Article 1 on the composition of the Union took its present form and the category of Associate Member was removed. The principle of the universality of the Union was specified, its Members were listed (Annex 1) and the conditions of membership were defined.

The *rights and obligations of Members* are implicit in the provisions of the Convention as a whole. However, the Geneva Convention (1959) was the first to devote a specific article to the "rights of Members in respect of their participation in the conferences, meetings and consultations of the Union", as it appears in the Malaga-Torremolinos Convention, which also specifies that "Members... shall have the rights and shall be subject to the obligations provided for in the Convention".

The Madrid Convention did not establish the site of the Union headquarters although it referred repeatedly to "the Government of the country in which the Bureau of the Union has its seat". The Bureau was installed at Berne. Article 3, establishing the *seat of the Union* in Geneva, appeared in the Atlantic City Convention (1947).

Article 4 on the *Purposes of the Union* appeared for the first time in the Atlantic City Convention, where they were defined as follows:

- To maintain and extend international co-operation for the improvement and rational use of telecommunication of all kinds.
- To promote the development of technical facilities and their most efficient

operation with a view to improving the efficiency of telecommunication services, increasing their usefulness and making them, so far as possible, generally available to the public.

- To harmonize the actions of nations in the attainment of those common ends.

The second part of the article listed certain means of achieving those ends and required the Union to:

- Effect allocation of the radio frequency spectrum in order to avoid harmful interference.
- Foster the establishment of rates at levels as low as possible consistent with an efficient service and independent financial administration of telecommunication on a sound basis.
- Promote the adoption of measures for ensuring the safety of life.
- Undertake studies, formulate recommendations and publish information for the benefit of all Members.

The activities to be undertaken to meet the objectives were amended and were specified in all subsequent Conventions, with the exception of the Buenos Aires Convention, as follows: the Geneva Convention (1959) required the Union to “co-ordinate efforts to eliminate harmful interference ... and to improve the use made of the radio frequency spectrum” and to “foster the creation, development and improvement of telecommunication equipment and networks in new or developing countries by every means at its disposal, especially its participation in the appropriate programmes of the United Nations”; the Malaga-Torremolinos Convention also instructed it to “co-ordinate efforts with a view to harmonizing the development of telecommunications facilities, notably those using space techniques”.

The Nairobi Convention includes among the purposes of the Union “to promote and to offer technical assistance to developing countries in the field of telecommunications” and stipulates that to achieve that objective the Union should “foster international co-operation in the delivery of technical assistance to the developing countries”.

Anticipating Article 5, *Structure of the Union*, various articles appeared in the Madrid Convention on such organs of the Union as: the Plenipotentiary Conference, administrative conferences and the International Consultative Committees, which in those days were the Inter-

national Telegraph Consultative Committee (CCIT), the International Telephone Consultative Committee (CCIF) and the International Radiocommunication Consultative Committee (CCIR); there was also the Bureau of the Union which, although not a permanent organ, was the forerunner of the General Secretariat mentioned in the Atlantic City Convention.

The latter also mentions the Administrative Council and, as a permanent organ, the International Frequency Registration Board (IFRB). The International Telegraph and Telephone Consultative Committee (CCITT) also came into being with the amalgamation of the CCIF and the CCIT.

In the Malaga-Torremolinos Convention, a distinction is drawn between the Plenipotentiary Conference, which had always been known as such, administrative conferences and the Administrative Council, on the one hand, and the permanent organs, which were the General Secretariat, the IFRB, the CCIR and the CCITT, on the other.

The organizational structure of the Union gives it a federal character which differentiates it from the other United Nations specialized agencies.

No specific article was devoted to the *Plenipotentiary Conference* until the Atlantic City Convention. It was mentioned along with administrative conferences in the Madrid Convention, which also stated that “the provisions of the present Convention are subject to revision by conferences of plenipotentiaries of the Contracting Governments”, making these conferences the supreme body of the Union, although their status was not explicitly established until the Convention of Montreux (1965).

Besides the power to revise the Convention, already stipulated in the Madrid version, the Atlantic City Convention contained a specific list of the Plenipotentiary Conference’s duties. Let us now consider these together with the changes that have been made in other Conventions:

“Shall consider the report of the Administrative Council on the activities of the Union”: the content of this report underwent various changes, more formal than substantial in subsequent Conventions, and the Nairobi one specified that it should relate to “the activities of all the organs of the Union since the previous Plenipotentiary Conference”.

“Shall establish the basis for the budget of the Union for the next five years.” The Buenos Aires Convention specified this function together with the need to

“determine a fiscal limit for the ordinary expenditure” and, instead of “the following next five years”, read “until the next Plenipotentiary Conference”. The Malaga-Torremolinos Convention added that the fiscal limit on expenditure should be determined “after considering a programme of the administrative conferences and meetings”. The wording of this provision has been amended in the Nairobi Convention and the factors to be taken into account in determining the limit now include, rather vaguely, “any medium-term plan submitted by the Administrative Council”.

“Shall finally approve the accounts of the Union”, which in the Malaga-Torremolinos Convention became “shall examine the accounts of the Union and finally approve them, if appropriate”.

“Shall elect the Members of the Union which are to serve on the Administrative Council.” This electoral power was subsequently broadened to include, in the Geneva Convention, the Secretary-General and Deputy Secretary-General, in the Malaga-Torremolinos Convention, the members of the IFRB and, in the Nairobi Convention, the Directors of the International Consultative Committees.

“Shall, if necessary, enter into ... or revise any ... agreement between the Union and any other international body.” This provision was expanded in the Buenos Aires Convention to cover the examination of provisional agreements concluded by the Administrative Council, which was empowered to do so.

The final requirement was to “deal with such other telecommunication questions as may be necessary”.

The Buenos Aires Convention included the establishment by the Plenipotentiary Conference of the basic salary scales of elected officials and of all the Union staff, and the Malaga-Torremolinos Convention, the provision of “any general directives dealing with the staffing of the Union”.

What had previously been implicit was written out in the Geneva Convention (1959) which instructed the Plenipotentiary Conference to “determine the general policies for fulfilling the purposes of the Union”.

The interval between Plenipotentiary Conferences was first established as five years in the Atlantic City Convention. The Geneva and Montreux Conventions made no stipulation in this respect, while that of Malaga-Torremolinos stated “It shall be convened at regular intervals and normally every five years”. The Nairobi Convention states that “the

interval between successive Plenipotentiary Conferences shall not exceed six years”.

Administrative conferences are mentioned in the Madrid Convention under which their basic duty, which remains unchanged, was to revise “the provisions of the Regulations annexed to the present Convention”.

In the Atlantic City Convention they were divided into administrative conferences, radio administrative conferences and extraordinary administrative conferences. The first two were qualified in the Buenos Aires Convention as “ordinary”, a point which was implicit in the previous Convention given the extraordinary nature of the third, and a new category was added, namely, special conferences which included regional and service conferences. This classification was simplified in the Montreux Convention, which referred to world administrative conferences and regional administrative conferences.

Their duties, too, have evolved, although the basic one of revising the Regulations annexed to the Convention has always been retained. Thus, all the Conventions from Atlantic City to Montreux mentioned the duty of radio administrative conferences to elect the members of the IFRB; those from Atlantic City to Geneva specified that they should “deal with all other matters deemed necessary within the terms of the Convention and the General Regulations and any directive given by the Plenipotentiary Conference”. In subsequent Conventions this function was limited, revision of the General Regulations being removed and a stipulation being inserted in the Conventions of Montreux and Malaga-Torremolinos reading: “Administrative conferences shall normally be convened to consider specific telecommunication matters. Only items included in their agenda may be discussed by such conferences”. Lastly, the Nairobi Convention goes even further by stating: “When adopting resolutions and decisions, administrative conferences should take into account the foreseeable financial implications and shall try to avoid adopting resolutions and decisions which might give rise to expenditure in excess of the upper limits on credits laid down by the Plenipotentiary Conference”.

Regional administrative conferences will be able to deal only with “specific telecommunication questions of a regional nature” and their decisions “must in all circumstances be in conformity with the provisions of the Administrative Regulations”, a provision which has appeared in all the Conventions since Montreux.

Under the Atlantic City Convention, the *Administrative Council* was established as the body which “in the intervals between Plenipotentiary Conferences, ... shall act on behalf of the Plenipotentiary Conference within the limits of the powers delegated to it by the latter”.

The same Convention laid down that the Council “shall be composed of 18 Members of the Union elected by the Plenipotentiary Conference with due regard to the need for equitable representation of all parts of the world”. The Members ... are eligible for re-election. The number was increased to 25 at Geneva, to 29 at Montreux, to 35 at Malaga-Torremolinos and to 41 at Nairobi.

Each Member has one vote, as was already provided at Atlantic City. This principle, although not so worded in the later Conventions of Malaga-Torremolinos and Nairobi, is still valid since it is stipulated that “each Member of the Council shall appoint a person to serve on the Council ...”.

While the Atlantic City Convention provided “In cases not covered by the General Regulations, it (the Administrative Council) may adopt its own rules of procedure”, the formulation “The Administrative Council shall adopt its own rules of procedure” appeared in the Convention of Buenos Aires and is still used today.

Other tasks of the Administrative Council include taking “steps to facilitate the implementation by the Members of the provisions of the Convention, of the Administrative Regulations, of the decisions of the Plenipotentiary Conference, and, where appropriate, of the decisions of other conferences and meetings of the Union”, as provided in the Convention of Atlantic City although the present wording dates from Malaga-Torremolinos; ensuring “the efficient co-ordination of the work of the Union”, a provision in the Atlantic City Convention which was supplemented at Malaga-Torremolinos by the words “and exercise effective financial control over its permanent organs”; the Geneva Convention specified the promotion of international co-operation, especially through Union participation in the appropriate programmes of the United Nations; lastly, the Nairobi Convention requires that the Council “shall determine each year the policy of technical assistance”.

Although the Bureau of the Union might be termed the forerunner of the *General Secretariat*, since it was already mentioned in the Madrid Convention, the latter body was created by the Atlantic City Convention which stated that it should be directed by a Secretary-General aided by two Assistant Secretaries-

General, a number which was reduced to one by the Geneva Convention. The number of times persons could be re-elected to these posts was unlimited until the Nairobi Convention, which stipulates that they may be re-elected only once.

The Secretary-General’s responsibility to the Administrative Council for the performances of his duties first appeared in the Atlantic City Convention. The formulation was revised in the Geneva Convention which stated that he was responsible “for all the administrative and financial services of the Union”. The present improved wording appeared in the Montreux Convention which made the Secretary-General responsible “for all the administrative and financial aspects of the Union’s activities”.

His authority to “act as the legal representative of the Union” was introduced in the Montreux Convention.

The *International Frequency Registration Board* (IFRB) first appears in the Atlantic City Convention with as its essential duties “to effect an orderly recording of frequency assignments made by the different countries” and “to furnish advice to Members ... with a view to the operation of the maximum practicable number of radio channels”. The Buenos Aires Convention added “to any additional duties concerned with the assignment and utilization of frequencies ... in preparation for or in pursuance of the decisions of a (competent) conference” and “to maintain such essential records as may be related to the performance of its duties”. The Malaga-Torremolinos Convention included “recording of the positions assigned by countries to geostationary satellites” and “advice to Members ... with a view to the equitable, effective and economical use of the geostationary satellite orbit”. Lastly, the Nairobi Convention instructs the IFRB to take account of “the needs of Members requiring assistance, the specific needs of developing countries, as well as the special geographical situation of particular countries” and “to provide technical assistance in making preparations for and organizing radio conferences ... and assistance to the developing countries in their preparations for these conferences”.

Under the Atlantic City Convention the IFRB was composed of “independent members, all nationals of different countries”. It was the Geneva Convention that first stated that the Board should consist of 11 members, a number which was reduced to 5 by the Montreux Convention.

The *International Consultative Committees* were referred to in the Madrid

Convention as having the task of studying "questions relating to the telecommunication services".

Although not explicitly mentioned until Atlantic City, the International Telegraph Consultative Committee (CCIT), the International Telephone Consultative Committee (CCIF) and the International Radio Consultative Committee (CCIR) were already in being before that date. The merger of the first two of those Committees is foreseen in Protocol II annexed to the Buenos Aires Convention and the International Telegraph and Telephone Consultative Committee (CCITT) thus appears in the Geneva Convention.

The role assigned jointly to the International Consultative Committees in the Madrid Convention was specified in respect of each Committee at Atlantic City. Briefly, it may be said that they conduct studies and formulate recommendations, the CCIR on "technical and operating questions relating specifically to radiocommunication" and the CCITT on "technical, operating and tariff questions relating to the telecommunication services", with the exception of those that fall within the competence of the CCIR.

The administrations of Members of the Union and private recognized operating agencies have been members of the International Consultative Committees since these were set up.

The Plenary Assemblies, although not explicitly named in the Madrid Convention, have been in existence since the creation of the International Consultative Committees and the Study Groups appear in the Atlantic City Convention. The World and Regional Plan Committees are mentioned in the Montreux Convention.

Prior to the Atlantic City Convention, which refers to the Directors of the CCIs, their secretariats were the responsibility of the Bureau of the Union.

Although the *Co-ordination Committee* was introduced in 1948, it was first mentioned in the Montreux Convention. Some of the functions then assigned to it were not retained in either the Malaga-Torremolinos or the Nairobi Conventions, and at present its duty is to "advise and give the Secretary-General practical assistance on all administrative, financial and technical co-operation matters affecting more than one permanent organ, and on external relations and public information" as well as to "consider matters with which it is entrusted under the Convention and any matters referred to it by the Administrative Council".

When created, it consisted of the Secretary-General, as Chairman, the Deputy Secretary-General, the Directors of the International Consultative Committees and the Chairman of the IFRB. Under the Nairobi Convention, the Vice-Chairman of the IFRB also has become a member.

Since the Government of the Swiss Confederation was responsible for the organization of the Bureau of the Union, the Madrid Convention contained no provision concerning the status of Union staff. No specific article appeared until the Geneva Convention, although the subject was dealt with at Atlantic City in the article on the General Secretariat. The article with its present title, *Elected officials and staff of the Union*, was introduced in the Montreux Convention. It laid down the General principles to be followed by the officials in the performance of their duties and by Members in their relations with them: "neither the elected officials nor the staff of the Union shall seek or accept instructions from any government or from any other authority outside the Union", and they were forbidden to "participate in any manner or have any financial interest whatsoever in any enterprise concerned with telecommunications".

The article specified that elected officials "shall all be nationals of different countries, Members of the Union" and emphasized that staff should be recruited "on as wide a geographical basis as possible".

Article 17 of the Madrid Convention, on the Bureau of the Union, established principles which, broadly speaking, have been included in the subsequent Conventions in a single article entitled *Finances of the Union*.

The Madrid Convention quoted a scale of contributory units from 3 to 25, with a total of six classes. Two more classes of 30 units and 1 unit were added at Atlantic City. The Buenos Aires Convention introduced the half-unit and five other intermediate units. The Nairobi Conference has extended the scale to include classes of 40 units and 1½ units as well as ¼ and ⅛ units, the last-named to be reserved "for the least developed countries as listed by the United Nations and other countries determined by the Administrative Council". Since the Madrid Convention every Member has been free to choose its class of contribution.

The Madrid Convention referred to a limit on the general expenses of the Bureau of the Union and stated that expenditure for Plenipotentiary Conferences and administrative conferences should be borne by all the Governments taking part therein in proportion to the

contribution which they pay for the working of the Bureau of the Union".

The Atlantic City Convention classified expenditure as ordinary and extraordinary, the former including the costs of the Administrative Council and the permanent organs of the Union and the latter the expenses of Plenipotentiary Conferences, administrative conferences and meetings of the International Consultative Committees. These expenses were borne by the Members which agreed to participate in the conferences and meetings, in a manner similar to that established by the Madrid Convention. The Geneva Convention included in Union expenses those of the Administrative Council and the permanent organs of the Union as well as the costs of the Plenipotentiary Conferences and world administrative conferences, stipulating that "expenses incurred by special conferences ... of a regional nature ... shall be borne ... by all the Members ... of that region, and by any Members of other regions which may have participated in such conferences".

The Nairobi Conference also includes in the expenses of the Union the costs of "technical co-operation and assistance provided to the developing countries".

The article on *languages* in the Madrid Convention provided "the language used for drawing up the acts of Conferences and for all the documents of the Union in French" and "in the discussions at conferences the French and English languages are admitted". The Atlantic City Convention made Chinese, English, French, Russian and Spanish the official languages of the Union and specified "in case of dispute, the French text shall be authentic". It also stated that the final documents of the Plenipotentiary Conferences and administrative conferences as well as the service documents of the Union should be drawn up in those languages, while all other documents were to be published in English, French and Spanish. The Buenos Aires Convention introduced the classifications "working" languages—Spanish, French and English—and "official" languages which, besides these three, included Chinese and Russian.

The Malaga-Torremolinos Convention provided for the use of Arabic at Plenipotentiary Conferences and administrative conferences, while the Nairobi Convention has made it an official language.

Curiously enough, it was not until the Malaga-Torremolinos Convention that an article appeared on the *Legal capacity of the Union* reading "The Union shall enjoy in the territory of each of its Members such legal capacity as may be necessary for the exercise of its functions and

the fulfilment of its purposes". It may be said to have been implicit in the previous Conventions, however, and in Annex 5 to the Atlantic City Convention, containing the Agreement between the United Nations and the International Telecommunication Union, the United Nations recognized the International Telecommunication Union as one of its specialized agencies enjoying the privileges and immunities granted to those bodies.

Conclusion

What does the future hold? Above all, concern for the stability of the Union, which was first voiced at Montreux but did not arouse much enthusiasm at Torremolinos. Interest was revived at Nairobi and there is no longer any hesitation about the need for a constitutional Charter (or Constitution) which affirms the lasting nature of certain standards and basic provisions, to give solidity and permanence to the Union.

This concern is reflected in Resolution COM 8/5.

The Nairobi Conference adopted almost 80 Resolutions, Recommendations and Opinions, many of which will affect the very structure of the Union as well as the operation and possibly the future of some of the permanent organs. These include:

- Resolution PLEN/3 (provisional title) on the rationalization of work by the application of modern office technology;
- Resolution PLEN/11 on attendance at ITU meetings of liberation organizations recognized by the United Nations;
- Resolution PLEN/14 on the development of national frequency management;
- Resolution PLEN/16 on cost profiles for conferences and meetings;
- Resolution PLB/1 on computerization within the IFRB;
- Resolution PLC/4 establishing permanent liaison with other organizations, particularly UNESCO, on the "International Programme for the Development of Communication";
- Resolution COM 4/8 on decisions adopted by administrative conferences and plenary assemblies of the International Consultative Committees which have financial implications;
- Resolution COM 6/1 on ITU regional presence;
- Resolution COM 6/3 on budgetary and organizational aspects of ITU

technical co-operation and assistance;

- Resolution COM 6/13 on the interrelations between telecommunication infrastructure and socio-economic development;
- Resolution COM 6/15 on the establishment of an independent international commission for world-wide telecommunications development;
- Resolution COM 7/1 concerning a review in the light of changing circumstances of the long-term future of the International Frequency Registration Board;
- Resolution COM 7/7 on the official and working languages of the Union;
- Resolution COM 8/2 on participation of international organizations in Union activities;
- Resolution COM 8/4 on the role of the ITU in the development of world telecommunications.

This list, which is not exhaustive will have to be carefully examined, particularly by the Administrative Council, in order to provide the next Plenipotentiary Conference, to be held in France in 1989, with a proper framework for the International Telecommunication Union of the year 2000.

(Original language: Spanish)

ITU Plenipotentiary Conference — 1982

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An ITU Plenipotentiary Conference is a busy and complex event dealing with dozens of important issues. The following description is an attempt to highlight the more important achievements of the Nairobi Conference, the sixth Plenipotentiary since World War II. The Conference elected as its Chairman Kenya's Minister of Transport and Communications, H.E. Kosgey. Minister Kosgey, his colleagues, and all Kenyans were most generous and warm in the hospitality extended to delegates, and their preparations and support for the Conference were detailed and excellent.

ORGANIZATION OF THE CONFERENCE

Conference business was conducted through meetings of the Plenary, nine Committees, and three Working Groups. All meetings were open for participation by all delegations. The more important Committees and Working Groups (with the names of the chairmen) were: Committee 4 — Finances of the Union (T.V. Srirangan of India); Committee 6 — Technical Cooperation (M. Samoura of Senegal); Committee 7 — Structure of the Union (A.C.

Ituassu of Brazil); Committee 8 — Purposes of the Union (E.J. Wilkinson of Australia); Working Group PL-A — Program of the Future Conferences (M. Huet of France).

POLITICAL QUESTIONS

The complexity and number of subjects before a Plenipotentiary makes it difficult for delegations to be knowledgeable and prepared on all matters, particularly delegations from smaller countries lacking the resources to undertake conference preparation months in advance. The best-informed delegations tend to be from countries that sit on the Administrative Council, which meets at Geneva for three weeks each spring, with oversight responsibility in the period between Plenipotentiaries. Consequently its members are informed on all ITU principal activities.

The limited background of some delegations on a number of subjects was revealed occasionally at Nairobi, and resulted in time-consuming, but necessary, educational debate. This obstacle to moving steadily through discussion and examination to decision has led in the past to recommendations for more frequent Plenipotentiaries and/or increased authority for the Administrative Council so that fewer matters remain for decision by the Plenipotentiary.

Early in the Conference (October 4) several countries — principally Arab — introduced a draft resolution noting Israel's actions in Lebanon and calling for Israel's exclusion from the Plenipotentiary and

other ITU meetings as long as it did not "comply with its international obligations." Several countries — principally the USA and Western European nations — opposed the move, pointing out that the only legal basis in the Convention for a member's exclusion is when its payments are in arrears or it has not ratified the Convention.

The USA delegation stated that, should Israel be excluded, the USA would leave Nairobi, withhold payment of its annual financial assessment, and review the question of its future relations with the ITU. Fortunately, after long hours of debate, good sense prevailed and, by secret vote, an amendment was adopted replacing the "excluding" paragraph with one instructing the Secretary-General to study and report to the Administrative Council on measures to assist Lebanon in the repair of telecommunications facilities destroyed during the invasion. However, it was not until the fourth week of the Conference (October 22) that the compromise was reached, thus causing the work of the Plenipotentiary to fall seriously behind schedule.

DEVELOPED AND DEVELOPING NATIONS

A number of issues tended to divide on a line between developing and developed countries in what some describe as a political or politicization process. However, the differences most often are not political or ideological, but rather are differences in perspective. In earlier days ITU

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ITU Organization: A Specialized Agency in the UN system, the ITU, with 157 member-countries, is the principal and dominant international telecommunications body. Plenipotentiaries are convened periodically to determine general policy, establish budgets, elect officials, and revise the Convention if necessary. The last Plenipotentiary was held at Malaga-Torremolinos, Spain in 1973. The Union's permanent organs and their functions are:

General Secretariat: The Secretary-General, assisted by a Deputy, ensures the economic use of resources and is responsible for all administrative and financial aspects of the Union's activities.

International Frequency Registration Board: The IFRB records frequency assignments of member-countries, and geostationary satellite positions assigned by countries. It advises members as to problems of harmful radio interference, and the equitable, effective, and economical use of the geostationary orbit.

International Radio Consultative Committee: The CCIR studies and issues recommendations on radio technical and operating questions.

International Telegraph and Telephone Consultative Committee: The CCITT studies and issues recommendations on telegraph and telephone technical, operating, and tariff questions.

policies were determined largely by the industrialized states with advanced telecommunications systems. Now a majority of members are developing countries, each with a vote and each with opinions that deserve a respectful hearing.

Many new ITU members believe that its policies, programs, and choice of elected officials have been dominated by the industrialized countries. The newer members ask for a larger voice in the Union's management and greater representation among senior officials; in efforts to achieve these goals they ask for equitable distribution and rotation of senior positions and elected offices, enlargement of the Administrative Council, etc.

What developing countries see as necessary changes to reflect more accurately the priorities of the majority, frequently are perceived by others as political initiatives. Resis-



R.E. Butler, Secretary-General of the ITU.

tance to change can create strong emotions, and a balanced examination of the issues is more difficult. To find compromise or consensus in a large, diverse membership often is not easy but nonetheless must be sought by both groups — developed and developing.

Although there were occasional lapses during the Plenipotentiary's six weeks, there was recognition and a striving by most delegates for the Union's broad interests. Some may be disappointed but the ITU with its much larger membership is solid and able to bridge differences, to advance the interests of all.

ELECTIONS

Secretary-General

Four excellent candidates announced their candidacy for the posi-

tion of Secretary-General — the incumbent **M. Mili** of Tunisia, **T. Larsson** of Sweden, **T.V. Srirangan** of India, and **Richard E. Butler** of Australia. Although highly qualified and well-known internationally, neither Mr. Larsson nor Mr. Srirangan attracted the broad support needed, and the election was a contest between Mr. Mili and Mr. Butler who had served as Deputy Secretary-General since 1968. Mr. Butler won easily on the second ballot. Those who know him well agree that he is intelligent, very hard working, dedicated to the ITU, and better-informed on all Union activities and intricacies than any other person.

The somewhat autocratic managerial style and temperament of the outgoing Secretary-General has contributed in recent years to internal bickering and competition for resources among the Permanent Organs at Geneva headquarters, creating an atmosphere occasionally not helpful to efficiency and harmony. Mr. Butler's more open personality, easy and informal style, and accessibility to staff should bring a more relaxed and productive environment.

Deputy Secretary-General

There were only two serious candidates — **T. Bouraima** of Benin and **Jean Jipguep** of Cameroon. The winner by a slim margin, Mr. Jipguep has a long career in the Cameroon telecommunications administration. Over a period of years he has participated in a number of important ITU meetings including representation of the Cameroon on the Administrative Council since 1973. Intelligent and articulate, he has demonstrated ability as a forceful and persuasive spokesman in support of developing country positions but also has a reputation as a good and careful listener who looks for solutions acceptable to all parties.

The Butler-Jipguep team is well-balanced. Each encourages the views of all sides before making a decision, not favoring one group or bloc over another. The new leadership should bring a new tone to Geneva — a more imaginative and innovative managerial style leading to increased effectiveness.

International Frequency Registration Board

The Board is composed of five members, each a radio expert drawn from one of the ITU's five geographic

regions. Each serves, not as a representative of his country or region, but as the custodian of an international public trust. Prior to 1973 the Board was elected by general world administrative radio conferences; in that year it was decided that future Members should be chosen by Plenipotentiaries.

Those elected at Nairobi were:

- Region A (The Americas) — **G.C. Brooks** (Canada)
- Region B (Western Europe) — **W.H. Bellchambers** (UK)
- Region C (Eastern Europe and Northern Asia) — **P.S. Kurakov** (USSR)
- Region D (Africa) — **A. Berrada** (Morocco)
- Region E (Asia and Australia) — **Y. Kurihara** (Japan)



J. Jipguep, Deputy Secretary-General of the ITU.

Administrative Council

Acting on behalf of the Plenipotentiary in the interval between Conferences, the Council ensures the coordination of the Union's work and exercises financial controls. Thus it is the ITU's most important continuing policy formulation and supervisory body. Because its composition must reflect a balanced geographic distribution, the Plenipotentiary selects countries from each of five geographic regions. As is the practice with election to the IFRB, each delegation votes for countries in all five regions.

The 1973 Plenipotentiary increased the number of members from 29 to 36 and Nairobi further expanded the Council to 41, authorizing an additional seat for Region A and two additional seats each for Regions D

and E. Countries elected are listed below:

Region A: Argentina, Brazil, Canada, Colombia, United States, Mexico, Peru, and Venezuela.

Region B: Federal Republic of Germany, Spain, France, Italy, United Kingdom, Sweden, and Switzerland.

Region C: German Democratic Republic, Romania, USSR, and Yugoslavia.

Region D: Algeria, Benin, Cameroon, Egypt, Ethiopia, Kenya, Morocco, Nigeria, Senegal, Tanzania, and Zambia.

Region E: Saudi Arabia, Australia, China, India, Indonesia, Japan, Kuwait, Lebanon, Pakistan, Philippines, and Thailand.

The membership increase led to some grumblings that the Council's size may endanger its ability to work efficiently. However, similar concerns were voiced in 1973 and at earlier increases in membership. History shows that Council members—whether from developing or developed countries—approach their duties seriously and prepare for the annual Council sessions thoroughly. As ITU membership has grown there has been an understandable impetus to expand the Council. There probably is a limit to size beyond which efficiency falls off but 41 appears to be quite manageable.

CCI DIRECTORS

The work of the CCIR and CCITT is conducted by study groups that

submit recommendations to respective Plenary Assemblies (which meet at three to four year intervals to consider recommendations), approve a new study program, and elect a Director. Proposals were introduced at Nairobi to elect future Directors at Plenipotentiary Conferences.

The supporting arguments were that all other elected officials are chosen by a Plenipotentiary Conference, which is the supreme organ of the Union, and it is important that Directors have the same status; most countries participate in Plenipotentiaries but only part of the membership is present at Plenary Assemblies (and most of the missing are developing countries).

Opponents countered that the CCI's function quite well at present and there is no evidence that a change in the election practice will improve their operation. In fact, a danger exists that the effect may be the opposite, for the possible consequences have not been studied. The low attendance at Plenary Assemblies reflects the free choice of members, they argued, but participation in recent Plenaries had increased and that trend was expected to continue. Also, because the CCI's work is highly technical, it is important that the Directors be elected by Assemblies of experts and not the broader policy-oriented Plenipotentiary. The arguments were rejected by a majority and in a vote divided on developed-developing lines it was decided that starting in 1989 Direc-

tors will be elected by Plenipotentiaries.

There is understandable uncertainty regarding the decision's impact—whether, for example, it may lead to diminished CCI study group participation by manufacturers and scientific organizations of Japan, North America, and Western Europe. There is a strong feeling of loyalty and dedication to the CCI's. If the perception is that their high standards are imperiled by the change, a fall-off in participation may result. It is hoped that CCI supporters will sit back, reflect, and let the emotion associated with the Nairobi decision subside. A procedure in which one representative body approves work and study programs and another elects the Director may pose problems but it should not be unmanageable.

SCHEDULE OF CONFERENCES

One of a Plenipotentiary's most important and complicated subjects is agreement on the schedule of major conferences and meetings (primarily radio). There were differences of opinion on scheduling priorities (particularly strong disappointment among developing countries at the decision to schedule the HF Broadcasting and Space conferences for dates later than those recommended by WARC 79) but there was general agreement that the Working Group produced an acceptable solution to a difficult task. The schedule is shown in the box below.

ITU CONFERENCES

February 1983 — World Administrative Radio Conference for Mobile Services

June 1983 — Regional Administrative Radio Conference for the Planning of the Broadcasting-Satellite Service in Region 2

January 1984 — First Session of the World Administrative Radio Conference for the Planning of HF Bands Allocated to the Broadcasting Service

October 1984 — Second Session of the Regional Administrative Conference for FM Sound Broadcasting in the VHF Band (Region 1 and certain countries in Region 3)

June 1985 — First Session of the World Administrative Radio Conference on the Use of the Geostationary-Satellite Orbit and Planning of the Space Services Using It

First half of 1986 — First Session of the Regional Administrative Planning Conference for the Broadcasting Service in the Band 1605-1705 kHz in Region 2

October 1986 — Second Session of the World Administrative Radio Conference for the Planning of HF Bands Allocated to the Broadcasting Service

First half of 1987 — First Session of the Regional Administrative Conference to Review and Revise the Provisions of the Final Acts of the African VHF/UHF Broadcasting Conference

September 1987 — World Administrative Radio Conference for Mobile Services

November 1987 — Regional Administrative Conference to Establish Criteria for the Shared Use of the VHF and UHF Bands Allocated to Fixed, Broadcasting, and Mobile Services in Region 3

June 1988 — Second Session of the World Administrative Radio Conference on the Use of the Geostationary-Satellite Orbit and on the Planning of Space Services Utilizing It

Third Quarter 1988 — Second Session of the Regional Administrative Planning Conference for the Broadcasting Service in the Band 1605-1705 kHz in Region 2

December 1988 — World Administrative Telegraph and Telephone Conference

Beginning 1989 — Plenipotentiary Conference

September 1989 — Second Session of the Regional Administrative Conference to Review and Revise the Provisions of the Final Acts of the African VHF/UHF Broadcasting Conference

Note: ITU Radio Regions are:

Region 1 — Europe and Africa

Region 2 — The Americas

Region 3 — Asia

ANNUAL BUDGET AND CONTRIBUTORY SHARES

The ITU's Ordinary Budget, used to meet general expenses, is relatively modest and substantially less than that of several UN Specialized Agencies such as WHO or UNESCO. Ordinary Budget annual ceilings set at Nairobi for the years 1983-89 average USA \$41.9 million. Assessment of members' annual share is based on each member's voluntary choice among a range of contributory units that rise in increments from 1/8 to 40. The previous lower limit of 1/2 was reduced to 1/8 to accommodate the pressing financial circumstances of the least-developed countries. A balancing consequence was a raise in the upper limit from 30 to 40.

Each member informs the Secretary-General of its contributory choice. The total number of contributory units is divided into the annual budget to determine the value of a unit, and each member's annual assessment is then computed. There are two supplemental budgets — the Technical Cooperation Special Account, which is funded by money received from the United Nations Development Fund (UNDP), and the Publications Budget, the income for which is derived from the sale of publications.

TECHNICAL COOPERATION

In Plenipotentiaries going back to 1959 decisions have been taken authorizing an expanding program of technical cooperation. However, developing countries believe the existing program is inadequate and they came to Nairobi determined to set a new direction. The debate was not primarily over the program's magnitude — although that was an important consideration — but how it should be funded. With some minor exceptions, the existing Convention does not permit use of the Ordinary Budget for technical assistance. The Union's principal revenue source for technical cooperation activities is the UNDP. The ITU acts as an executing agency for UNDP funds allotted to telecommunications projects, and takes from project funds a charge for administrative costs.

There are other external funding sources which are a mixture of voluntary contributions of cash, equipment, personnel, training, etc., but about 80 percent of total funds administered come from the UNDP. While the Convention drafted at Malaga-Torremolinos shied away from openly authorizing use of the

Ordinary Budget, it did, in fact, approve certain expenditures that were understood to be technical cooperation activities. It authorized a Group of Engineers in Geneva to offer short-term assistance in response to requests from developing countries, approved the organization of seminars, and encouraged the IFRB and CCI's to extend certain assistance to developing countries.

This somewhat convoluted approach to use of the Ordinary Budget was an accommodation principally for industrialized countries which favored funding technical assistance by institutions such as the UNDP. They were opposed in principle to creating additional separately funded programs, and had the additional concern that should the door be opened it would be difficult to resist what might be increasing demands.

The problem with that defense at Nairobi was that the door had already been opened in the existing Convention by its authorization of the Group of Engineers, etc. During the years 1977-81 about 6.5 percent of the Ordinary Budget went to the Group of Engineers, seminars, and training for developing countries. The Nairobi debate therefore centered on whether the new Convention should openly and specifically authorize use of the regular budget and, if so, what activities should be covered and what would be an acceptable ceiling.

The outcome was never really in doubt, but the debate and negotiations continued throughout the whole of the Conference and the issue was decided only at the end. Discussions were brisk at times, and there was some developing-country feeling that the industrialized countries were insensitive to their needs. Developed countries felt that the other side was asking too much. Both sides recognized that more should be done in the field of technical cooperation. In the end all parties acted responsibly and a solution was found. It was surprising that the search took so long.

It was agreed that Article 4, stating the Union's Purposes, would be amended to include a paragraph on technical assistance and use of the Union's own resources. Other parts of the new Convention instruct the Administrative Council to provide funding within the Ordinary Budget but urge that, wherever possible, these expenditures be offset by effecting economies elsewhere. Resolutions authorize an ITU regional presence,

establish a special voluntary program for technical cooperation, list several activities that might be funded from the Ordinary Budget, and expand the work of the Group of Engineers.

One interesting decision is the establishment of an Independent Commission for telecommunications development. Drawing from industry, administrations, operating agencies, and financial institutions, the Secretary-General shall select members of the highest international reputation. Expected to complete its work in about a year from its formation, the Commission shall recommend methods for stimulating telecommunications development in the developing world.

OTHER DECISIONS

Among other important decisions were: a) the monetary unit of the International Monetary Fund (IMF), as well as the gold franc, is now accepted in the establishment of international accounts; b) an expenditure of almost USA \$11 million was authorized to expand substantially the IFRB's computer capability; c) Arabic was added to Chinese, English, French, Russian, and Spanish as one of the Union's official languages; and d) the Conference accepted an invitation from the Government of France to hold the next Plenipotentiary in that country in early 1989.

REFERENCES

The following articles on the ITU and related activities have appeared in *Telecommunications* in recent months: "The ITU's Leadership Changes," A.M. Rutkowski, Nov 82, p 79; "Action at the ITU 12th Plenipotentiary," J.J. O'Neill, Jr., Nov 82, p 86; "The CCITT: Organization, Recommendation Development, and USA Participation," D.M. Cerni, Oct 82, p 62 (global edition); "The International Telecommunication Union and Technical Cooperation," J. Jipguep, Aug 82, p 60; "ITU Election Issues," C.E. White, Aug 82, p 66; "The 1985 Space WARC Advisory Committee," A.M. Rutkowski, Nov 81, p 83; "ITU and the Information Era," D.V. Doran-Veevers, Aug 81, p 54; "Agenda: Nairobi, 1982," G.A. Coddington, Jr., July 81, p 59; and "Role of the International Frequency Registration Board," A. Berrada, June 81, p 58. For a summary of the purposes and history of ITU Plenipotentiaries and a forecast of Nairobi issues, see G.A. Coddington, Jr., *The 1982 ITU Plenipotentiary Conference, a Pre-conference Briefing Paper*, International Institute of Communications, London 1982. The basic reference book on the ITU is G.A. Coddington, Jr. and A.M. Rutkowski, *The ITU in a Changing World*, Artech House Inc., 1982. □

The International Radio Consultative Committee (CCIR):

Part 1

Ernest K. Smith and Richard C. Kirby

INTRODUCTION

The International Radio Consultative Committee, abbreviated CCIR in deference to the French word order, is the technical advisory body for radio matters to the International Telecommunication Union (ITU). Part 1 of this two-part paper deals with the question of how the CCIR came to occupy the position it does today. Much of this story is perforce a history of the ITU and its predecessor organizations: the International Telegraph Union and the International Radio Union. Part II will consider the present-day CCIR, its technical program, and its future emphasis.

The detailed history of the ITU may be found in several excellent treatises. The early history of the ITU and its predecessor organizations, the International Telegraph Union and the Radio Telegraph Union, has been principally drawn from three volumes. They are: Coddington's *The International Telecommunication Union* [1]; Leive's *International Telecommunications and International Law; The Regulation of the Radio Spectrum* [2]; and, finally, Michaelis' *From Semaphore to Satellite* [3]. The recent history is drawn from the official documents of the ITU and from U.S. delegation reports. For convenience, we consider first the International Telegraph Union during the period of its existence (1865-1932), and secondly the Radio Telegraph Union from its birth (1903) to the time of its merger with the International Telegraph Union (1932) to form the International Telecommunication Union. The ITU prior to World War II, its reconstitution following WW II, and the evolution of its modern structure are then treated. The development of the CCIR inside this organizational framework is next considered, starting from its origin in the Radio Telegraph Union in 1927, to its present form following the XIIth Plenary Assembly of CCIR in 1970 in New Delhi. Figs. 1 and 2 chart this period.

THE INTERNATIONAL TELEGRAPH UNION (1865-1932)

By 1850 the telegraph had become an important communication medium on both sides of the Atlantic, primarily for military reasons and as an adjunct to the railroads. The first telegraph union of record was the *Austro-German Telegraph Union*, which lasted from 1850-1872. It inaugurated the scheme of dividing the written agreements into two categories. Those which were considered of a rigid nature, such as the legal relations between the contracting states and the bases for the fixing of tariffs, were placed in a Convention. Other provisions, more likely to alter, were embodied in Regulations,

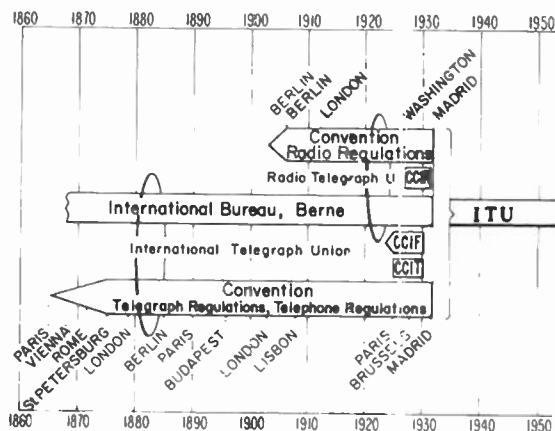


Fig. 1. The early years of the International Telegraph Union and the Radio Telegraph Union to the time of their consolidation in 1932 to form the International Telecommunication Union.

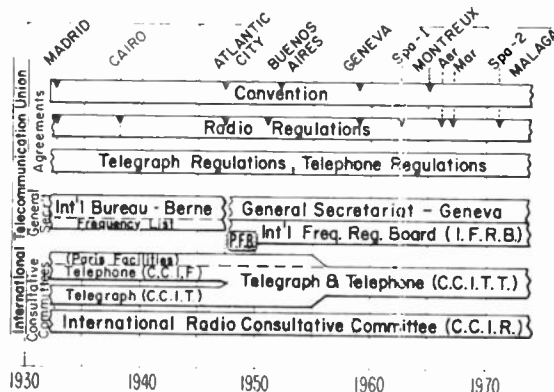


Fig. 2. The main streams of the International Telecommunication Union from the consolidation date (1932) to the present time.

which were annexed to the Convention and permitted alteration as technology progressed.

The first conference which might be called truly international took place in Paris in 1865 with the purpose of negotiating a uniform international telegraph system. It was attended by 20 states, all European, and they signed the first international telegraph Convention. Annexed to the Convention was a set of telegraph Regulations. Both the Convention and the Regulations were to come into effect on January 1, 1866, for all of the contracting states. These three features (Convention, Regulations, and a later effective date) are still relevant to present-day practice.

In 1868, the members of the new union met for their first formal meeting in Vienna, at which time it was agreed to create a permanent bureau in Switzerland which would be charged with all the routine administrative work of the union.

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It was to be headed by a permanent director and was to be located in Berne, Switzerland. Its official name was International Bureau of Telegraph Administration, but it came to be known as either the International Bureau or the Berne Bureau. It proved to be so effective that it provided the example for the creation of other international bodies in Switzerland, such as the International Bureau of the Universal Postal Union in 1875. There followed a conference in Rome in 1871-1872 which made changes to both the Convention and Regulations. This in turn was followed by the St. Petersburg Telegraph Conference in 1875.

The St. Petersburg Convention, signed that year, was to endure until 1932. This conference also marked the first occasion the United States sent observers. The St. Petersburg Conference also defined the arrangements under which future conferences were to be constituted: if designated plenipotentiary (i.e., consisting of diplomats empowered to act for their governments), they could revise the Convention; or if designated administrative, they were expected to revise the Regulations.

The division of international agreements into a Convention and Regulations had both political and technical reasons. From the political aspect, the actual Convention (i.e., the agreement between governments) was and is a diplomatic instrument. The Regulations, however, being agreements on applying the Convention, were and are essentially technical. Originally telegraphy and later other forms of telecommunications were not actually operated, or even controlled, by government agencies, but were entrusted on the basis of a concession to private firms. As a consequence, discussion on international technical matters had to be delegated in many cases to representatives of such firms (and this is the origin of Recognized Private Operating Agencies being members of the CCI's, although not of the ITU). The International Telegraph Union was to have only one more plenipotentiary conference (Madrid 1932), but it did have a series of administrative conferences: the International Telegraph Conferences of London, 1879; Berlin, 1885; Paris, 1890; Budapest, 1896; London, 1903; Lisbon, 1908; Paris, 1925; and Brussels, 1928.

By 1908 the Union consisted of 52 countries and 25 private companies. While North America was not represented among these countries, several South American nations were, in particular, Bolivia, Brazil, Chile, and Uruguay.

While the telephone had become important in the 1800's and some clauses were first introduced into the Regulations at the Berlin Conference of 1885, it was not until the London meeting of 1903 that the telephone Regulations became an important part of the work of the Union.

BIRTH OF THE CCI's

At the 1925 Administrative Conference in Paris, two semi-independent consultative bodies were established. The International Telephone Consultative Committee (CCIF) and the International Telegraph Consultative Committee (CCIT). The Telephone Committee, due to its head start, had both a laboratory and a secretariat located in Paris when brought into the Union. Codding [1] has the following to say about these two committees.

In general, the organization of the two committees was similar. Both had as their principal organs the "Plenary Assembly" which met periodically. Between meetings of the Plenary Assembly, special studies were carried out by "Study Groups." The Study Groups submitted reports on their work to the Plenary Assembly which issued recommendations on conclusions based thereon.

THE RADIO TELEGRAPH UNION (1903-1932)

The United States was one of the nine nations meeting in Berlin in 1903 to make preliminary arrangements for the international regulation of radio. The Marconi Co., Ltd., licensed in Great Britain, had a virtual monopoly over ship-to-shore radio communications. The factor which particularly indicated the need for international control was that operators of Marconi equipment were under instruction to exchange wireless signals only with the other stations also manned by Marconi operators, (as were users of the German Telefunken group's maritime radio equipment). At the first Radio Conference in Berlin in 1906, attended by 29 nations, a Radio Convention was drawn up which was closely modeled after the St. Petersburg Convention in 1875, and, in further analogy, a set of Radio Regulations was annexed to this Convention. The conference also decided that, rather than set up their own international bureau, they would ask the Berne Bureau of the International Telegraph Union to look after their needs.

There was a divergence of opinion at the 1906 Conference as to which government should be entrusted with the management of common affairs, one group maintaining that, as essentially maritime communications were involved, a government having maritime interests would be preferable, while another group felt that, as maritime radiocommunications were essentially an extension, through coast stations, of telegraphy, it would be natural to ask the Swiss Confederation to take this responsibility, particularly as the existing arrangements for the International Telegraph Union were entirely satisfactory. From ITU records (Herbstreit [4]) it appears that the decision was made on the basis of economy to entrust the interests of the Radio Telegraph Union to the Swiss Confederation, and in fact, a kind of Siamese twin was created in Berne. This provisional situation lasted until 1932, when the two Unions were merged into the ITU at the Madrid Conference. Even then the distinction between the Telephone and Telegraph Division and the Radio Division was maintained; the two Divisions had separate budgets and even, to some extent, different memberships. This latter distinction disappeared in 1947 in Atlantic City.

Radio moved forward rapidly during the decade following the 1903 meeting. A Radio Conference was held in London in 1912 which met three months after the disaster of the Titanic. This had the consequence that some strong actions were taken relative to obligatory installation of radio aboard ships and the maintenance of a continuous radio watch.

The next Conference of the Radio Telegraph Union took place in Washington in 1927 and was attended by 80 countries, 64 private companies, and assorted international bodies. As was the practice in both unions, the inviting country presided over the conference, and in Washington in 1927, Herbert Hoover was in the chair. Also, in conformance with prior practice, French was the official language. At the request of the American delegation, the following new rule of procedure was adopted. "French is the official language of the Conference. Nevertheless, since the presiding administration has so requested, as an exceptional measure, English may be used. Delegations are recommended to use this privilege with discretion." Today, the ITU has five official languages: Chinese, English, French, Russian, and Spanish. There are three working languages: French, English, and Spanish, with French still the lead language (i.e., in case of dispute between translations, the French text shall prevail).

The CCIR was born at the 1927 Radio Conference, although it did not appear to have been known by these initials

until later. Quoting Michaelis [3]:

Undoubtedly one of the most important actions of the Washington Conference of 1927 was to set up a radio consultative committee, similar in terms of reference to those dealing with the telegraph and telephone. . . . One of the main arguments for setting up the Comité Consultatif International Technique des Communications Radio Electrique was to "undertake studies and present conclusions to the next conference, thus eliminating part of the burden of exhaustive technical studies that have been necessary during conference time."

The procedure by which the Radio Telegraph Union and the International Telegraph Union combined forces was to schedule the 13th International Telegraph Conference and the 3rd International Radio Telegraph Conference at the same time in Madrid in 1932. A Joint Convention Committee and other joint committees then coped with the interleaving of the two organizations. A single new Convention was produced, plus three sets of Regulations: radio, telegraph, and telephone. All 80 countries signed, including the United States, making telecommunications truly international (the U.S. had not previously been a member of the International Telegraph Union). The new term telecommunication was defined at Madrid as follows:

Any telegraph or telephone communication of signs, signals, writings, images and sound of any nature, by wire, radio or other system or processes of electric or visual (semaphore) signaling.

The current definition is:

Any transmission, emission or reception of signs, signals, writings, images and sounds, or intelligence of any nature by wire, radio, visual or any other electromagnetic systems.



Some of the participants on the first Plenary Assembly of the CCIR at The Hague, Netherlands, 1929. (Photo courtesy ITU.)

THE ITU PRIOR TO WORLD WAR II (1932-1939)

The early years after its formation were relatively quiet for the new International Telecommunications Union. It continued to use the Berne International Bureau which now, however, had the additional task of maintaining Frequency Lists. The CCI's held meetings busily, but had no changes in organization. The Radio Conference in Cairo in 1938 was perhaps the most noteworthy feature of this era. It is remembered in radio propagation circles by the so-called "Cairo curves," representing the variation of field strength with distance at medium frequencies.

THE ITU AFTER WORLD WAR II

Great strides were made in the use of the radio during World War II, particularly in radar and microwave communica-

tions. The upper limit of frequency allocation at the Cairo Conference in 1938 was 200 MHz. However, during World War II frequency usage was quite active to 10 GHz and occasionally to 30 GHz. World War II also demonstrated the soundness of locating secretariats of international organizations in Switzerland. The general disruption in communications during World War II was, of course, very great, and many countries were faced with the need for rather complete overhaul of their communications systems. In view both of the advances in technology during World War II and the widespread devastation experienced by many members of the union, it was generally felt that a complete review of the rationale for the future role of the ITU in the post World War II world was in order. This review took place in the discussions preparatory to and at the Atlantic City Conference in 1947. This Conference was at once both an International Telecommunication Convention and a Radio Conference (it undertook the overhaul of both the Convention and the Radio Regulations). Some of the important changes effected at the Atlantic City Conference were [5] the following.

Article 2, entitled *Seat of the Union*, states: "The seat of the Union and its permanent organs shall be at Geneva."

Article 4, entitled *Structure of the Union*, reads: "The organization of the Union shall be as follows:

- 1) the Plenipotentiary Conference which is the supreme organ of the Union;
- 2) Administrative Conferences;
- 3) the permanent organs of the Union, which are:
 - a) the Administrative Council
 - b) the General Secretariat
 - c) the International Frequency Registration Board (IFRB)
 - d) the International Telegraph Consultative Committee (CCIT)
 - e) the International Telephone Consultative Committee (CCIF)
 - f) the International Radio Consultative Committee (CCIR)."

The creation of the Administrative Council is treated in Article 5. Basically this was to be made up of 18 members (now 36, following Malaga-Torremolinos, 1973) elected by the Plenipotentiary Conference with due regard for equitable representation and charged with representing the Plenipotentiary Conference between its meetings. The Administrative Council normally meets annually and is chaired by a different country each year. It has served to alleviate the need for more frequent Plenipotentiary meetings. The major elected officers of the ITU normally have the right to participate in the deliberations of the Administrative Council. The Secretary General acts as Secretary of the Administrative Council.

The International Frequency Registration Board (IFRB) was created to record frequency assignments. The number and method of selection of its members was delegated to the Ordinary Administrative Radio Conference. The Board is also to advise member countries with a view to operation of the maximum practicable number of radio channels in those portions of the spectrum where harmful interference may occur.

The General Secretariat was created to replace the International Bureau of Berne but with an important distinction, namely, that the Secretariat was to be made up of individuals chosen from the member nations (The Berne Bureau had been 93 percent Swiss).

Relations with the United Nations were defined by Agreement. The Agreement with the U.N. will be reentered as an

Annex of the Convention (Malaga-Torremolinos, 1973).

Part 2 of the General Regulations of the Atlantic City Conference treated the International Consultative Committees and spelled out the conditions of participation, the holding of Plenary Assemblies, and the composition of Study Groups, as well as the duties of the Director and of the specialized Secretariat.

The Plenipotentiary Conference at Atlantic City also set up a Provisional Frequency Board (PFB) to meet at Geneva during 1948-1949. The PFB was charged with taking account of the new technical regulations adopted at Atlantic City and coming up with a frequency-allocation plan accordingly in conjunction with the IFRB. The IFRB at that time was to consist of 11 members plus Secretariat. The members were to be chosen by geographic area.

Plenipotentiary Conferences since Atlantic City have taken place in Buenos Aires (1952), Geneva (1959), Montreux (1965), and most recently in Malaga-Torremolinos (September-October, 1973). Fig. 2 presents the main changes in the International Telecommunications Union during this period. The portrayed consolidation of the CCIF with CCIT to form CCITT (International Consultative Committee for Telephone and Telegraph) was ordered by the Administrative Council in 1955 to become effective in 1956.

The Plenipotentiary Conference in 1959 decreed that administrative conferences could be made up of two types. Ordinary administrative conferences would look broadly at the regulations, while extraordinary administrative conferences would look at a limited agenda, normally restricted to a particular service. Hence the first space conference in 1963 was called the Extraordinary Administrative Radio Conference to Allocate Frequency Bands for Space Radiocommunication Purposes, and the radio conference in 1966 was titled Extraordinary Administrative Radio Conference for the Preparation of a Revised Allotment Plan for the Aeronautical Mobile (R) Service.

The Plenipotentiary Conference, Montreux, Switzerland, in 1965 changed the names of the types of administrative confer-

ences to "world administrative conferences" and "regional administrative conferences," and indicated they would normally be convened to "consider specific telecommunication matters." The Montreux Convention didn't take effect until January 1967, so that the 1966 Aeronautical Mobile Conference was still called an extraordinary administrative conference. Subsequent conferences for specialized services, however, are known as world administrative conferences; thus the 1967 Maritime Mobile Conference was titled "World Administrative Conference to Deal with Matters Relating to the Maritime Mobile." The second space conference (1971) was the World Administrative Radio Conference—Space Telecommunications (abbreviated WARC-ST or SPA-2). The most recent conference, which incidentally will also have considered IFRB vacancies, is the World Administrative Radio Conference for Maritime Mobile Telecommunications, Geneva, April 22-June 7, 1974.

The structure, functions, and procedures of the CCIR (and CCITT) are laid out in the General Regulations, Chapters 10 and 11 of the Montreux Convention, 1965 [6].

THE EVOLUTION OF THE CCIR

The CCIR has now held twelve Plenary Assemblies (the XIII is scheduled for July, 1974). They are:

Ist	1929	The Hague
IInd	1931	Copenhagen
IIIRD	1934	Estoril (Lisbon)
IVth	1937	Bucharest
Vth	1944	Stockholm
VIth	1951	Geneva
VIIth	1953	London
VIIIth	1956	Warsaw
IXth	1959	Los Angeles
Xth	1963	Geneva
XIth	1966	Oslo
XIIth	1970	New Delhi
XIIIth	1974	Geneva.

The new look really began to take effect at the Vth

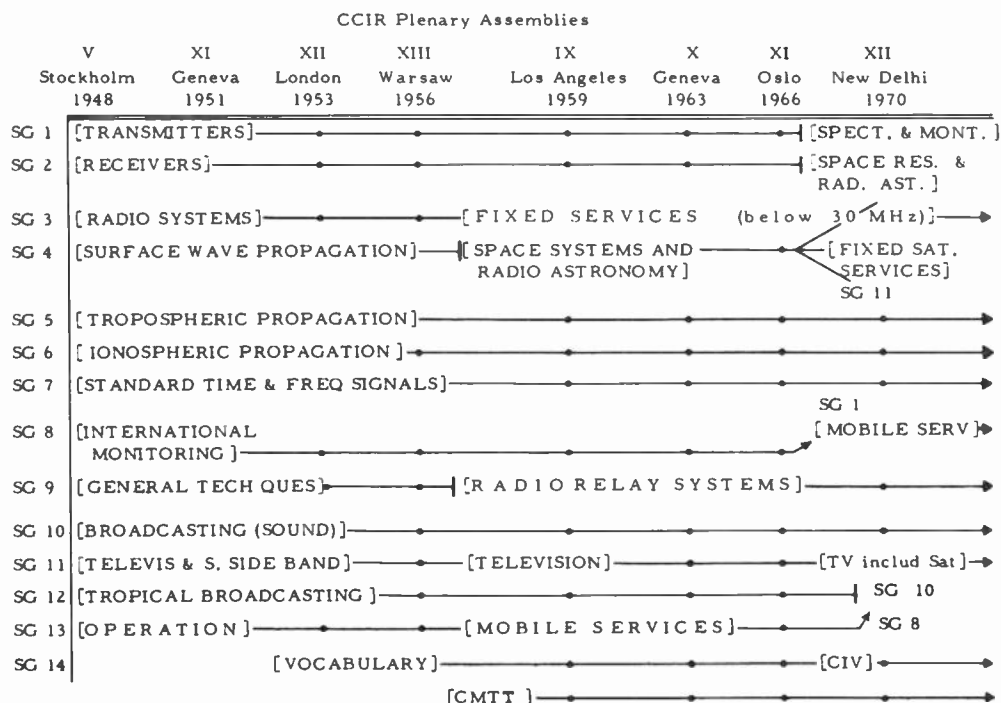


Fig. 3. The evolution of the CCIR Study Groups since their origin in 1948 to the present time. A solid vertical line indicates termination of consideration by that Study Group of the subject on the left.

Plenary Assembly of the CCIR held in Stockholm in 1948. By this time the recommendations from Atlantic City (1947) were in hand. (This modern era, 1948 to the present, is charted in Fig. 3.) Accordingly a Director, Prof. Balh van der Pol, was appointed (he was to remain the Director until after the VIIIth Plenary Assembly at Warsaw). In conformance with international practice, the host country (Sweden) provided the Chairman for the Vth Plenary Assembly. He appropriately took the lead in suggesting the Study Group structure and a slate of chairmen in response to a resolution stemming from the Atlantic City (1947) Conference. As proposed by Sweden, these were as follows (the name after the subject is the proposed Chairman, and his nationality is then shown in parentheses):

- Study Group I Radio Transmitters
Dr. Ernst Metzler (Switzerland);
- Study Group II Receivers
Mr. Pierre David (France);
- Study Group III Complete Radio Systems Employed by Different Services
Dr. H. C. A. van Duuren (Netherlands);
- Study Group IV Surface Wave Propagation
Prof. L. Sacco (Italy);
- Study Group V Tropospheric Radio Propagation
Dr. R. L. Smith-Rose (U.K.);
- Study Group VI Ionospheric Radio Propagation
Dr. J. H. Dellinger (U.S.A.);
- Study Group VII Radio Time Signals and Standard Frequencies
Mr. B. Decaux (France);
- Study Group VIII Monitoring
Mr. Joseph Ehrlich (Czechoslovakia);
- Study Group IX General Technical Questions
Mr. C. F. Booth (U.K.);
- Study Group X Broadcasting
Mr. Robert Burton (U.S.A.),
or alternatively
Mr. Phillip F. Siling (U.S.A.);
- Study Group XI Television
Mr. E. Esping (Sweden);
- Study Group XII Operation
Mr. J. D. H. Van der Toorn (Netherlands).

During the ensuing discussion, Dr. Rao of India requested an additional Study Group on Tropical Broadcasting and assumed the chairmanship. Study Group XII then became "Tropical Broadcasting" and Study Group XIII "Operation."

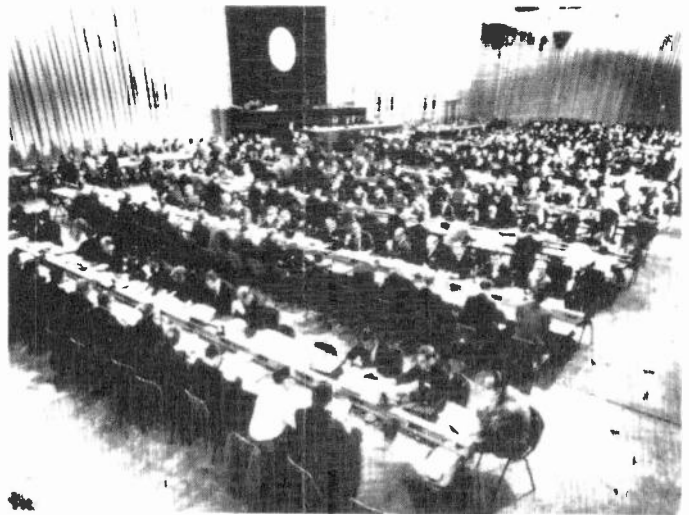
The VIIth Plenary Assembly of the CCIR was held in London in 1953. In Study Group IX, Mr. Booth had been replaced by Mr. Stainsby, also of the U. K.; in Study Group X, Mr. Burton had been replaced by Mr. McNaughton of the U.S.A.; while in Study Group XII, Mr. Rao was replaced by Mr. Baliga, also of India. The Minutes show that Study Group XIII (Operations) made no report because nothing had been referred to it, and Study Group XIV (Vocabulary, under the chairmanship of Mr. Gorio of Italy, had made its appearance.

The VIIIth Plenary Assembly was held in Warsaw in 1956. Dr. Dellinger did not attend that Plenary and Dr. D. K. Bailey replaced him in Study Group VI (and has served as its chairman ever since). During the mid 1950's the question of availability of channels in the 5-30 MHz spectrum region was of prime importance, and this resulted in heavy concentration of attention on Study Group VI (Ionospheric Propagation).

The IXth Plenary Assembly was held in Los Angeles in 1959. By this time the space age was upon us and Study

Group IV, formerly "Surface Wave Propagation" (Prof. Sacco, Italy, chairman) was renamed "Space Systems" and given as terms of reference "to study technical questions regarding systems and telecommunications with and between locations in space." The chairmanship was given to Prof. I. Ranzi of Italy. Mr. A. Prose Walker of the U.S.A. took over Study Group X, Broadcasting.

The Xth Plenary Assembly was held in Geneva in the winter of 1963 (and miserable weather prevailed). The Director of the CCIR here, as in Los Angeles, was Dr. Ernst Metzler, but he was having problems with a brain tumor and died shortly thereafter. This was the Plenary which had been scheduled for New Delhi and the date picked to optimize comfort there. Study Group IV, now renamed Space Systems and Radio Astronomy, grew from essentially no agenda in 1959 to the largest and most vigorous of the Study Groups by 1963. This was perhaps understandable in view of the forthcoming space conference (Extraordinary Administrative Radio Conference to Allocate Frequency Bands for Space Radiocommunication Purposes, Geneva 1963).



The XIth Plenary Assembly of CCIR held at Oslo, Norway, 1966. (Photo courtesy ITV.)

The XIth Plenary Assembly of the CCIR was held in Oslo in the summer of 1966 and saw no marked changes in structure or direction. The highlight at Oslo, for those who were there, was certainly the election of a new Director of the CCIR, which saw the heads of delegations of the 92 nations represented march forward successively to cast their ballots. Three ballots were required before Mr. Jack W. Herbstreit, the U.S. candidate, was elected.

The question of international standards for color television came into prominence on the occasion of a CCIR Sub-Group meeting of Study Group XI in London in 1964, followed by a memorable meeting of that Study Group in Vienna in 1965. The last great debate on the subject took place in the CCIR at the XIth Plenary Assembly in Oslo in 1966.

The XIIth Plenary Assembly took place in New Delhi in 1970. The Study Groups had met for their Final Meetings beforehand in Geneva. At the Plenary in New Delhi, the structure which had seen little change since Stockholm in 1948, was overhauled. The new structure is shown below. The principal changes are the introduction of a new Study Group 1 on Spectrum Utilization plus Monitoring and a new Study Group 2 on Space Research and Radio Astronomy Services; Study Group 4 is renamed as "Fixed Service Using Satellites."

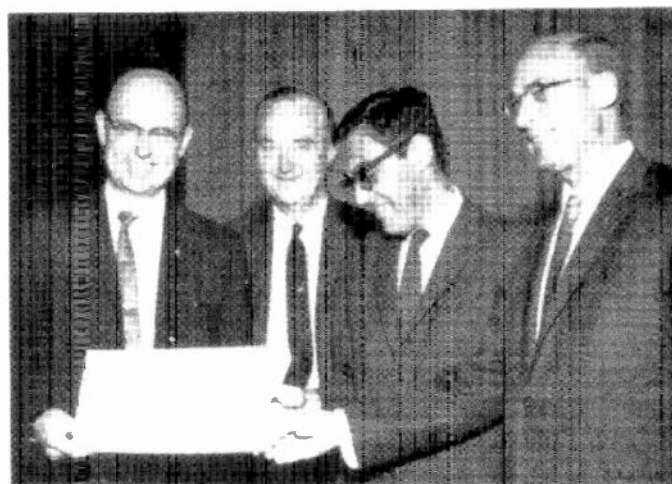
Study Group 8 is renamed "Mobile Services." Study Group 12 on Tropical Broadcasting is eliminated and its mission added to that of Study Group 10 (Broadcasting-sound). Mobile Services, which had been Study Group 13, is now Study Group 8. The old Study Group 14 is now titled CMV (Joint CCIR/CCITT Study Group on Vocabulary). The result is an excellent consolidation of effort and a movement towards service-oriented Study Groups. Transmitters, receivers, and satellite aspects are now to be considered in each service group as needed.

An important decision made at New Delhi was to convene those Study Groups concerned with space telecommunications in Geneva in February of 1971 in order to prepare for the Space Telecommunications Conference later that year (WARC-ST). It is interesting to note that in the report of Ambassador Tyson (the Chairman of the U.S. Delegation to the World Administrative Radio Conference for Space Telecommunications, Geneva, Switzerland, June 7-July 17, 1971) the following statement appears:

Many frequency allocation decisions made by the Conference were based on the technical recommendations of the International Radio Consultative Committee (CCIR), particularly the report by the Special Joint Meeting (SJM) of the CCIR Study Group . . .

The present practice in the CCIR is for each Study Group to hold two meetings prior to the Plenary Assembly. The first, or "interim," meetings of the Study Groups took place in the spring and summer of 1972 and the second, or "final," meetings took place in February and March 1974.

According to Article 14, No. 186 of the International Telecommunications Convention (Montreux, 1965), the duties of the CCIR are to "Study technical and operating questions relating specifically to radiocommunications and to issue recommendations on them."



Ernie Smith, far left, receiving a scroll of appreciation on behalf of government participants in U.S. CCIR work at a ceremony at the U.S. State Department in October of 1967. Others pictured, from the left, are Tom Nelson, director of the Office of Telecommunications in the State Department; Frank Loy, then Deputy Assistant Secretary of State (making the presentation); and Prose Walker (then with Collins Radio, now chief of the Amateur Radio Bureau at the FCC) receiving on behalf of industry participants.

The official listing of the CCIR Study Groups, their terms of reference, and international officers, is as follows [7].

THE CCIR STUDY GROUPS FOLLOWING THE XIIth PLENARY ASSEMBLY (1970)*

Study Group 1 (Spectrum Utilization—Monitoring)

Terms of reference:

1) To study, in collaboration with the other Study Groups, questions relating to the efficient use of the radio frequency spectrum and, in particular, problems of frequency sharing, bearing in mind the attainable characteristics of radio equipment (transmitters, receivers, antennae, etc.) and systems.

2) To study principles for classifying emissions.

3) To develop means of specifying and measuring the characteristics of emissions and other forms of radiation likely to give rise to harmful interference.

4) To study techniques for measuring at a distance the parameters of emissions and spectrum occupancy; to devise means for identifying emissions and for locating sources of harmful interference; and to improve, in collaboration with the I.F.R.B., procedures for presenting the corresponding reports.

Chairman: Y. Place (France).

Vice-Chairman: S. Ryżko (P.R. of Poland).

Study Group 2 (Space Research and Radioastronomy Services)

Terms of reference:

1) To study questions relating to the communications for scientific satellites, space probes, spacecraft, and exploration satellites (e.g., meteorological and geodetic).

2) To study questions relating to interference problems concerning the radioastronomy and radar astronomy services.

Chairman: J. Ranzi (Italy).

Vice-Chairman: J. Hagen (U.S.A.).

Study Group 3 (Fixed Service at Frequencies Below About 30 MHz)

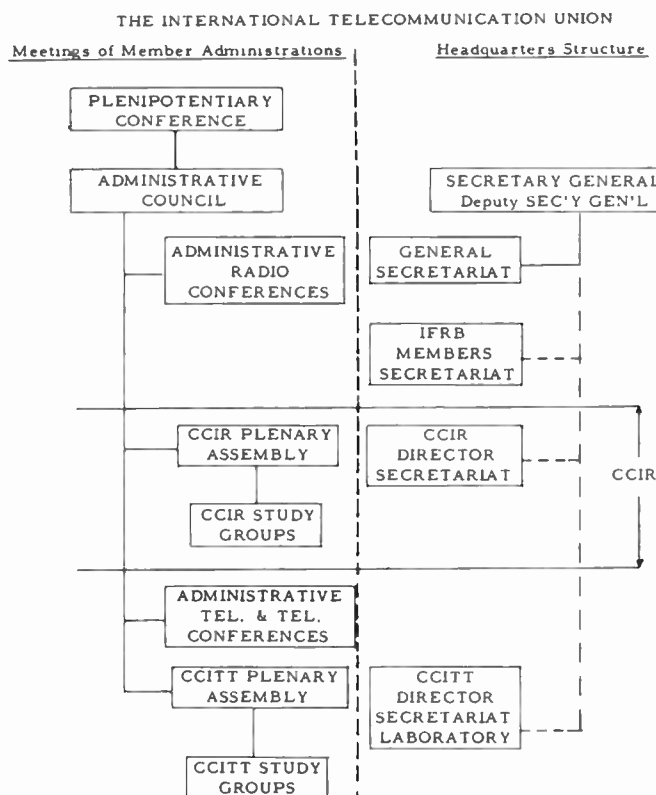


Fig. 4. The place of the CCIR in the ITU structure. Generally speaking, the boxes on the left exist only during their periodic meetings, while the boxes on the right exist continuously in the General Headquarters of the ITU.

*CCIR Information from Vol. VII, XIIth Plenary Assembly, New Delhi 1970 [7].

Terms of reference:

To study questions relating to complete systems for the fixed service and terminal equipment associated therewith (excluding radio-relay systems). Systems using the so-called ionospheric-scatter mode of propagation, even when working at frequencies above 30 MHz, are included.

Chairman: S. Aritake (Japan).

Vice-Chairman: N. Chistiakov (U.S.S.R.).

Study Group 4 (Fixed Service Using Satellites)

Terms of reference:

To study questions relating to systems of radiocommunication for the fixed service using satellites (including the associated tracking, telemetry, and telecommand functions).

Chairman: W. Klein (Switzerland).

Vice-Chairman: E. R. Craig (Australia).

Study Group 5 (Propagation in Nonionized Media)

Terms of reference:

To study the propagation of radio waves (including radio noise): at the surface of the Earth; through the nonionized regions of the Earth's atmosphere; in space, where the effect of ionization is negligible; with the object of improving radio-communication.

Chairman: J. A. Saxton (United Kingdom).

Vice-Chairman: A. Kalinin (U.S.S.R.).

Study Group 6 (Ionospheric Propagation)

Terms of reference:

To study the propagation of radio waves (including noise) through the ionosphere, with the object of improving radiocommunication.

Chairman: D. K. Bailey (U.S.A.).

Vice-Chairman: C. Terzani (Italy).

Study Group 7 (Standard Frequency and Time-Signal Services)

Terms of reference:

1) To coordinate a worldwide service of standard frequency and time-signal emissions.

2) To study the technical aspects of emission and reception in this service, and to improve the accuracy of measurement.

Chairman: J. T. Henderson (Canada).

Vice-Chairman: G. Becker (F.R. of Germany).

Study Group 8 (Mobile Services)

Terms of reference:

To study the technical and operating aspects of the aeronautical mobile, maritime mobile, land mobile, and radio-determination services, including the use of satellites.

Chairman: G. H. M. Gleadle (United Kingdom).

Vice-Chairman: P. Mortensen (Norway).

Study Group 9 (Fixed Service Using Radio-Relay Systems)

Terms of reference:

To study questions relating to line-of-sight and trans-horizon radio-relay systems operating via terrestrial stations at frequencies above about 30 MHz.

Chairman: E. O. Dietrich (F.R. of Germany).

Vice-Chairman: T. Kilvington (United Kingdom).

Study Group 10 (Broadcasting Service [Sound])

Terms of reference:

1) To study technical aspects of the broadcasting service (sound) including the use of satellites.

2) To study special problems of sound broadcasting in the Tropical Zone, taking into account standards required for

good quality service; interference in the shared bands; power required for an acceptable service; design of suitable transmitting antennae; receiving equipment; optimum conditions for utilization of the frequency bands; and other associated questions.

3) To study standards for sound recording to facilitate the international exchange of programs.

Chairman: A. Prose Walker (U.S.A.).

Vice-Chairman: S. S. Aiyar (India).

CIV* (Interim Study Group on Vocabulary)

Terms of reference:

To study, in collaboration with the other Study Groups and, if necessary, with the CCITT, the radio aspect of the following: vocabulary of terms and lists of definitions, lists of letter and graphical symbols and other means of expression, systematic classification, measurement units, etc.

Chairman: R. Villeneuve (France).

Interim Vice-Chairman: B. A. Durán (Spain).

Joint CCIR/CCITT Study Group

CMTT (CCIR/CCITT Joint Study Group for television and sound transmission)

Terms of reference:

To study, in cooperation with the Study Groups of the CCIR and CCITT, the specifications to be satisfied by telecommunication systems to permit the transmission of sound and television broadcasting programs over long distances.

Chairman: Y. Angel (France).

Vice-Chairman: W. G. Simpson (United Kingdom).

As this Joint Group is administered by the CCIR, the Chairman is elected by this Committee, and the Vice-Chairman by the CCITT. Requests for participation in its work should be addressed to the Director, CCIR.

THOUGHTS AS TO THE FUTURE

All indications are that the CCIR has an important future before it. While increasingly close working relations with CCITT are seen, there remain distinct technical problems in international radio to warrant the emphasis and expertise which CCIR commands. Frequency sharing and efficient overall spectrum utilization remain unique and essential CCIR topics.

CCIR has already performed a monumental task in space telecommunications. This subject will remain important and become increasingly sophisticated in the next decade. A variety of space applications for mobile communications, navigation, meteorology earth resources, space exploration, and broadcasting require intricate international planning.

CCIR has been the scene of discussion for digital transmission for television and other wide-band services, suggesting the direction of development of future radio relay systems.

Technological complexity is not the only challenge for future CCIR work. Resolutions 28 and 29 of the Montreux (1965) Plenipotentiary Conference emphasize the role intended for the ITU and its CCI's to assist progress in telecommunications in new or developing countries.

The World Plan Committee, and the Regional Plan Committees for Africa, Latin America, Asia, and Europe are joint committees of the CCITT and CCIR. These are intended to facilitate the planning of international telecommunication services, and also to submit to the CCI's questions which are of

*Now joint with CCITT and listed as CM V.

particular importance to new or developing countries. The ITU provides four telecommunication specialist engineers to work with the CCI's and the IFRB to provide information and advice of a practical nature to new or developing countries.

The Malaga-Torremolinos Plenipotentiary Conference (1973) considered the possibility of a new consultative committee focused especially on "technical cooperation" but decided to continue the provision for such assistance within the framework of the CCITT, CCIR, and General Secretariat.

In international problems of radio telecommunication, technical aspects really tend to remain paramount. However, they are subtle, and unless one's own experts are involved, one is not apt to be in a position to take full advantage of technological opportunities, nor in a position to be sure that a political or economic coup is not hidden in some other nation's technical plan.

The point has been made that trust in our institutions is paramount for future success in international negotiations. It seems clear that CCIR is an organization widely trusted by the international community. Its reputation for integrity gives it a crucial role to play in international telecommunications.

ACKNOWLEDGMENT

The authors would like to express their appreciation for many helpful suggestions made by Jack Herbstreit, Director

CCIR; Gordon Huffcutt, U.S. National Chairman CCIR, Department of State; Will Dean, Associate Director, Office of Telecommunications Policy, Executive Office of the President; and by their colleagues in Boulder, Colo.

REFERENCES

- [1] G. A. Coddington, *The International Telecommunication Union—An Experiment in International Cooperation*. Leyden, Netherlands: E. J. Brill, 1952 (republished by Dover).
- [2] D. M. Leive, *International Telecommunications and International Law*, published under the auspices of the American Society of International Law. Leyden, Netherlands: A. W. Sijthoff, and Dobbs Ferry, N.Y.: Oceana Publications, 1970.
- [3] A. R. Michaelis, *From Semaphore to Satellite*. Geneva, Switzerland: International Telecommunications Union, 1965.
- [4] J. W. Herbstreit, CCIR, private communication, June 1973.
- [5] "Final Acts of the International Telecommunication and Radio Conferences, Atlantic City, 1947," ITU, printed in the U.S.A.
- [6] "International Telecommunication Convention, Montreux, 1965," General Secretariat of the ITU, Geneva, Switzerland.
- [7] CCIR XII Plenary Assembly, vol. VII, New Delhi, 1970. ITU, Geneva, Switzerland, 1970.

International Frequency Registration Board (IFRB) Assistance to Member Countries of the ITU in Matters Relating to Frequency Management

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Abstract—The main duties of the International Frequency Registration Board (IFRB) of the International Telecommunication Union (ITU) are described. Emphasis in this paper is placed on the assistance to administrations in the field of radio spectrum utilization (e.g., looking for alternative frequencies to avoid probably harmful interference, investigating cases of harmful interference or alleged contravention or nonobservance of the ITU Radio Regulations, etc.). In accordance with the ITU Radio Regulations, administrations can seek the assistance of the IFRB when the direct intra-administration approach does not result in a satisfactory solution of harmful interference cases. The Master International Frequency Register (MIFR) maintained by the IFRB is mentioned. Other areas of assistance such as preparation for conferences, seminars on frequency management, programs for trainees sent by administrations, and long-term studies of specific bands are discussed.

INTRODUCTION

THE International Telecommunication Union (ITU) was one of the first intergovernmental organizations to be established and, with the Universal Postal Union (UPU), is the oldest of all the international organizations in the United Nations system.

The Administrative Radio Conference of Cairo (1938), in its decisions, recommended that frequencies be used in accordance with the "Table of Frequency Distribution" and frequency assignments were published for information only in a service document called the "Frequency List." The Administrative Radio Conference of Atlantic City (1947) changed that state of affairs by making conformity of the frequency assignments with the table compulsory, and by according frequency registrations in the "Master International Frequency Register" a certain juridical value in order to fix the reciprocal rights and obligations, for various countries, deriving from the use of a frequency by one country for a clearly defined purpose. The keystone of these procedures is the findings based on the results of an assessment of the probabilities of interference made each time a new station is put into service or when the characteristics of an existing station are changed. These findings are issued by an international body, the International Frequency Registration Board (IFRB) of the ITU. The main duties of the Board, whose functions are described in detail in Article 8 of the Radio Regulations [1] may be summed up as follows:

a) processing frequency assignment notices received from administrations for recording in the Master International Frequency Register (MIFR);

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b) reviewing entries in the MIFR with a view to amending or eliminating, if appropriate, those which do not reflect actual frequency usage;

c) studying, on a long-term basis, the usage of the radio spectrum with a view to making recommendations for its more effective use;

d) investigating, at the request of one or more of the interested administrations, harmful interference;

e) assisting administrations in the field of radio spectrum utilization;

f) coordinating the use of frequencies for HF broadcasting;

g) doing the technical planning for radio conferences;

h) participating in an advisory capacity in conferences and meetings where questions relating to the assignment and utilization of frequencies are discussed.

In 1951, radio conference procedures were developed and in 1959 the functions and activities of the IFRB were extended; as a result, the IFRB is now able to play a significant part in effective frequency management [2].

II. ASSISTANCE IN UTILIZING THE RADIO SPECTRUM

The assistance the IFRB gives to administrations is mostly direct in nature where the Board studies, if necessary with the help of other administrations, the special requirements of an individual country for one or more radio frequencies to meet its specific telecommunication requirement.

The Administrative Radio Conference, Geneva 1959, adopted a recommendation (Rec. No. 35) inviting the IFRB "to provide administrations of countries in need of special assistance with the necessary information and technical data, including the detailed explanation of the radio regulations, which will permit these countries to choose and obtain proper frequency assignments for their operations."

The purpose of this recommendation is illustrated by a number of provisions introduced into the Radio Regulations. Under these provisions the Board shall conduct a study of the following problems of frequency utilization:

i) looking for alternative frequencies to avoid probable harmful interference;

ii) searching additional frequencies within a specified portion of the radio spectrum;

iii) cases where two or more frequencies in the same megahertz order are not used due to harmful interference;

iv) alleged contravention or nonobservance of the Radio Regulations or harmful interference;

v) computation of the increases in noise temperature in

space systems, preparation of diagrams showing coordination areas or any other assistance of a technical nature to complete the procedures of coordination, notification and recording in the Master International Frequency Register of Frequency Assignment to Radio Astronomy and Space Radiocommunication Stations (Article 9A of the Radio Regulations) [1].

The IFRB regularly receives requests for assistance from administrations attempting to find suitable frequencies for their radio services. Some administrations seek the advice of the IFRB on general questions of national and international frequency coordination and management in all parts of the radio frequency spectrum. Apart from individual administrations, some international organizations also ask the Board for advice on problems of radio spectrum utilization, such as the World Meteorological Organization (WMO), the International Civil Aviation Organization (ICAO), the International Electrotechnical Commission (IEC), etc.

In relation to the special assistance to be given to administrations, the Board has the responsibility of conducting studies and making recommendations to administrations in cases where suitable frequencies, free of interference, are needed by countries to ensure the regular operation of their services. Also the Board deals with those cases of harmful interference which occur in practice and recommends suitable solutions to the problems.

In addition, the Board collects and analyzes the data received from monitoring stations spread throughout the world, with particulars of observations on the transmissions made by radio stations, which, in a summarized form, is distributed to all administrations. The Board also compiles and publishes four seasonal schedules per year of high-frequency broadcasting operations and assists administrations in finding suitable frequencies for their high-frequency broadcasting services. The Board also renders indirect assistance, or assistance in kind, by conducting general studies such as technical planning for radio conferences, long-term studies of special problems, and seminars on frequency management and use of the radio frequency spectrum [3].

III. ASSISTANCE IN RESOLVING PROBLEMS OF HARMFUL INTERFERENCE

Harmful interference is one of the major problems in radio-communication. As more and more administrations attempt to introduce new communication services in an already congested radio spectrum, greater are the risks of harmful interference. This state of affairs is becoming more serious because, in addition to the rapid expansion of communications, countries which are becoming independent naturally wish to establish their own communication links with the outside world. New and developing countries find it increasingly important to have effective communication centers connected by direct circuits with the major world capitals. The establishment of those direct communications requires, in many cases, frequencies suitable for high-power wide-band transmissions, usually in the most congested part of the radio frequency spectrum. By virtue of its responsibilities, the IFRB spends a considerable amount of time not only trying to find frequencies for these

new circuits, but also finding solutions to the problems of harmful interference between existing services. As an example of the spectrum congestion in the broadcasting bands see the Annex in [4]. The Board also assists administrations in seeking coordination under agreed procedures and organizes seminars and training courses.

The ITU considers the problem of harmful interference from the *legal, technical, operational, and administrative* angles.

Legally, the position in this respect is defined in Article 35 of the International Telecommunication Convention (Malaga-Torremolinos, 1973) [5]. This article requires members to ensure that all stations, whatever their purpose, are established and operated in such a manner as not to cause harmful interference to the radio services or communications of other members and associate members, or of recognized private operating agencies or of other duly authorized operating agencies which carry on radio services, and which operate in accordance with the provisions of the Radio Regulations. The same article also states that members must recognize the desirability of taking all practicable steps to prevent the operation of electrical apparatus and installations of all kinds from causing harmful interference to the radio services or communications mentioned above.

In accordance with the Radio Regulations, administrations can seek the assistance of the IFRB when the direct inter-administration approach does not result in a satisfactory solution of cases of harmful interference. In such cases the Board conducts studies and makes recommendations, in accordance with Section VII of Article 9 of the Radio Regulations. In case of need the Board asks administrations of countries in suitable geographical positions to carry out monitoring operations to identify the interfering stations. In general, when harmful interference was observed in the HF bands allocated exclusively to the Aeronautical and Maritime Mobile Services, the Board was able to intervene and eliminate interference to communications involving safety of life. The Board's task was facilitated by the prompt information and assistance given by individual administrations and international organizations. But the solution of certain cases of interference, in particular those involving medium-frequency broadcasting stations, can be slow and difficult.

The role of the IFRB in resolving matters of harmful interference is outlined in No. 478 of the Radio Regulations, which stipulates "the investigation, at the request of one or more of the interested administrations, of harmful interference, and the formulation of recommendations with respect thereto."

Above we have seen how the ITU considers the problem of harmful interference from the legal, technical, operational, and administrative angles. We have also seen that the radio spectrum is a resource open for international exploitation and every user has the obligation to keep the spectrum "clean." The convention establishes the legal position. The technical provisions are found in Articles 12 and 14 of the Radio Regulations [1]. The administrative action necessary for the prevention of occurrence is also found in Article 14 of the said Regulations. Article 15 of the Radio Regulations [1] gives the administrative procedure whereby administrations may settle

their disputes. It will be instructive to mention here that attention is expressly invited to the procedure outlined in this article for the settlement of disputes in various regional agreements on the use of frequencies.

IV. EFFICIENT SPECTRUM UTILIZATION

One of the most important measures which has been adopted by the ITU for efficient use of the radio frequency spectrum is the establishment of the MIFR. This register gives a full, world-wide picture of the use to which the radio frequency spectrum is put; the more faithful it is to reality the more useful it remains to all the countries in planning their future exploitation of the spectrum. It is therefore essential that all the countries, members of the ITU, periodically check the entries appearing in the MIFR on their behalf and delete those which no longer reflect their current usage. The Administrative Radio Conference, Geneva, 1959, adopted certain provisions (in Article 9 of the Radio Regulations) whereby the IFRB is charged with the responsibility of keeping the MIFR up to date. These were further supplemented by the Space Conferences of 1963 and 1971 and the Maritime Conference of 1974 and responsibility was extended to bands above 28 MHz.

V. PLANNING CONFERENCES, STUDYING SPECIAL PROBLEMS, HOLDING SEMINARS, AND TRAINING STAFF

A. Preparation for Conferences

Another important function of the Board is to carry out the technical planning for conferences, assembling the necessary technical and other data which may be required by the conferences for frequency planning or other purposes.

For this purpose, the Board assembles relevant documentation and conducts preliminary studies, which include the analysis of data, formulation of conclusions based on this analysis, and study of various alternatives and their implications on the matters to be treated by the conference. Preparation for a conference also involves the examination of the existing Radio Regulations in the light of the Board's experience with the regulations applications as well as the proposals submitted by the administrations. It may involve remaining in touch with other specialized agencies, such as the ICAO or other international or regional organizations, such as the Asian Broadcasting Union (ABU), European Broadcasting Union (EBU), International Organization for Radio and Television (OIRT), etc. In order to provide the conference with the technical material or standards necessary for its decisions, the Board enlists the help of the International Radio Consultative Committee (CCIR). Sometimes, it may be necessary to hold a preparatory meeting prior to the conference, the conclusions of which then form the technical basis of the conference.

When a conference is convened to establish a frequency plan for a given service, the Board takes steps to obtain the relevant material on frequency requirements from the various administrations. The Board may also prepare a draft plan of

frequency utilization for presentation to the conference. The Board may also request administrations to monitor certain frequency bands with a view to presenting the data on frequency usage thus obtained to the conference in the appropriate form. This is done, particularly, in services dealing with the safety of human life, such as aeronautical and maritime services. The Board has made extensive use of the computer in the technical planning of conferences, especially where the examination of very wide frequency ranges is involved.

At the end of each conference the IFRB prepares circular letters to administrations, analyzing the decisions of the conference and providing guidance for the implementation of those decisions.

B. Long-Term Studies

In addition, the long-term study of radio spectrum usage is one of the functions assigned to the Board by the Radio Regulations. The purpose of these long-term studies is the management and utilization of the radio spectrum. To carry out these long-term studies effectively, the IFRB keeps in touch with similar work being done elsewhere, and its members participate in conferences and meetings where questions relating to the utilization of frequencies come under discussion. It also participates very closely in the meetings of the CCIR with the same objective.

The studies carried out by the Board also help in improving the technical standards developed by the Board to carry out its tasks under the Radio Regulations. Mention also could be made here of the study carried out in 1961 and 1963, by a panel of experts, on ways and means of relieving pressure on the bands between 4 and 27.5 MHz.

C. Seminars on Frequency Management

During the seventeenth session of the Administrative Council in 1962, the idea of organizing periodical seminars on frequency management and the use of the radio frequency spectrum was first accepted by the Council. The first seminar was held during March-May 1963. Since then, the IFRB has continued periodically to organize seminars in Geneva on frequency management and the use of the radio frequency spectrum, and seven more seminars were organized on each in 1964, 1966, 1968, 1970, 1972, 1974, and 1976.

The purpose of the seminars is to familiarize administrations of new and developing countries with the practical aspects of organizing and establishing their radio services, within the framework of national regulations pertaining to the operation of these services and with the means of ensuring the observance of related international regulations.

In order for the seminars to be as useful as possible to participants, they have always consisted of lectures on a variety of subjects covering the entire gamut of radio spectrum utilization, including special problems pertaining to national frequency planning and management. The lectures were given by the members of the Board and the staff of its Specialized Secretariat. In addition, lectures on specific problems of radio-communications were given at each seminar by specialists from member countries. These lectures were followed by discussions.

Besides the seminars organized by the IFRB itself, the Board provided lecturers for other seminars organized by the ITU or by administrations in which questions of radio frequency utilization and management were discussed.

D. Trainees Sent by Administrations

Apart from seminar participants, who stay on after seminars to familiarize themselves with the work of the IFRB, the Board has regularly received visits from many trainees who wish to study the procedures used for processing frequency assignment notices and to receive advice about frequency assignments suited to their countries' communication systems. Visits of this sort have proved to be an effective means of helping administration officials to familiarize themselves with frequency management procedures, the use of the radio spectrum, and the work of the Board. In the last few years the

Board has developed a special program for these trainees within the framework of the IFRB's activities.

REFERENCES

- [1] *Edition of 1976 Radio Regulations, Appendices, Resolutions and Recommendations*, International Telecommunication Union, Place des Nations, CH 1211, Geneva 20, Switzerland, 1976.
- [2] "Activities of the International Frequency Registration Board," *Telecommunication Journal*, vol. 40 VIII, pp. 402-407, 1973.
- [3] "Seminar on frequency management and the use of the radio frequency spectrum: Assistance to administrations" (organized by the IFRB), International Telecommunication Union, Geneva, Switzerland, Document no. 18/76-E, Sept. 1976.
- [4] M. K. Khabiri and L. M. Tiguine, "IFRB assistance to administrations in matters relating to frequency management" (paper J-5), presented at the 2nd Symposium and Technical Exhibition on Electromagnetic Compatibility, Montreux, Switzerland, June 23-30, 1977.
- [5] *International Telecommunication Convention Final Protocol, Additions, Provisions, Resolutions, Recommendations and Opinions*, (Malaga-Torremolinos, Spain) International Telecommunication Union, Geneva, Switzerland, 1973.

Regulating International Airwaves: The 1979 WARC

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I. INTRODUCTION: INFORMATION ORDERS OLD AND NEW

The past decade has seen a flowering of interest in international policy issues concerning communications. In part, this interest reflects the increasingly visible and important role of communications and information services in international economic, social, and political relations. The dramatic growth of telecommunications services, such as satellite communications, is one illustration.¹ Another is the equally impressive growth in the use of computers, which has facilitated communications and data flows.² Moreover, beyond the growth of distinctively international communications and information systems, the growth in domestic systems has stimulated global interest. Indeed, it is increasingly difficult to distinguish national from international communications; each has become almost inevitably the other, in effect if not by design.³

The increased economic and social importance of the new communications and information systems has prompted some specula-

1. Over two thousand satellites have been launched since 1957. UNESCO INTERNATIONAL COMMISSION FOR THE STUDY OF COMMUNICATION PROBLEMS, *MANY VOICES, ONE WORLD* 63 (1980). Besides facilitating communications in the conventional sense, satellites serve other functions such as radiolocation (radar), meteorological and earth sensing (remote sensing), and surveillance. In a broad sense, all of the satellites convey "information."

An estimated two-thirds of the satellites in use are military. *Id.* at 63 n.2. Aside from military systems, international communications satellite service is dominated by a single system, INTELSAT, a global consortium of some 102 member countries which directly or indirectly serves over 130 countries. COMSAT Study, 77 F.C.C.2d 564, 589-90 (1980). COMSAT, a semipublic corporation, represents the United States in the INTELSAT consortium. For a description of the system, see *id.* at 589-99. INTERSPUTNIK, a Soviet counterpart to INTELSAT, also claims to be a global system, but essentially is limited to the Eastern Bloc. UNESCO INTERNATIONAL COMMISSION FOR THE STUDY OF COMMUNICATIONS PROBLEMS, *supra*, at 63.

There recently have emerged specialized systems such as INMARSAT, a newly established global consortium on the model of INTELSAT, which will provide maritime satellite communications to some 40 countries. INMARSAT will replace MARISAT, a U.S. system operated by COMSAT. See HOUSE COMM. ON FOREIGN COMMERCE, INTERNATIONAL MARITIME SATELLITE TELECOMMUNICATIONS ACT, H.R. REP. NO. 95-1134, 95th Cong., 2nd Sess. 5-10 (1978). For many years there has been consideration of an aeronautical satellite system (AEROSAT); however, plans are in limbo for the indefinite future primarily because of budgetary constraints and waning U.S. interest. See HOUSE COMM. ON SCIENCE AND TECHNOLOGY, AUTHORIZING APPROPRIATIONS TO THE FEDERAL AVIATION ADMINISTRATION FOR RESEARCH AND DEVELOPMENT, H.R. REP. NO. 95-95, 95th Cong., 1st Sess. 30-32 (1977).

Only a handful of domestic and regional satellite systems exist, but they are an increasingly important component of global communications. Major systems include Westar, Comstar, and Satcom in the United States, Canada's Anik, the Soviet Union's Molnia, and Indonesia's Palapa. Domestic or regional systems are under development throughout the world, not only in Western Europe and Japan, but also in countries such as India, Nigeria, Colombia, Thailand, and the Arab countries of the Middle East. Many of these countries now lease INTELSAT circuits for domestic use, but there is a strong movement towards independent national or regional systems. See Wigand, *The Direct Satellite Connection: Definitions and Prospects*, J. COM., Spring 1980, at 140.

2. Computerized communications have sparked a major controversy over transborder data flows transferring sensitive information across national boundaries. See, e.g., Gotlieb, Dalfen & Katz, *The Transborder Transfer of Information by Communications and Computer Systems: Issues and Approaches to Guiding Principles*, 68 AM. J. INT'L L. 227 (1974); Symposium—*Transnational Data Flows: New Frontier—Or None?*, J. COM., Summer 1979, at 113-55.

3. Depending on power, propagation characteristics, and patterns of use, virtually all radio communications are potentially international. For most countries it is extremely difficult to avoid transborder "spillover" of satellite signals. On the other hand, some national satellite systems, e.g., national meteorological or remote-sensing satellites, are designed to have extraterritorial effects. Even though these systems do not transmit signals across borders, their social and economic impact is the subject of significant debate. See note 11 *infra*.

Apart from such direct effects, indirect effects of communications/information activity inevitably cross national boundaries. For example, many popular U.S. television and film productions are purchased by and rebroadcast over foreign networks. CBS' *Dallas*, for instance, is seen by audiences around the world. Such cultural "spillover" is a basic issue in the whole debate over information flow. See note 10 *infra* & accompanying text.

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tion about the coming "information age."⁴ It also has sparked some interesting but quite abstract discussion of the public policy implications of the new dependence of economies and societies on information and communications technology.⁵ One aspect of the latter, namely, how new communications and information activities can be developed fairly and equitably to the advantage of all nations, raises global policy implications.

In many respects, the concern over the equitable development of these activities is just one aspect of a larger debate. The North-South dialogue over fair and equitable distribution of economic wealth produced some years ago several U.N. resolutions calling for a "New International Economic Order."⁶ Another slogan recently has emerged to address specifically the newly discovered importance of information and communication activity: the "New World Information Order."⁷ Although recently endorsed by the United

4. It has been forecast that revolutionary technological advancements in telecommunications and electronic computing will precipitate significant economic, institutional, and political changes in society. See, e.g., Porat, *Communication Policy in an Information Society*, in COMMUNICATIONS FOR TOMORROW 3 (G. Robinson ed. 1978).

5. Porat's analysis states clearly the broad social and economic implications of an "information economy," but it also makes some highly dubious generalizations about the impact of an information economy on such matters as productivity, property rights, and literacy. See *id.* at 32-43. The entire concept of an "information economy" or "information society" is built upon a set of abstractions that are too grand for useful policy analysis in most instances. Porat's own calculations, which show, for example, that nearly one-half of the U.S. gross national product originates in the production and distribution of information, *id.* at 8-11, involve some manipulation of national income accounts in ways that are more sociologically interesting than economically relevant.

6. G.A. Res. 3201, U.N. Doc. A/Res/3201 (6th Special Session 1974) (Declaration on the Establishment of a New International Economic Order); G.A. Res. 3202, U.N. Doc. A/Res/3202 (6th Special Session 1974) (Programme of Action on the Establishment of a New International Economic Order); G.A. Res. 3281, 29 U.N. GAOR, Supp. (No. 31) 50, U.N. Doc. A/9631 (1974) (Charter of Economic Rights and Duties of States). See generally CLUB OF ROME, *RESHAPING THE INTERNATIONAL ORDER* (1976).

7. See, e.g., M. MASMOUDI, *THE NEW WORLD INFORMATION ORDER* (UNESCO International Commission for the Study of Communications Problems, Report No. 31, 1978); UNESCO, *INTERNATIONAL COMMISSION FOR THE STUDY OF COMMUNICATION PROBLEMS*, *supra* note 1, at 137-55. On the relationship between the economic and information orders, see C. HAMELINK, *THE NEW INTERNATIONAL ECONOMIC ORDER AND THE NEW INTERNATIONAL INFORMATION ORDER* (UNESCO International Commission for the Study of Communication Problems, Report No. 34, undated). The new international information order has been defined as the "international exchange of information in which states, which develop their cultural system in an autonomous way and with complete sovereign control of resources, fully and effectively participate as independent members of the international community." *Id.* at 8. A new information order is viewed by some as essential to the advent of a new economic order. *Id.* at 1.

Nations in a slightly modified form,⁸ the slogan is yet without much definition. It is the product of a debate over international information flows—specifically over competing principles of "free" versus "balanced" flow of information across national boundaries.⁹ The debate has been fueled by Third World expressions of discontent with the "cultural imperialism" of the existing "order"—which the new information order supposedly is intended to correct.¹⁰ A parallel but more highly focused controversy over information flow is the seemingly ageless debate in the U.N. Committee on the Peaceful Uses of Outer Space over satellite broadcasting and remote satellite sensing.¹¹ Branching out from the concern over these issues is the issue of equitable distribution of information resources which in turn has sparked discussion of development assistance programs in the communications and information field.¹² Finally, related to that issue is the newly emerging concern over the global management and use of the one com-

8. See G.A. Res. 33/115, 33 U.N. GAOR, Supp. (No. 45) 72, 74, U.N. Doc. A/Res/33/115 (1979) ("A new, more just and better balanced world information and communication order").

9. For a good short review of the debate, see ACADEMY FOR EDUCATIONAL DEVELOPMENT, *THE UNITED STATES AND THE DEBATE ON THE WORLD "INFORMATION ORDER"* 26-33 (undated).

10. Literature on "cultural imperialism" typically condemns the dominance of information flows and resources by developed countries, especially the United States. See, e.g., H. SCHILLER, *MASS COMMUNICATIONS AND AMERICAN EMPIRE* (1970). Some works provide a more balanced treatment. See, e.g., W. READ, *AMERICA'S MASS MEDIA MERCHANTS* (1976); J. TUNSTALL, *THE MEDIA ARE AMERICAN* (1977).

11. For direct-broadcast satellites, the issue is whether satellite broadcasting across national boundaries should be subject to the prior consent of the country receiving the signal. Insisting on the free flow of information, the United States has opposed any requirement of prior consent, although it has supported a condition of prior consultation. Most other countries, however, are more concerned about the political or cultural impact of unrestrained broadcasting than about free flow of information. U.S. opposition effectively has stalemated the direct-broadcast satellite negotiations by preventing consensus on the Outer Space Committee. See Dizard, *Satellite Broadcasting and Communication Policy—The U.S. Position: DBS and Free Flow*, J. COM., Spring 1980, at 157, 167. See generally K. QUEENEY, *DIRECT BROADCAST SATELLITES AND THE UNITED NATIONS* (1978); Note, *Toward the Free Flow of Information: Direct Television Broadcasting by Satellite*, 13 J. INT'L L. & ECON. 329 (1979).

For remote sensing, the central legal issue again is prior consent. Many countries seek to prohibit data derived from remote sensing from being disseminated to any country without the consent of the sensed country. Some countries even have proposed that prior consent be a prerequisite to the act of sensing itself. See DeSaussure, *Remote Sensing by Satellite: What Future for an Informational Regime?*, 71 AM. J. INT'L L. 707, 720 (1977). See generally Comment, *Earth Resource Satellites, a Puzzle for the United Nations*, 16 HARV. J. INT'L L. 648 (1975).

12. This debate has taken place primarily in UNESCO, which is a common forum for Third World discontent. See UNESCO INTERNATIONAL COMMISSION FOR THE STUDY OF COMMUNICATION PROBLEMS, *supra* note 1, at 219-22.

mon communications resource, the radio spectrum.¹³ This latter debate has been conducted within the International Telecommunications Union (ITU), and most recently was the subject of negotiations at the 1979 World Administrative Radio Conference (WARC or Conference).

This article is a report on the 1979 WARC and its implications for the ITU. It is not about the new world information order, but the widespread identification of that movement with the WARC warrants some comment. Anticipating the 1979 WARC, many observers of the new world information order debate predicted that the Conference would provide a major opportunity to put the new world information order to the test.¹⁴ It was a reasonable prediction given the proximity of the Conference to the U.N. endorsement of the new information order slogan. Although the agenda of WARC was highly technical, the political importance of international radio spectrum regulation to modern communications and information systems cannot be doubted. Much of the debate over such issues as international broadcasting, direct-broadcast satellites, and remote sensing obviously depends upon successful international regulation of radio frequencies because without some degree of cooperation and regulation these activities themselves would cease. In fact, in light of the dependence of other means of information transmittal, if the radio spectrum could not be used effectively, the entire debate over free flow of information would be rendered largely moot as the scale of international communications would be curtailed to negligible proportions.¹⁵ One could indeed go further and point out that the uses of the radio spectrum affect virtually every facet of modern life throughout the world. Insofar as these uses would be influenced by the 1979 WARC, one might thereby leap to the conclusion that this Conference would be not

only a major vehicle for debating the new world information order but one of the great international events of an era.

It was something less than that. The 1979 WARC was not required or expected to establish new principles of spectrum use; its task was to adjust, at the margin, existing regulations governing spectrum allocations and use to accommodate new and future requirements. Nevertheless, such a task is undeniably important to the uses of communications and information, and thus could have significant influence on the new world information order dialogue. For this reason alone there was reason to believe that the same debate over political principles of the information order that have preoccupied other U.N. forums would reoccur at the 1979 WARC.¹⁶

It did not. The debate on general principles was left essentially untouched by WARC. What did occur, however, could have significant implications for the world information order old and new. Before examining what these might be, it is necessary to review briefly the structure and functions of the ITU, WARC's, and radio regulation in general.

II. THE ITU AND INTERNATIONAL RADIO REGULATION

The ITU, a specialized agency of the United Nations, is the oldest of all existing international agencies, with a lineage which dates back to 1865.¹⁷ The basic purposes and powers of the ITU are prescribed by a permanent convention which is subject to periodic revision at plenipotentiary conferences.¹⁸ The last such conference was held in 1973, and the next is scheduled for 1982. The operational rules, standards, and procedures of the ITU are prescribed in two sets of administrative regulations, one governing the international use of radio and one governing telephony and telegraphy.¹⁹ These regulations are established and revised by periodic

13. The radio spectrum is a vast, yet finite resource upon which telecommunications services depend. Although the spectrum cannot be used up, it cannot be used at all without careful coordination and effective management. See INTERNATIONAL INSTITUTE OF COMMUNICATIONS, TELECOMMUNICATIONS—NATIONAL POLICY AND INTERNATIONAL AGREEMENT—A BRIEFING PAPER IN PREPARATION FOR THE WORLD ADMINISTRATIVE RADIO CONFERENCE OF 1979, at 1-5 (1977).

14. See, e.g., Clippinger, *The U.S. Faces WARC: The Hidden Agenda*, J. Com., Winter 1979, at 197; Kramer, *Radio Spectrum—The Next Arena for Nonaligned Nations' Challenge*, Wash. Post, Sept. 23, 1979, § F, at 1, col. 1.

15. Even the print media would be all but destroyed to the extent that they depend on radio telecommunications, and hence the radio spectrum, to assist in news gathering and dissemination.

16. See note 9 *supra* & accompanying text.

17. The ITU became part of the United Nations pursuant to an agreement resulting from the Atlantic City Radio Conference of 1947. International Telecommunications Convention, Oct. 2, 1947, 63 Stat. 1399, T.I.A.S. No. 1901, 30 U.N.T.S. 316. For an excellent review of the evolution of the ITU, as well as a comprehensive analysis of its functions in the area of radio spectrum management, see D. LEIVE, INTERNATIONAL TELECOMMUNICATIONS AND INTERNATIONAL LAW: THE REGULATION OF THE RADIO SPECTRUM (1970).

18. The original convention is the International Telecommunications Convention, Oct. 2, 1947, 63 Stat. 1399, T.I.A.S. No. 1901, 30 U.N.T.S. 316 (entered into force Nov. 15, 1947). Revisions are found at 18 U.S.T. 575, T.I.A.S. No. 6267 (entered into force May 29, 1967), and 28 U.S.T. 2497, T.I.A.S. No. 8572 (entered into force Apr. 7, 1976).

19. The radio regulations are contained in International Telecommunications Union,

world administrative conferences with separate conferences being held for radio and telephony/telegraphy.²⁰ Since the Atlantic Radio Conference of 1947 in which the ITU joined the U.N. system, there have been two general world administrative radio conferences, one in 1959 and the other the 1979 WARC. These general WARCs were authorized to deal with virtually all aspects of radio spectrum allocation and regulation.²¹ In between these general conferences there were seven specialized WARCs which dealt with particular areas of the spectrum or particular services.²² In addition to these conferences, there are occasional regional radio conferences to plan frequency use within particular regions.²³ All of these conferences are scheduled by an Administrative Council, which currently is composed of 36 members elected by ITU countries at the plenipotentiary conferences. In addition, the Council meets annually to provide routine oversight of ITU operations.

The ongoing operation of the ITU is the responsibility of a permanent bureaucracy. The permanent staff is somewhat balkanized into four more or less independent organizations, among whom there is considerable rivalry for influence of ITU affairs. General administrative and financial support of ITU activity is provided by a General Secretariat, directed by a Secretary-General and Deputy Secretary-General, both of whom are elected at plenipotentiary conferences. In addition, the Secretariat has the important func-

tion of administering technical assistance to members on behalf of the U.N. Development Programme (UNDP).²⁴

Technical advice on standards and operating procedures for radio services is provided by a consultative committee, the International Radio Consultative Committee (CCIR).²⁵ The CCIR, like the other organs of the ITU, is supported by its own permanent staff. The CCIR meets regularly in permanent study groups to deal with particular aspects of telecommunications. The topics studied, *e.g.*, interference protection standards and orbit utilization, may be suggested by the group itself or by an ITU Conference. Recommendations of the study group are presented to periodic conferences for endorsement in final CCIR recommendations or reports. These reports and recommendations in turn may be utilized in the implementation of ITU regulations, though generally they are not incorporated into the regulations. Although CCIR standards are not binding as a treaty obligation, they have been accepted and used by the ITU. As a result, the work of the CCIR has been extremely important in creating effective international standardization and regulation. Because of the technical professionalism of the group, the CCIR has offered a means of obtaining international agreement with minimal dispute over abstract or ideological issues. In this respect the CCIR has contributed substantially to the technical, apolitical character of the ITU itself.

The International Frequency Registration Board (IFRB) advises and assists developing countries in the effective use and registration of radio frequencies.²⁶ Because of its sympathetic advice and assistance to Third World countries, the IFRB has become a political rival to the Secretariat for influence in the ITU. Operationally, it is the key staff organ of the ITU. The IFRB consists of five members elected at plenipotentiary conferences. The IFRB maintains the international list of frequency assignments and, in the case of geostationary satellites, orbit positions. Responsibility for frequency assignments gives the IFRB central responsibility for interpreting and administering the radio regulations governing fre-

World Administrative Radio Conference Radio Regulations (1979) [hereinafter cited as ITU Radio Regulations]. The regulations are cited by article number. Regulations governing telegraphy and telephony are contained in International Telecommunications Union, Final Acts of the World Administrative Telegraph and Telephone Conference—Telegraph Regulations, Telephone Regulations (1973). Telephone and telegraph regulations are developed under the auspices of the ITU International Telegraph and Telephone Consultation Committee (CCITT).

20. See D. LEIVE, *supra* note 17, at 29-40.

21. This requires some qualification. For example, the 1979 WARC agenda was limited to reviewing and revising those regulations relating to more than a single radio service, regulations allocating more than one service to any one band. The WARC agenda is set out in International Telecommunication Union, World Administrative Radio Conference [hereinafter cited as ITU-WARC], Agenda of the Conference, Doc. No. 1 (Sept. 29, 1978).

22. The specialized conferences were a 1963 Space Conference, a 1964/1966 Aeronautical Conference, a 1967 Maritime Conference, a 1971 Space Conference, a 1974 Maritime Conference, a 1977 Broadcasting Satellite Conference, and a 1978 Aeronautical Conference.

23. There are three ITU regions: Region 1 consists of Europe, Africa, the U.S.S.R., and Mongolia, Region 2, the Americas, and Region 3, the remainder of Asia and Oceania. THE INTERNATIONAL LAW OF COMMUNICATIONS 61 (E. McWhinney ed. 1971). Examples of regional conferences include the 1975 LF-MF Broadcasting Conference for Regions 1 and 3, the 1980 MF Broadcasting Conference for Region 2, and the forthcoming 1983 Broadcast Satellite Conference for Region 2.

24. See note 115 *infra* and accompanying text.

25. A counterpart to the CCIR, the International Telegraph and Telephone Consultation Committee (CCITT), provides similar advice on wireline communications.

26. For an explanation of the functions of the IFRB, see Khabiri, *International Frequency Registration Board Assistance to Member Countries of the ITU in Matters Relating to Frequency Management*, 19 IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY 179 (1977).

quency allocations and use. Each frequency and orbit assignment notified to the IFRB by ITU members must be examined for conformity to the ITU regulations—for example, whether the assignment is in accordance with the international table of frequency allocations and whether it is compatible with other registered assignments. Although the Secretariat, and not the IFRB, is responsible for general technical assistance using UNDP funds, in fact much of the assistance involves IFRB expertise. In addition, the IFRB provides regular advice and assistance to members in connection with the selection and the proper notification to the IFRB of radio frequencies. Because selection and registration of frequencies are essential to international recognition, which in turn can be critical to effective use of any radio system, the IFRB functions obviously put it in a position of central influence and power.

It is not possible here to explain in detail the rather elaborate procedures for allocating and regulating the radio spectrum.²⁷ A general outline of the process, however, is a prerequisite to understanding the 1979 WARC. The regulatory scheme established by the ITU Convention contemplates making allocations of radio frequencies by broad service categories established at general administrative radio conferences. These service categories include radio-location (radar), broadcasting, fixed service (point-to-point), and a wide array of satellite services—the services encompassing all the known uses of the radio spectrum. In making allocations, the degree of global uniformity varies. In some cases, allocations will be identical throughout the world; in other cases, they will be uniform only throughout a particular region; in still other cases, allocations are specific to a group of countries or even a single country.²⁸ Although in some instances allocations may be limited to a particular country, normally frequencies are not apportioned among individual countries. Frequencies allocated to a service are available for

use by any country subject only to technical or geographic limitations contained in the table of allocations or other regulations. Exception is made for certain services which are subject to so-called “a priori” or allotment plans²⁹ in which specific bands allocated to these services are parcelled out among individual countries in advance of specific use requirements. For example, certain maritime and aeronautical service frequencies are planned, as are broadcast-satellite service frequencies (and associated orbit segments) in one particular band, 12 GHz.³⁰ In addition, individual regions have various allotment plans for services—most commonly broadcasting services—within their respective regions.³¹

For unplanned services a country seeking to put a frequency allocation to use makes an “assignment” to an individual station. If the use could cause interference outside the territory of the country, or if it is for international communication, or if the assigning country seeks international recognition for its assignment, it must notify the IFRB and seek registration in the international frequency list.³² Upon receipt of notification the IFRB reviews the assignment to ensure it conforms with the table of allocations and regulations and will not cause harmful interference with another registered assignment. If the IFRB makes a favorable finding, it registers the assignment. If it makes an unfavorable finding, it re-

29. In the formal parlance of the ITU, “allocation” denotes the distribution of a frequency with a service, “allotment” denotes a distribution exclusively to an area or country, and “assignment” denotes a distribution to an individual station. *Id.* art. N7/5 No. 3414A.

30. See *id.* Appendices 25 (plan for coast radiotelephone stations operating in certain maritime mobile bands), 26-27 (plan for certain aeronautical frequencies) & 29A (plan for broadcasting satellite service at 12 GHz). Radio waves often are specified by reference to a particular frequency. This may be misleading; to carry information at all, a wave must contain all the frequencies within a “band.” The greater the frequency spread, or bandwidth, the more information may be transmitted. The specified frequency is the frequency at the center of this band. R. BROWN, *TELECOMMUNICATIONS* 94-95 (1970).

31. A list of regional agreements appears in the ITU annual reports. Not all of the regional agreements prescribe allotment plans. For example, broadcast assignments in Region 2 currently are not planned, although they are subject to various regional and bilateral agreements designed to protect against interference, e.g., North American Regional Broadcasting Agreement, Nov. 15, 1950, 11 U.S.T. 413, T.I.A.S. No. 4460 (*entered into force* Apr. 19, 1960). Region 2, however, recently decided to develop an allotment plan for MF (AM radio) broadcasting. See *The last act in Buenos Aires: U.S. must draw up five-year plan for AM allocations*, *BROADCASTING*, Apr. 7, 1980, at 30-32.

32. See ITU Radio Regulations, *supra* note 19, arts. N12/9, N13/9A. Many terrestrial frequency uses, e.g., microwave relay systems, are contained effectively within national boundaries and hence are not registered with the ITU. Coordination arrangements with border countries usually suffice unless the terrestrial service is aligned with and must be coordinated with space services.

27. A concise and current review of the basic process is given in International Telecommunication Union, *Frequency Management and the Use of the Radio Spectrum and of the Geostationary Orbit*, Doc. No. SYD/4b (1979) (mimeo paper prepared for regional seminar in Sydney, Australia, preparatory to the 1979 WARC) (copy on file with the author). A partially outdated but still useful explanation of the process is given in D. LEIVE, *supra* note 17, at 81-143.

28. See ITU Radio Regulations, *supra* note 19, art. N7/5 Nos. 3415-3449. Countries seeking allocations in addition to or different from those approved by a majority of ITU members typically seek a special footnote provision to the table of allocations. If approved, as they usually are, such special footnote allocations have equal status with table allocations. *Id.* art. N7/5 Nos. 3433-3440.

turns the notice for modification as appropriate to eliminate the problem. However, the notifying country still can obtain registration and favorable recognition if no interference complaints have been made in a specified period of time.³³ In the case of unplanned services, the precise legal protection that a first-notified frequency receives under the regulations is uncertain,³⁴ but in general, the intent of the regulations is to give the first-in-time protection in accordance with priority of registration dates—a system frequently but misleadingly described as “first-come, first-served.”³⁵

There are special provisions which very significantly qualify this oversimplified description. One example is the case of frequencies subject to allotment plans. Another is the case of international broadcasting, for which the procedure for coordination of program schedules recognizes no priorities. Instead, over one hundred countries that engage in international broadcasting exchange, on a quarterly basis, their respective program schedules so that they may coordinate their schedules and adjust them as necessary to avoid interference.³⁶ There is also a special procedure for satellite services under which administrations must give advance notice of

intent to assign frequencies and to use orbital space with a view to making advanced coordination—and adjustments as appropriate—among administrations.³⁷

III. THE 1979 WARC

The 1979 WARC was the largest conference in the history of the ITU, in terms of the numbers of participants, proposals, and decisions made.³⁸ It also may have been the most significant conference since 1947, although the long term effects of the Conference will not be known for some time to come. For the present, possibly the greatest accomplishment of the Conference lies not in what was done but in how it was accomplished—with a minimum of rhetorical or ideological confrontation and a strong emphasis on compromise and consensus.³⁹ It was widely predicted that WARC would be the occasion for a North-South confrontation over the princi-

33. *Id.* arts. N12/9 Nos. 4310A-4310C & N13/9A No. 4616.

34. In the case of services subject to allotment plans and certain other assignments singled out by the 1979 WARC for special recognition, *see id.* art. N12/9 No. 4439, the protection is unequivocal: Frequency assignment in accordance with the plan receive protection from any subsequently registered assignment. In the case of unplanned services, however, the precedence of prior over later assignments is less clear. *See* D. LEIVÆ, *supra* note 17, at 155-58. Compare ITU Radio Regulations, *supra* note 19, art. N12/9 No. 4439 with *id.* art. N12/9 No. 4440.

35. *See* D. LEIVÆ, *supra* note 17, at 158. The phrase, “first-come, first-served,” misleadingly suggests that a prior use of a frequency necessarily forecloses subsequent use. In practice, it is often possible to make room for a new assignment by relatively minor changes in operations. For example, the 1979 WARC adopted provisions empowering the IFRB to facilitate entry of new assignments in the high-frequency bands (the most congested part of the spectrum) by suggesting changes in either the new or the recorded assignment. ITU Radio Regulations, *supra* note 19, art. N12/9 Nos. 4462-4465. If no actual interference is reported, it may not even be necessary to make an adjustment. *Id.* art. N12/9 Nos. 4310-4311. The frequency list itself is a poor guide to what frequencies are available for use because the recorded assignments often do not reflect existing usage. The problem of so-called “dead-wood” assignments has persisted for a long time despite efforts to correct it. *See* D. LEIVÆ, *supra* note 17, at 99-105. The 1979 Conference adopted regulations directing the IFRB to review and update the frequency list. *See* ITU Radio Regulations, *supra* note 19, art. N12/9 Nos. 4454A-4454E. Whether or not such review will resolve the problem, the provisions which give the IFRB new powers to facilitate registration and protection of frequencies by newcomers may ameliorate the problem by reducing the importance of priority of assignments.

36. ITU Radio Regulations, *supra* note 19, art. N15/10. *See also* D. LEIVÆ, *supra* note 17, at 179-81.

37. ITU Radio Regulations, *supra* note 19, art. N11.

38. One hundred forty-two members of the ITU were represented at the Conference by over 1600 delegates and advisors. The U.S. delegation numbered 67, plus two congressional advisors and a support staff of 40. In addition, a number of other international organizations (U.N. agencies, INTELSAT, etc.) sent observers. *See* U.S. DEPARTMENT OF STATE, REPORT OF THE CHAIRMAN OF THE UNITED STATES DELEGATION TO THE WORLD ADMINISTRATIVE RADIO CONFERENCE OF THE INTERNATIONAL TELECOMMUNICATION UNION, SEPT. 24-DEC. 6, 1979, at 9 (undated) [hereinafter cited as WARC DELEGATION REPORT].

The total number of proposals is unknown, but it is estimated that in the area of allocations alone there were nearly 13,000. *Id.* at 32. The remainder of the proposals ran the gamut of technical (e.g., technical characteristics of stations), regulatory (e.g., assignment procedures), and administrative items (e.g., identification of medical transport communications). *See generally id.* at 20-91.

39. This is not to say that everyone agreed on everything. The United States entered reservations refusing to accept Conference decisions on five allocations issues. A total of fifty-one statements—mostly reservations—and thirty-two “counter statements” repudiating the reservations were filed in the WARC Final Protocol. *See* ITU-WARC, Final Protocol, Doc. Nos. 942 (Dec. 3, 1979) & 945 (Dec. 5, 1979). For the United States, this was a departure from past practice. Only once before, at the 1974 Maritime Conference, had the United States reserved on a conference decision. Most of the reservations, for the United States as for the other countries, concern relatively small details and do not undermine the effectiveness of the decisions taken. More troublesome was the increased use of footnotes to provide special allocations to individual countries different from those provided for the majority. Such special allocations are important for recognizing the distinctive needs of individual countries or groups of countries; however, easy resort to “tailor-made” allocations can undermine the uniformity that is needed for an international regime. For a good sketch of the WARC results on issues of primary importance to the United States, *see Why the sky didn't fall at WARC*, BROADCASTING, Dec. 17, 1979, at 44; *WARC is over; U.S. 'satisfied,' says Robinson*, BROADCASTING, Dec. 10, 1979, at 82. Technical detail is given in the WARC DELEGATION REPORT, *supra* note 38.

ples of a new information order.⁴⁰ Some thought such a debate desirable as well as inevitable and strongly criticized the U.S. position that such a debate should be avoided.⁴¹ According to these critics, WARC was an opportunity, to be seized and not shunned, for the United States to take a stronger initiative to support Third World aspirations and needs. Such initiatives never were defined precisely, but the thrust of the critics' demand was that the United States should offer greater technical assistance and should support Third World proposals to obtain "more equitable access" to the spectrum.

The U.S. position⁴² was not hostile to considering such issues at WARC, insofar as they were relevant to the agenda, but the United States was not prepared to accede to all of the demands made by Third World countries or First World critics. Contrary to what was asserted with ritualistic regularity by critics before WARC,⁴³ the United States had no illusions that the WARC would be *purely* "technical." There was never any doubt that "political" factors—in a broad sense of that term—would be critical, despite the ostensibly technical character of the subject matter. One could scarcely imagine it otherwise; nations do not come together to discuss radio engineering in a vacuum of social, economic, and political interests. Technical factors of, for example, electromagnetic compatibility, should be and usually are a factor in deciding whether to allocate a particular frequency to a particular service, but such factors would be dispositive only if there were no competing social, economic, and political interests at stake. Purely technical cases are as uninteresting as they are exceptional. Just how exceptional can be appreciated if one surveys the process by which U.S. objectives and priorities were developed from among hundreds of competing government, industry, and other private sector demands.⁴⁴ In very few cases was the conflict resolved by simple

reference to engineering data alone. Discussions with other delegations reveal that this same process is common for other countries having significant spectrum requirements.

A subject of political dispute *within* nations can scarcely be less so *among* them and WARC was not exceptional in this regard. What was exceptional, at least in the context of typical U.N. activity, was that the political negotiations and debate seldom ranged more broadly than the agenda required. Principles of North-South "equity," for example, generally were contained within issues directly relevant to particular issues under consideration—issues which were "technical" in form if not in ultimate significance. In this sense the U.S. objective of a technically oriented Conference was fully successful, and it obviously corresponded to the objectives of the overwhelming majority of Conference participants.

As always, one must acknowledge some exceptions to prove the rule. There were some instances of purely ideological or general political debate that went beyond the immediately relevant issues as defined by the Conference agenda. Most of these episodes were trivial as well as tangential to the main business.⁴⁵ Two "political"

the spectrum, the National Telecommunication and Information Administration (NTIA) was responsible for all federal agency uses; and the Department of State looked after general foreign policy interests. Throughout, the emphasis was on compromise and consensus, responding to a broad and diverse constituency. Virtually no decisions were imposed without exhausting the possibilities for a consensus of affected agency and other interests. The internal domestic and international processes were in this respect remarkably similar.

The U.S. preparations for the 1979 WARC involved far greater effort than for any previous ITU conference. Preparations began as early as 1974 with the establishment of special study groups by NTIA's predecessor agency, the Office of Telecommunications Policy, and with the initiation by the FCC in 1975 of a public inquiry process to seek public comment and proposals. Over the ensuing five years, the preparations involved the active participation of some eighteen major federal agency users represented on the Interdepartment Radio Advisory Committee (a permanent planning unit of the NTIA), industry interests as diverse as AT&T and the offshore drilling industry, and public groups as diverse as the radio astronomers and church groups.

45. Illustrative is a controversy between North and South Korea over assignment of call signs. In essence North Korea demanded one-half of a particular call sign series which had been assigned to the "Republic of Korea" since 1959 and which previously had been assigned simply to "Korea." Since North Korea was not a member of the ITU at the time when the assignment was changed, it claimed that the assignment was invalid for want of representation of its interests. South Korea resisted the fifty-fifty split on the ground that the 1959 designation had been proper and the call signs legitimately had come to be associated with it. Also, South Korea claimed a greater need for call signs than the North; hence, a fifty-fifty split appeared unreasonable in any case. Nothing of substance was involved other than a political contest over status recognition since other call sign series were available, yet the issue consumed excessive time and patience as each side lobbied every delegation repeatedly. The issue finally was resolved by what was labeled a compromise even

40. See note 14 *supra*.

41. See Branscomb, *Waves of the Future, Making WARC Work*, 34 FOREIGN POL'Y 139 (1979); White, *Uprooting the Squatters*, *id.* at 148.

42. The U.S. position on these and other general issues is outlined in Robinson, *The U.S. Faces WARC: The U.S. Position*, J. COM., Winter 1979, at 150. See also WARC '79: *Curtain going up on telecommunications future*, BROADCASTING, Sept. 17, 1979, at 35. The formal U.S. proposals are contained in ITU-WARC, Doc. Nos. 40-50.

43. See, e.g., White, *supra* note 41.

44. The U.S. preparatory process is outlined in WARC DELEGATION REPORT, *supra* note 38, at 5-7. Essentially, three agencies coordinated their respective interests. The Federal Communications Commission (FCC) was responsible for all private, i.e., nonfederal, uses of

issues that were not trivial are worth passing mention. One was the issue of sovereignty claims to the geostationary orbit, a perennial U.N. topic.⁴⁶ After sharp debate, Colombia succeeded in attaching

though it gave North Korea practically everything it sought. See WARC DELEGATION REPORT, *supra* note 38, at 83; ITU-WARC, Summary Records of the Twenty-Second Meeting of Committee 7, Doc. No. 925, para. 1.4, at 2 (Nov. 24, 1979); Summary Records of the Twenty-Ninth Meeting of Committee 7, Doc. No. 969, paras. 1.1.1-3, at 2 (Nov. 29, 1979).

Other minor contests included a flurry of excitement in the credentials committee over the credentials of Democratic Kampuchea (the Pol Pot government), which the Soviets and their allies protested but the United States and the People's Republic of China supported. The credentials were accepted in committee, and the matter was not raised in plenary. (Kampuchea was, in any event, unable to vote because it had not ratified the ITU Convention.) A second minor skirmish arose when the Soviet Union challenged the authority of certain West German delegates who reside in Berlin, on the ground that the Quadripartite Agreement forbade Berliners from representing the Federal Republic of Germany. The committee rejected the challenge, which was not pursued further in plenary. See WARC DELEGATION REPORT, *supra* note 38, at 21; ITU-WARC, Summary Records of the First and Second Meetings of Committee 2, Doc. Nos. 176 (Oct. 2, 1979) & 725 (Nov. 21, 1979).

The credentials issues are noteworthy because they reveal that despite pre-Conference fears, political activity was very restrained. A major concern prior to the Conference was the possibility of a challenge by Arab members to the credentials of Israel. At a recent meeting of the World Health Organization, there had been unsuccessful efforts to unseat Israel from the organization and to withdraw from Egypt a regional WHO office. A similar action had been threatened at the annual meeting of the Universal Postal Union in Rio de Janeiro which began just before the 1979 WARC. Many expected a similar controversy at WARC, but no such controversy emerged. There was one political conflict between Israel and the Arabs over a minor allocation issue. On its face the issue was apparently a matter of technical incompatibility between neighboring Israeli and Arab services. Only when one of the Arab administrations demanded an exceptional role call vote, instead of the usual show of cards, was it apparent that the conflict was more than technical. Israel immediately demanded a secret ballot, which provoked a long and acrimonious debate; the ballot finally was taken, and Israel won convincingly. There were no more such tests of strength. See ITU-WARC, Minutes of the Eleventh Plenary Meeting, Doc. No. 975, paras. 3.1 to 3.2.19, at 2-4 (Nov. 30, 1979).

46. Since the Bogotá Declaration (Declaration of the Equatorial States, signed in Bogotá, Dec. 3, 1976, reprinted in International Telecommunication Union, Broadcasting Satellite Conference, Doc. No. 81, Annex 4 (Jan. 17, 1977)), several equatorial countries, led by Colombia, have asserted sovereignty over those segments of the geostationary orbit that lie directly above their respective countries. The claim has been raised repeatedly at sessions of the U.N. Outer Space Committee, and it was raised at the 1977 Broadcast Satellite WARC. See Gorove, *The Geostationary Orbit: Issues of Law and Policy*, 73 AM. J. INT'L L. 444, 450-59 (1979). At the 1979 WARC, the claim was raised, more or less ritualistically, in the opening plenary session. There was no public debate on the claim until the end of the Conference when Colombia and others submitted two protocol statements on the sovereignty issue. One statement purported to interpret the future space services planning conference resolution to imply recognition of the equatorial sovereignty claim. Allotment planning is fundamentally in conflict with the assertion of any special rights by equatorial countries; the very essence of a plan is to make an "equitable" distribution of the orbit resource to all countries, regardless of where they are located. What Colombia evidently sought was to preserve its options to argue against an allotment plan and to argue that any such plan would be dependent on the consent of equatorial countries to use of their orbit space.

two protocol statements to a Conference resolution calling for a future conference for space services planning. The United States and others attached statements repudiating the Colombian interpretation of the resolution. The second issue was a controversy over election of a Conference chairman. Fortunately, despite some bitterness in the debate, a consensus was reached, allowing the Conference to proceed to duller but more substantive business—although the result may have long-term political implications for ITU leadership.⁴⁷

The Conference made hundreds of decisions in disposing of thousands of individual proposals.⁴⁸ I shall not attempt to cata-

The Colombian protocol statement was submitted not as an original protocol but as a "reply protocol" to which no response normally could be made. Other countries, notably the United States and the United Kingdom, argued that as the statement was not in fact in reply to any original statement, Colombia obviously was attempting to avoid rebuttal of the claim by other countries. The conflict was resolved by compromise allowing the United States and others to include a protocol statement repudiating the Colombian interpretation. See ITU-WARC, Final Protocol, Doc. Nos. 942, Protocol 40 (Dec. 3, 1979) & 944, Protocol 75 (Dec. 5, 1979). A summary of the debate is contained in ITU-WARC, Minutes of the Sixteenth and Last Plenary Meeting, Doc. No. 980, para. 2, at 2-4 (Dec. 5, 1979).

47. The Conference began with a prolonged, and at times bitter, conflict over the selection of chairmen for the Conference and for major committees. Some of the developed countries, especially the United States, the United Kingdom, and New Zealand, were concerned about LDC insistence that the chairman must be from a member of the nonaligned movement (NAM). Only a few weeks earlier, the NAM summit in Havana had adopted a resolution, initiated by India, that the WARC chairmanship should be filled by a nonaligned spokesman. The United States and others saw this as a sign that the NAM intended to use the chairmanship to establish bloc solidarity and to dominate the 1979 WARC and the ITU generally. There was even broader concern that NAM success at WARC would set an undesirable precedent for other U.N. conferences.

The conflict could have been resolved by a vote, in which case the NAM and the Indian candidate probably would have won. ITU tradition dictated, however, that the chairman and officers be elected by consensus. The NAM may have been reluctant to press for a vote at least on the Indian's candidacy, because there was some doubt that he would prevail on a secret ballot. At the same time, the NAM bloc opposed any western candidate, even one from neutral Switzerland. The nonaligned, for their part, were content to withdraw support from the Indian candidate but had great difficulty choosing another. Finally, the non-aligned turned the choice over to the South American delegations nominated an Argentine as a regional candidate. Argentina, although formally nonaligned, is not active in the movement. Most of the western group resisted the NAM demands, but feared that if the issue were forced to a vote, they would lose by a vote so large that the strength of the developing countries would be demonstrated conclusively. The matter finally was settled by a consensus approval of the Argentine as chairman and the Swiss candidate as a special vice-chairman. See WARC DELEGATION REPORT, *supra* note 38, at 16-17. Although the election can be viewed as a compromise, it does set a precedent for future NAM claims to leadership positions in the ITU. In retrospect, given the Conference record on political issues, this possibility is not such a concern now as it was then.

48. These decisions are found in International Telecommunication Union, Final Acts of

logue, let alone review, all of these individual decisions. The vast majority of them are, in any case, of limited, specialized interest. For particular industries or services, many of these specialized decisions doubtless will be important, but that importance is not such as to warrant comment here.⁴⁹ I shall limit my sketch—it is no more than that—to a handful of major issues that provided the occasion for the most extensive and excited controversies at the Conference.⁵⁰

In very general terms it is convenient to separate these major controversies into two groups: (1) allocations and regulatory issues involving satellite services above 1 GHz; and (2) those involving terrestrial services in the high frequency (3-30 MHz) region of the spectrum. This grouping is a huge oversimplification even of the allocations and regulatory work of the Conference. It ignores satellite services below 1 GHz; more significantly it ignores terrestrial services in all but a fairly narrow range of the spectrum.⁵¹ Nevertheless this grouping fairly reflects the major areas of greatest global interest and controversy.⁵² Many Conference proposals and decisions also involved regional, and even national, allocations,⁵³

for example, the Region 2 12 GHz broadcast satellite issue examined more closely below.

A. *Satellite Communications*

Disputes involving the satellite services were generally the most contentious of the entire Conference. The most notable exception involved remote sensing services on which there was a remarkable, and unexpected, degree of consensus.⁵⁴

The reasons for controversy over satellite communications services are not difficult to discern. In the past 20 years, satellite communications have emerged from the status of an unproved technology to become a central component of modern international and domestic communications systems. The technology and the service are pervasive throughout the world. Through INTELSAT and INTERSPUTNIK, most countries are direct or indirect users of fixed satellite service communications. Many also have domestic satellite service, provided either by domestically owned systems or by special arrangements with INTELSAT.⁵⁵

As important as satellite communications have become for advanced developed countries (particularly those with large territories such as the United States and Canada), they are potentially even more important for emerging Third World countries which lack a terrestrial communications infrastructure on which to develop a modern communications system. For a country like the

the World Administrative Radio Conference (1979) [hereinafter cited as WARC Final Acts].

49. For a review of these decisions see sources cited in note 39 *supra*.

50. My review of these issues is necessarily very condensed and therefore also somewhat superficial. It does not attempt to relate the full interaction of all the different participants. My treatment also may be skewed insofar as it is limited to those issues in which the United States had a significant interest. For example, this article does not discuss such issues as the proposal for a planning conference for Europe, the proposal to reallocate frequencies in Africa, the proposal to create a new region in Africa, and revisions made in the 1978 Broadcast Satellite Plans for Regions 1 and 3. As it turns out, however, most of the major controversial issues at WARC involved the United States. Finally, and perhaps needless to say, my official position as chairman of the U.S. delegation may be reason to suspect my views on policy issues, but the factual narrative can be checked against the ITU records of the Conference.

51. For a breakdown of the spectrum according to major bands and types of services using those bands, see H. LEVIN, *THE INVISIBLE RESOURCE* 20-21 (1971). For details on how the services in each of these bands were affected by WARC, see generally WARC DELEGATION REPORT, *supra* note 38.

52. There are many significant issues that are of regional and national concern. The VHF and UHF frequencies, for example, are extremely important in every country; however, the limited propagation of most of the domestic VHF and UHF services confines most of the spectrum management problem to particular regions.

53. For example, in Region 2, the United States proposed adding fixed and mobile services to be shared with broadcasting throughout most of the 470-960 MHz band. Although the United States was unable to obtain a uniform table of allocations on these services for the entire band, it met its objectives through a combination of table allocations changes and special footnotes. See ITU Radio Regulations, *supra* note 19, art. N7/5 & notes 3650B, 3669A, and 3670A. In general, issues presented by such regional proposals were of lesser interest at WARC than those involving worldwide allocations.

54. Remote satellite sensing is used to obtain information on land, sea, and atmospheric conditions. The practical and scientific applications are broad, including use in farming, forestry, land and marine resources management, and environmental pollution monitoring. See generally NATIONAL ACADEMY OF SCIENCES, *REMOTE SENSING FROM SPACE: PROSPECTS FOR DEVELOPING COUNTRIES* (1977). While present sensing programs use primarily optical sensing techniques, future sensing satellites will rely heavily on the use of microwave radio frequencies in two ways: passive sensors receiving natural electromagnetic emissions from land, oceans, and atmosphere; and active sensors reading reflections of signals radiated by the satellite. To accommodate both types of operation the United States proposed numerous new frequency allocations with striking success. Particularly noteworthy was the absence of any debate over the political aspects of remote sensing. Whatever the views of many countries on the issue of regulating the dissemination of sensing data, see note 11 *supra*, there was at WARC unexpectedly broad support for accommodating remote sensing. I attribute much of this success to the U.S. policy of sharing LANDSAT data. Under an agreement with the National Aeronautics and Space Administration (NASA), several countries operate earth terminals to receive data directly from the satellite. Thus, although LANDSAT is a domestic system, its benefits have been disseminated widely, much like the meteorological satellite systems operated as part of the World Weather Watch under the aegis of the U.N. World Meteorological Organization.

55. See note 1 *supra*.

United States, a domestic satellite system for relaying telecommunications messages from, say, New York to Seattle offers cost and service advantages over a terrestrial network. But the advantages are mostly marginal improvements in an already modern system. By contrast, satellite communications in countries like Brazil or Nigeria, which do not have fully developed terrestrial networks, offer a radical advance in the entire communications system, one which can leapfrog over the present generation of terrestrial relay links to achieve a technological parity with developed countries.

Thus, the development of advanced satellite communications generally will play an important role in any movement towards a new world information order. The international allocation and management of satellite frequencies (and, in the case of geostationary satellites, orbit slots) is, of course, only one part of that development. It is nevertheless a critical part. A scheme of allocations and related regulations governing use is a necessary condition of development. The efficiency of this allocations scheme, moreover, has a direct and important bearing on the cost of system development. For example, an allocations scheme which does not facilitate full exploitation of the spectrum may waste usable frequencies and orbit space and may create congestion in those sectors of each that are used. This congestion, of course, imposes additional costs on users either through degraded service quality, or through increased cost to invest in equipment less susceptible to interference.⁵⁶

If economic efficiency were the sole consideration, the task of developing an optimal allocations scheme would be difficult enough given the many different communications services that must be accommodated in any given portion of the spectrum. This difficulty is compounded by the fact that foreseeable future needs must in general recognize present use, and vice versa. Even within a single country such an accommodation of different uses, over different time periods, proves to be an extraordinarily complicated task.⁵⁷

In international negotiations, however, the difficulty of constructing an efficient set of allocations to accommodate different uses is almost the least problem. Far greater is the problem of accommodating the demands of different nations in varying stages of

technological and economic development, not to mention divergent political perspectives. Here, the goal of economic and technological efficiency becomes essentially secondary to the demand for fair and equitable access by all nations to the spectrum and orbit. Doubtless, "fairness," in some sense of the word, is an essential requirement for any global allocation of international resources. As an abstract matter no one disagrees with that proposition, in the ITU or any other international forum. But defining "fairness" in the context of a complex international environment is another matter.

WARC was reasonably successful in meeting the different fairness claims as applied to discrete allocations problems, and in most instances it met the demands without unacceptable sacrifice of practical efficiency goals. Many of the most vexing problems of reconciling the competing demands of fairness and efficiency nevertheless were deferred for future conferences.

1. *Fixed-Satellite Service*

Among the different satellite services, the fixed-satellite service, which essentially includes point-to-point telecommunications relay services, posed the most persistently controversial problems of the Conference. Virtually all delegations agreed that the past and projected future growth of international satellite telecommunications traffic alone made it important to secure additional frequency allocations, and projected demands for domestic systems made these needs more urgent. Beyond that general and superficial agreement, however, there was little consensus among the various proposals submitted to the Conference as to where the accommodation should be made.⁵⁸ In general terms, the dispute was whether additional allocations could be made below 10 GHz—now extensively used by fixed-satellite and various terrestrial services—or whether they could be accommodated only in higher portions of the spectrum which offered less congestion but substantially increased satellite system costs. Unfortunately, the cost penalty proved largely unavoidable under either option. Additional allocations above 10 GHz would impose costs on new fixed-satellite communications, especially on INTELSAT, whose requirements were the critical element of the controversy. On the other hand, additional allocations below 10 GHz could be made only at the cost of displacing, crowd-

56. In broad terms there are two options: to employ new equipment less susceptible to interference; or to move to higher, less congested regions of the spectrum. Either option entails increased investment, increased operating costs, or both.

57. See note 44 *supra*.

58. ITU-WARC, Twenty-Seventh and Twenty-Eighth Reports of Working Group 5D, Doc. No. 722 (Nov. 16, 1979).

ing, or otherwise adversely affecting existing terrestrial services. As one would expect from observing the different levels of national economic development represented at the Conference, the incidence of these respective costs was not uniform. Because the developed countries have disproportionately greater investment in existing terrestrial systems in the below-10 GHz bands than the developing countries, the cost of expanding satellite services into these bands would fall most heavily on them. At the same time, developed countries are, relative to developing countries, better able to bear the greater costs of operating satellites at higher frequencies.

For the United States, both terrestrial and satellite services below 10 GHz could be accommodated by a careful selection of certain bands for additional satellite allocations. But it proved impossible to reach a consensus on enough of the U.S. proposed frequencies to accommodate essential downlink requirements.⁵⁹ The resulting impasse prompted India, backed by other Third World countries, to demand that a major part of the accommodation for the fixed-satellite service be made by downgrading certain allocations in the 3 GHz band used for vital national and allied defense radar systems by the United States and the United Kingdom.⁶⁰ This band long has been shared equally by radars and fixed satellites, but because of assumed incompatibility with the radars, the fixed-satellite service had not been implemented by INTELSAT, as it has been by INTERSPUTNIK. The proposed downgrading would have given radars a secondary status, requiring them to avoid interference with fixed-satellite service.

The proposal was unacceptable to the United States, the United Kingdom, and a number of other allies that had shared defense interests. Notwithstanding that opposition, India was able initially to command a majority in favor of its proposal.⁶¹ The United

States then declared that it could not accept any decision to downgrade the status of its radar systems, and it would not implement those fixed-satellite frequencies in the United States. In effect, this would foreclose use of those frequencies by INTELSAT because the United States provides a critical part of the traffic which would use them. The United States further declared that it would not protect the fixed-satellite service from radar interference.⁶²

This threat had little initial effect on India's proposal. I suspect the reason is that, notwithstanding India's professed objective of helping INTELSAT (a claim which garnered extensive Third World support), India desired the frequencies primarily to accommodate her own future domestic satellite needs. The fact that the United States effectively could foreclose the use of the frequencies to INTELSAT would not impair India's domestic use. Ultimately, however, the other Third World countries supporting India recognized that their interest in providing for INTELSAT could not be forced over steadfast U.S. opposition. At the eleventh hour of the Conference, a U.S. compromise was approved by a coalition of Third World interests led mainly by Jamaica and Brazil, which recognized the continued coexistence of the fixed-satellite and radar allocations until such time as the latter could be relocated.⁶³ For their part, the United States and other developed countries pledged to take all practicable measures to insure that the fixed-satellite service would be accommodated.⁶⁴

band when practicable. India, however, insisted on specifying a date by which radiolocation would lose its coequal status—a condition the United States and its allies refused to accept. At the committee level, India's condition was accepted by a close vote.

62. *Id.* To strengthen its position, the United States also applied these conditions to the use of another frequency band, 4500-4800 MHz, which was proposed to be used in conjunction with the 3400-3600 MHz band for the fixed satellite service. *Id.* para. 1.3.4.2, at 5. It is the satellites, not the radars, which stand to suffer interference when the two share frequency bands.

63. ITU-WARC, Minutes of the Eleventh Plenary Meeting, Doc. No. 975, paras. 5.3.1-12, at 9-10 (Nov. 30, 1979). The compromise proposal, introduced by Jamaica, essentially reinstated the original U.S. proposed compromise that had been reached in the working group but rejected in committee. See note 61 *supra*. The Jamaican proposal is contained in ITU-WARC, Allocations to the Fixed-Satellite Service in the Bands 3.4-3.6 GHz and 4.5-4.8 GHz, Doc. No. 880 (Rev. 1) (Nov. 30, 1979). India finally withdrew its insistence on a specific date for reducing radiolocation to a secondary status, and the compromise was adopted by consensus. See ITU-WARC, Summary Record of the Twentieth Meeting of Committee 5, Doc. No. 955 (Nov. 21, 1979).

64. ITU-WARC, Summary Record of the Twentieth Meeting of Committee 5, Doc. No. 955 (Nov. 21, 1979).

59. Because a radio communications satellite cannot use the same frequencies to transmit and receive at the same time without interfering with its own message, a certain width of the applicable band must be designated for transmissions from earth to the satellite (the uplink), and another portion of the band employed for transmissions from satellite to earth (the downlink). THE FUTURE OF SATELLITE COMMUNICATIONS 13 (report of the Twentieth Century Fund Task Force on International Satellite Communications 1970).

60. ITU-WARC, Twenty-Seventh and Twenty-Eighth Reports of Working Group 5D, Doc. No. 722 (Nov. 16, 1979).

61. See ITU-WARC, Summary Record of the Twentieth Meeting of Committee 5, Doc. No. 955, paras. 1.1.1-3, at 2 (Nov. 21, 1979). In the working group the United States and its allies had agreed to a provision that urged countries to move radiolocation (radar) out of the

2. Feeder Links

Closely parallel to the controversy over additional allocations for fixed satellites was a problem of identifying uplink frequencies to "feed" the broadcast satellite device at 12 GHz. The 1977 Broadcast Satellite Conference had developed for ITU Regions 1 and 3 an allotment plan for broadcast satellites operating in this frequency segment.⁶⁵ The 1977 plan covered only downlinks and not uplinks or so-called "feeder links." Because feeder links are included within the fixed-satellite service, any fixed-satellite allocation can be used. It is not necessary to designate feeder link frequencies. Nevertheless, many countries, especially those in the Third World, were apprehensive that unless specific bands were designated and planned for this purpose, there would not be adequate frequencies to accommodate the broadcast-satellite service planned in 1977. Countries that already had undertaken investments in developing direct broadcast-satellite service, on the strength of the 1977 conference, were particularly concerned. Virtually the entire ITU membership shared an interest in insuring that adequate, suitable spectrum was available for broadcast satellite "feeder links." The United States, though generally unenthusiastic about satellite frequency planning, nevertheless accepted the desirability of some designation or even a specific allotment plan for feeder links. As in the case of the fixed-satellite service the dispute centered on which frequencies to set aside.

Again the United States and other developed countries found themselves in a confrontation with Third World countries, led primarily by India, over a proposal to place the feeder links in the 14.5-15.35 GHz band. These links were intended to be shared on a primary basis with terrestrial fixed and mobile services.⁶⁶ The United States and a number of allies, preferring an allocation in the 17 GHz range, vigorously objected to sharing the 14.5-15.35 GHz band, particularly in the upper portion where they used present allocations for critical defense purposes.⁶⁷ In addition, the Soviet Union opposed the Third World Proposal because its current

uses would be incompatible with the proposed new feeder links.⁶⁸

The controversy over feeder links was sharp and prolonged. Once again a settlement was reached despite the threat of a major North-South political division. The Conference ultimately accepted a U.S.-initiated compromise which provided for use of several bands for uplinks at the option of individual administrations and for a future allotment plan to be developed by future conferences.⁶⁹

In both the fixed-satellite and feeder-link controversies the basic problem was not principally a matter of conflict between the respective requirements of developed and developing countries. All requirements were essentially the same, even though there were differences as to how best to meet these requirements. But, in reviewing the alternatives for doing so, what is striking is the fierce resistance by the developing countries to considering those alternatives which would not disrupt important present operations by the developed countries—not only the United States and its allies, but in the case of feeder links, the Soviet Union as well. By contrast, many Third World countries opposed any changes in HF frequency allocations which might have even slight impact on their existing services.⁷⁰ In part, this situation reflects the belief prevalent among many of the Third World countries that claims of economic impact on developed countries, especially the United States, could not be credited, but were either exaggerated or irrelevant.

The United States often faced this credibility problem, and nearly all the developed countries, including the Soviet Union, confronted it occasionally. Seldom could the problem be met by appeal to factual evidence or logical argument.⁷¹ In the end, these controversies typically were settled only when the developing countries realized that the United States and other countries were in a

68. *Id.*

69. See ITU Radio Regulations, *supra* note 19, art. N7/5 (allocations and accompanying notes for the frequencies 10.7-11.7 GHz, 14.0-14.8 GHz, and 17.3-18.1 GHz); ITU-WARC, Minutes of the Twelfth Plenary Meeting, Doc. No. 976, paras. 2.6-13, at 5-9 (Dec. 1, 1979); ITU-WARC, Minutes of the Eleventh Plenary Meeting, Doc. No. 975, para. 5.22, at 16-18 (Nov. 30, 1979). See also WARC Final Acts, *supra* note 48, Res. BQ & CH (future allotment planning for feeder links).

70. See text at notes 89-102 *infra*.

71. In fairness to the Third World, seldom did technical evidence or logic speak unambiguously on the issues. Even where no evidence was offered in rebuttal of developed country claims, there could be a question of whether the data were reliable, or whether the analysis was complete.

65. See WARC Final Acts, *supra* note 48, app. 29A; ITU Radio Regulations, *supra* note 19, art. N13/9A. Region 2 opted to postpone adoption of a plan until a future conference now slated for 1983.

66. ITU-WARC, Twenty-Sixth Report of Working Group 5D, Doc. No. 711 (Nov. 16, 1979).

67. *Id.*

position to block effective use of the proposed allocations unless their existing services were accommodated.

3. *Changes in the 12 GHz Band*

Of all the satellite allocations controversies, perhaps the most frustrating to the United States was that surrounding its proposal to change existing Region 2 allocations for the broadcast and fixed-satellite allocations in the 12 GHz range of the spectrum. In Region 2, broadcast and fixed-satellite service shared the 12 GHz band, and there was evident concern among South American countries that extensive implementation of the fixed-satellite service might foreclose opportunities for broadcast service. Accordingly, an interim arc segmentation plan was adopted which gave separate orbit segments to each service.⁷² Subsequently, it was discovered that this segmentation plan put severe and unnecessary constraints on the number of satellites, in both services, that could use the arc. The effect of such a constraint was especially severe on the United States inasmuch as its "open skies" policy commits it to multiple competitive entry in the domestic satellite field.⁷³ The United States proposed to expand the 12 GHz band and divide it into separate frequency segments—11.7-12.2 GHz for fixed satellites and 12.2-12.7 for broadcast satellites.⁷⁴ This would open up the entire Region 2 portion of the arc to each service and provide 500 MHz of spectrum to each service.

Before the Conference began, the United States discussed its proposal extensively with Canada and Latin American countries. Canada opposed the proposal, at first arguing that the U.S. proposal would interfere with Canada's planned terrestrial microwave system. The United States demonstrated that there would be no significant conflict with such a system. Canada next argued that the U.S. proposal would preclude Canadian operation of a hybrid satellite system operating in both the fixed and broadcast services. When it was pointed out that the 1977 arc segmentation scheme also would preclude such operation, Canada argued essentially that the whole allocation question should be put off until 1983 in order

to study other options. In the months before the Conference, both the United States and Canada lobbied the Latin Americans for support of their respective positions.

Going into the Conference the countries of Region 2 were split. Brazil and Chile agreed with the U.S. proposal; Venezuela, Argentina, and Mexico sided with Canada; and others were undecided.⁷⁵ A round of talks among the United States, Canada, and Brazil went nowhere for the first few weeks. Finally, a compromise among the three was struck which, in essence, divided the band in two as the United States proposed but provided hybrid systems special limited access to the two separate bands. When the compromise was put to the rest of the Region, however, most Latin American countries other than Brazil were reluctant to accept it without adding their own individual ideas. They proposed, accordingly, to reserve a 200 MHz segment in the middle of the band (12.1-12.3 GHz) for continued use by both services until the 1983 Conference, when a final division would be made. Though the technical or economic basis for such a postponement was never very well demonstrated, it was accepted and the issue resolved.⁷⁶

Although the issue was almost entirely an intraregional controversy⁷⁷ it had some of the same elements of North-South tension as the other two fixed-satellite controversies. Whatever the technical merits of Canada's objection to the first U.S. proposal, the controversy boiled down to a matter of political trust. The reason Canada was able to obtain the support of many Latin American countries was not a shared interest in hybrid satellites, but a shared apprehension that somehow the U.S. proposal would enable the United States to exploit the 12 GHz band before the Region could develop a specific allotment plan to protect the interests of all countries. Despite a demonstration that the U.S. proposal could increase by as much as three times the usable arc segment, which would redound to the benefit of *all* Region 2 countries, many were skeptical of U.S. motives and seized on Canada's technical objec-

75. There is little public record of the debate because virtually all of the discussion took place outside any meeting for which a report was made, other than the report of the final result. See ITU-WARC, Report of Region 2 ad hoc Group, Doc. No. 584 (Rev.1) (Nov. 12, 1979).

76. See ITU Radio Regulations, *supra* note 19, art. N7/5 (allocations for 12 GHz); WARC Final Acts, *supra* note 48, Res. CH.

77. There were minor but difficult questions on how to guarantee that there would be no interregional interference arising from the differences in service allocations between Region 2 and Regions 1 and 3.

72. International Telecommunication Union, Final Acts of the World Broadcasting-Satellite Administrative Radio Conference (1977).

73. See *In re Establishment of Domestic Communications-Satellite Facilities by Non-governmental Entities*, 35 F.C.C.2d 844 (1972).

74. The U.S. proposal is contained in ITU-WARC, Proposals for the Work of the Conference, Allocation Table in the Bands 1215 MHz 40 GHz, Doc. No. 45 (Jan. 31, 1979).

tion as a basis for advocating a postponement. Interestingly, when the United States, Canada, and Brazil presented a joint compromise, the majority of Latin American countries still resisted. A "solution" by the three major Region 2 "developed"⁷⁸ countries was almost as suspicious as one by the United States alone. At least for political reasons, the other Latin countries considered it essential to require still another compromise between "North" and "South."

4. *Planning of Space Services*

As expected, there was very broad support among developing countries for planning of the geostationary arc and frequencies allocated for some space services, particularly the fixed-satellite service. They supported such planning largely out of fear that developed countries were preempting the orbital positions and frequencies and consequently emerging needs would not be met under present ad hoc assignment procedures. The developing countries were divided, however, as to what services or which particular frequencies should be planned. For example, the People's Republic of China proposed that only new allocations to fixed-satellite service below 10 GHz should be planned.⁷⁹ India proposed that all fixed-satellite allocations, including allocations used for feeder links, should be planned.⁸⁰ Iraq went one step further and proposed that *all* space services be planned.⁸¹

The United States supported planning of the feeder links and accepted the decision taken at the 1977 Broadcast Satellite Conference to plan the broadcast satellite service at 12 GHz.⁸² Nevertheless, the United States and many other developed countries opposed the concept of a detailed orbital position and frequency allotment plan for the other services, arguing that such detailed plans were unnecessary to insure equitable access to frequencies and space positions and instead would lead to inefficient use of

these resources.⁸³ The clash of these two views at the Conference was prolonged and intense, though interestingly, the point of debate seemed to be a matter of administrative detail: the scope of the agenda of a future "planning" conference. Though the United States did not *in general* support "a priori" planning, it did not object to a future conference to consider feasibility and various planning options.⁸⁴ It argued, therefore, for an open-ended agenda which would not predetermine the issue. Proponents of planning sought the opposite. The resolution which finally emerged, calling for a future conference, was not completely satisfactory to the United States.⁸⁵ However, in the end the United States was alone in seeking to modify the resolution, and there seemed no point in holding out further by taking a reservation on the issue. Based on the debate about the agenda, the outcome of the future planning conference is likely to turn less on the technical merits and demerits of planning than on the political trust of developing countries in a scheme of resource allocation which they did not design and which many do not yet fully understand.

B. *High Frequency Communications*

Technological advances have opened up extremely high microwave frequency ranges for some uses such as satellite communications. Such advances, however, have not diminished the world demand for frequencies in the lower portions of the spectrum, most notably those frequencies which are anachronistically still labeled "high" frequencies, or "HF."

HF is used for a wide variety of different communications services including aeronautical, amateur, broadcasting, fixed, and maritime-mobile. Virtually every country, whether developed or developing, depends heavily on HF to support one or more of these services. In addition, virtually all of the HF terrestrial services have important international applications or effects.⁸⁶ Hence, international agreement on HF allocation and use is critical.

78. Brazil generally has eschewed a leadership role among Third World countries, no doubt in part because Brazil's level and rate of economic development often align its interests with those of developed countries. See Fishlow, *Flying Down to Rio: Perspectives on U.S.-Brazil Relations*, 57 FOREIGN AFF. 387 (1978).

79. ITU-WARC, People's Republic of China, Proposals for the Work of the Conference, Doc. No. 78 (Sept. 18, 1979).

80. ITU-WARC, India, Proposals for the Work of the Conference, Doc. No. 93 (Oct. 13, 1979).

81. ITU-WARC, Iraq, Draft Resolution Relating to Planning the Radiocommunication Satellite Services Using the Geostationary Orbit, Doc. No. 359 (Oct. 25, 1979).

82. On feeder links, see note 59 *supra*; on 12 GHz, see note 76 *supra*.

83. See WARC DELEGATION REPORT, *supra* note 38, at 76-79; ITU-WARC, First Report of Ad Hoc Group 2 to Committee 6, Doc. No. 482 (Nov. 5, 1979); ITU-WARC, Final Report of Ad Hoc Group 2 to Committee 6, Doc. No. 678 (Nov. 15, 1979).

84. ITU-WARC, Minutes of the Thirteenth Plenary Meeting, Doc. No. 977, para. 8.2.1, at 5 (Dec. 2, 1979).

85. See *id.*; WARC Final Acts, *supra* note 48, Res. BP. The resolution directs the Conference to "decide which space services and frequency bands should be planned." *Id.*

86. See note 3 *supra*.

The principal controversy at WARC centered around competing frequency demands to accommodate three services: broadcasting, fixed, and maritime-mobile. Competition between the first two represented the essential controversy over the HF band as a whole.

The United States sought a major increase in broadcasting allocations in order to accommodate the demands of its international broadcasting operations, such as Voice of America, Radio Free Europe, and Radio Liberty.⁸⁷ Other developed, and many developing, countries also sought substantial increases—though not all of equal magnitude—to support comparable operations.⁸⁸ It quickly became apparent that the increases sought by the United States and a few other countries were unrealistically ambitious, particularly insofar as they were proposed to be accommodated in the highly congested lower portions of the HF band. The difficulty lay in the fact that such increases could, as a practical matter, be accommodated only by displacement of the fixed service which is used extensively, especially in developing countries, for basic telecommunications relay service.⁸⁹ Such use clearly will diminish in the future as terrestrial and satellite microwave facilities are put into use. Nevertheless, many countries, especially in Latin America, were unwilling to anticipate such future changes or to accept any sacrifice now or in the immediate future in HF fixed allocations.⁹⁰ A compromise finally was struck which provided for modest increases in broadcasting allocations in the future, subject to the condition that assignment procedures be modified in certain respects, and that an

87. ITU-WARC, U.S. Proposals for the Work of the Conference, Allocation Table in the Bands Below 27.5 MHz, Doc. No. 43 (Apr. 2, 1979).

88. See, e.g., ITU-WARC, United Kingdom, Proposals for the Work of the Conference, Doc. No. 53A (Feb. 1, 1979); ITU-WARC, Pakistan, Proposals for the Work of the Conference, Doc. No. 55 (Feb. 1, 1979).

89. Although this is the dominant use, HF fixed-service frequencies also are used extensively, even in developed countries, as backup to more advanced systems. HF fixed-service frequencies are used extensively by the United States in military systems overseas for mobile communication, on condition of noninterference with fixed-service users. This extensive military use was a principal reason for a pre-WARC conflict within the United States between the Department of Defense and broadcasters—the latter seeking and the former resisting substantial changes in HF allocations from the fixed service to the broadcasting service. A prolonged contest was resolved essentially in favor of the broadcasters, but the increases actually obtained at WARC were of the same order as originally had been accepted by the Department of Defense.

90. See ITU-WARC, Third Report of Working Group 5BB, Doc. No. 644 (Nov. 13, 1979). The lineup of countries on the question of significant broadcast expansion is illustrated by the roll call votes on increases in the 6 and 7 MHz bands. See ITU-WARC, Minutes of the Ninth Plenary Meeting, Doc. No. 973, para. 6.555.5, at 16 (Nov. 28, 1979).

HF broadcast plan be developed at a future conference. The United States and other proponents of broadcasting still pressed hard for additional accommodation in two critically important bands below 10 MHz—the 6 and 7 MHz bands.⁹¹ The United States lost the effort by fairly narrow vote margins. Failing to obtain additional frequencies in these bands, the United States reserved the right to use these bands if the failure to make additional broadcast allocations were not remedied at the future broadcasting conference.⁹²

The conditions imposed on increased broadcasting allocations reflect the pervasive concern of developing countries that current procedures for handling frequency assignments are essentially “first-come, first-served”⁹³ and thus favor the interests of those countries having more developed communications systems and, hence, more mature demand for frequencies. As in the area of space services, these concerns reflect some dubious conceptions about how the assignment scheme actually operates. The misconception is particularly evident in the case of the proposed broadcasting plan which a future broadcasting conference will be asked to construct. The United States, along with many other countries, accepted in principle a future HF broadcasting plan designed to allay Third World concerns of inequity in present allocations. But in fact any “inequity” that exists is purely a function of larger social and economic disparities among broadcasting countries and not of any ITU mechanism. Certainly this is the case in international HF broadcasting, where assignments are made only after coordination of operational schedules.⁹⁴ There is no first-come, first-served priority based on date of registration. In effect, the present procedure is roughly equivalent to a short-term plan.⁹⁵ Developing countries have experienced difficulty in finding frequencies available to support increased broadcasting operations, but that difficulty is shared by developed countries as well. If it is a fact that developed countries have a larger number of broadcasting assign-

91. See ITU-WARC, Minutes of the Ninth Plenary Meeting, Doc. No. 973 (Nov. 28, 1979).

92. ITU-WARC, Final Protocol, Doc. No. 942, Protocol 38 (Dec. 3, 1979).

93. See text at notes 31-35 *supra*.

94. See text at note 36 *supra*.

95. See D. LEIVE, *supra* note 17, at 179-81. The present broadcasting procedure, unchanged by the 1979 WARC, was developed in 1959 after efforts to develop a long-term plan failed.

ments than developing countries, it is also a fact that they have more extensive operations. In any case, there is no *procedural* impediment to increased assignments for developing countries. Under the present rules, any country can ask for those frequencies necessary to support its quarterly schedule of operations and can demand that others coordinate with it to eliminate interference conflicts. Countries are constrained from obtaining more assignments only to the extent that overall limits on the amount of bandwidth allocated to the service must be accepted in order to avoid undue congestion. In other words, the problem with the present scheme is not that it is first-come, first-served, but that it is "everyone-come, everyone-served" until the band becomes overcrowded.

Of course, within the allocations constraints that exist, a broadcast plan might attempt a more egalitarian distribution of frequencies among countries. At least some Third World proponents of a future HF broadcast plan clearly see that as its ultimate objective. Such a plan presumably would set a fixed upper limit on the level of congestion, then ration the frequencies among users on the basis of some "equitable" formula.

Whether or not such a plan can be practically devised, it is unlikely to be acceptable to major international broadcasters unless there is enough further increase in broadcasting allocations to meet minimum projected demands over the next twenty years. The United States and other major proponents of increased broadcast allocations emphasized this point at the Conference. A plan which attempts merely to redistribute existing, or slightly augmented, allocations is not acceptable.⁹⁶

A detailed assignment plan was not the only means suggested at the Conference for redistributing frequency assignments. Algeria proposed a scheme for HF fixed-service assignments which would give to developing countries priority use of seventy percent of the HF allocations for each service.⁹⁷ The proposal represented a "solution" to a problem that had been misunderstood. Algeria and

some other developing countries, especially in Africa, evidently have been unable to locate sufficient HF frequencies to meet current fixed-service needs because of the extensive use, or at least prior registration of assignments, by other countries. By the imperative of popular Third World claims that the developed countries have monopolized the spectrum generally, it was inferred in this case that there was a maldistribution of HF fixed frequencies—hence the Algerian proposal.

For the United States, as for many countries, the issue was more a matter of principle and precedent than of immediate impact. The measure would have affected U.S. HF fixed-service requirements slightly, if at all,⁹⁸ but once recognized, such a measure could be applied to virtually every service and every part of the spectrum. For example, many developed countries saw it as only a short step from the Algerian proposal to schemes for setting aside certain fixed-satellite frequencies and orbital positions for developing countries.

Interestingly, the Algerian proposal was not warmly received by many developing countries despite its ostensible purpose of giving them priority *vis-à-vis* developed countries. Undoubtedly many saw the practical as well as political difficulties with the proposal.⁹⁹ In addition, many could see that Third World access to HF fixed frequencies is not impeded so much by use in developed countries as by competition among developing countries. The technical reason is elementary: The typical low-power HF fixed-service has a limited range; hence, the potential for interference exists usually between closely proximate countries, which means conflicts between developing countries themselves rather than between developing and developed. Thus, while U.S. domestic use of HF fixed

98. Most of U.S. HF fixed-service requirements are for overseas military operations, see note 90 *supra*, for which assignments are made by cooperative governments in the area of use. Frequently these are developing countries which would receive favorable treatment under the Algerian proposal. Given their limited propagation, fixed-service frequencies within the United States would conflict with few, if any, developing countries.

99. For one thing, there is no single accepted definition of "developing country." For another, the Algerian proposal provided no basis for establishing priorities *among* developing countries, that is, among most countries of the world. Given that the economic and technological differences among developing countries are as great as between many developing and developed countries, the Algerian proposal would achieve very little real "equity." In fact, it almost certainly would lead to attempts to subdivide developing countries according to economic or technological status. I think this was foreseen by some of the relatively more developed countries of the Third World, and it partly explains their lack of enthusiasm for the Algerian proposal.

96. The position of the United States and major proponents of broadcast allocations increases is reflected in the statement of the United Kingdom, summarized in ITU-WARC, Minutes of the Ninth Plenary Meeting, Doc. No. 973, para. 6.51.1, at 15 (Dec. 7, 1979), and in the statement of Pakistan quoted in ITU-WARC, Summary Record of the Twenty-Third Meeting of Committee 5, Doc. No. 958, para. 4.4.1, at 5 (Nov. 23, 1979). See also ITU-WARC, Final Protocol, Doc. No. 942, Protocol 38 (Dec. 3, 1979).

97. ITU-WARC, Algeria, Proposals for the Work of the Conference, Doc. No. 119 (June 18, 1979).

frequencies does not preclude Algeria's use of the same frequencies, Tunisia's use of HF frequencies clearly does.

In this respect, it is also noteworthy that, contrary to popular Third World rhetoric,¹⁰⁰ it is the developing, not developed, countries that dominate HF fixed-frequency assignments.¹⁰¹ Thus the factual base for any wholesale redistribution of fixed-service assignments was lacking. There was nevertheless a consensus that some measures should be taken to ease the difficulties which countries such as Algeria had experienced in meeting their requirements. The Conference adopted a series of measures to meet these needs. For example, it empowered the IFRB to provide special assistance to developing countries in selecting and registering frequencies, and it gave special recognition to HF fixed-service allocations in cases where alternative communications facilities are not available.¹⁰²

IV. THE ITU AFTER WARC

Before the 1979 Conference it was commonplace that the ITU today is not what it was twenty years ago. No doubt this is true. The new majority of Third World countries clearly has changed the former hegemony exercised by a handful of developed countries. But what that implies in the way of other changes in the ITU and its business is unclear. The 1979 WARC provides a few clues on which to base some cautious speculation.

100. Third World spokesmen frequently assert that the developed countries control ninety percent of the radio spectrum. See, e.g., M. MASMOUDI, *THE NEW WORLD INFORMATION ORDER* (UNESCO International Commission for the Study of Communication Problems, Report No. 31, 1978). The claim is general, but it is applied often to the fixed service in particular. So far as I am aware the evidentiary basis for this statement has never been identified, let alone verified. It is not even apparent what the unit of measurement is—bandwidth, number of assignments, transmitters, etc. In any event, the slogan is quite meaningless on any reference unit insofar as it incorrectly implies that use of particular frequencies is exclusive to a single user and that, therefore, frequency allocation is a zero-sum problem. Even the most casual acquaintance with the way in which the radio spectrum is allocated and used should be sufficient to show this is not the case. Nevertheless, through constant repetition, the slogan has gained a degree of acceptance even among those who should know better. See, e.g., Hudson, *The U.S. Faces WARC: Implications for Development Communications*, J. Com., Winter 1979, at 179, 180.

101. An informal analysis by the U.S. delegation of HF frequency registrations shows that only three developed countries, the Soviet Union, the United States, and Canada, are among the ten countries having the most assignments. Among the top five, only the Soviet Union falls in the category of developed countries.

102. See ITU Radio Regulations, *supra* note 19, art. N12/9. The key provisions are Nos. 4280A, 4326A-4326M, and 4439.

A. *The Politics of the No Longer Silent Majority*

To begin with, it is important to emphasize that the change in ITU membership has not substantially altered the essentially technical character of the ITU. WARC negotiations largely were contained within the framework prescribed by a technical agenda, which ensured that political considerations, though not absent, at least were filtered for relevance. The willingness to forego broad, abstract political objectives is evident in the character of the delegations sent to Geneva. Virtually every major delegation at the WARC was composed of and led by technical representatives from each country's telecommunications ministry and associated organizations. The United States was exceptional in having its delegation headed by a foreign ministry representative and in sending a cadre of foreign ministry delegates to attend to purely "political" issues.¹⁰³

Perhaps more important than the professional background of delegates to ITU conferences is the continuity of individual representation within the respective delegations. It used to be said that the ITU was an "old boys' club." Judging from the 1979 WARC, it remains so. Virtually all of the active delegations, including those from new ITU members, had extensive prior experience in ITU activities. Many of the same key representatives are expected to be active in future ITU conferences. If so, it is unlikely that the future will witness any radical departures from the pattern of negotiations in the 1979 WARC. Of course, we can expect to see increasingly influential Third World participation in the ITU. Nevertheless, I would not expect to see an overpowering Third World dominance for two reasons.

First, the developing countries are not a consistently unified bloc in the ITU any more than in any other international forum. Indeed, the potential for unified action is probably less in the context of ITU negotiations than in other U.N. forums because the ITU engages less in generalized political discourse, on which it is easier to develop a united position, than in the pursuit of specific economic or social objectives, where detailed negotiations quickly expose underlying differences. There may be as much divergence of social and economic interests among developing countries as there is between many developing and developed countries.

103. For a list of the U.S. delegates, see ITU-WARC, List of Participants, Doc. No. 982, at 28-31 (Feb. 1, 1980).

Second, power in international institutions is not a simple matter of majority vote. Many ITU observers have been troubled by the prospect of interests of the United States and other developed countries being jeopardized by the overwhelming voting power of developing countries in the ITU,¹⁰⁴ even though any ITU member may withhold its consent to any majority decision by entering an appropriate "reservation" in the final acts.¹⁰⁵ The effect of such a reservation leaves the country free to pursue its own use of the spectrum independent of other countries, but it does not give it the international recognition or protection which may be necessary for effective utilization of the frequencies. The prerogative of unilateral action is, however, an effective lever against majority control where a particular country needs no such protection or recognition to operate the stations in question. As a small example, at the WARC a majority of countries insisted on adding a requirement that in certain specified bands, mobile-satellite stations must operate on a noninterference basis with stations of other services sharing the allocation.¹⁰⁶ All of the NATO countries, which use these bands for a common mobile-satellite defense system, simply refused to accept the noninterference condition.¹⁰⁷ Presumably the majority then could have voted to deny the allocation to the mobile-satellite service, but that only would have provoked another reservation of the right to operate unilaterally which, in the circumstances, the NATO countries could do since they did not require protection from other services.

Moreover, there are other levers which strong countries can exercise to protect their interests against a majority. The controversy over fixed-satellite allocations, and the attempted displacement of U.S. and U.K. radar systems in the 3 GHz band is illustrative.¹⁰⁸ Once the practical consequences of forcing a decision over, in particular, U.S. opposition were pointed out by a small group of astute Third World delegates, the wisdom of a compromise settlement was perceived. The important point, however, is that the practical benefits of a consensus were recognized and were not foregone simply to record an ideological victory for the developing countries.

Despite the benign record of the Conference in terms of North-South politics, some observers have warned that this is deceptive as a guide to the future, since many of the most politically volatile issues were deferred to subsequent conferences.¹⁰⁹ The plenipotentiary conference, scheduled for 1982, will provide the first important occasion for an overtly political debate. In contrast to administrative conferences, the plenipotentiary does not have a technical agenda, but is concerned with more general political matters such as reviewing the basic charter of the ITU and electing the major officers. Because there are no technical issues of spectrum allocation and usage to be resolved, one can expect that this conference will give fairly free rein to general political discourse and rhetoric. One occasion likely to excite political controversy will be the election of a chairman. Based on the experience at the 1979 Conference, this election will be hotly contested.¹¹⁰

Apart from the important question of ITU leadership, the plenipotentiary conference almost certainly will examine institutional roles within the ITU. In particular the Third World probably will seek ways to strengthen the powers of the IFRB. This is in part a natural reflection of organizational function: Every country must look to the IFRB for assistance in registering and coordinating the use of frequencies.¹¹¹ Third World interest in the IFRB also reflects a belief that the IFRB and its staff are more sympathetic to, as well as more aware of, developing country interests. Particularly if the Secretary-General elected in 1982 is identified only weakly with developing country interests, the IFRB will grow in power. The 1979 WARC gave indications of the growth of power and influence of the IFRB.¹¹²

In contrast, the influence of the CCIR may diminish. The 1979 WARC showed that many of the Third World countries believe the CCIR is dominated by developed countries and has been used by

104. See Branscomb, *supra* note 41, at 143-44.

105. International Telecommunication Convention, Oct. 25, 1973, art. 77, para. 513, 28 U.S.T. 2497, T.I.A.S. No. 8572 (entered into force Apr. 7, 1976).

106. See ITU Regulations, *supra* note 19, art. N7/5 No. 3618.

107. ITU-WARC, Final Protocol, Doc. No. 942, Protocol 32 (Dec. 3, 1979).

108. See text at notes 61-64 *supra*.

109. See *Why the sky didn't fall at WARC*, BROADCASTING, Dec. 17, 1979, at 44, 52.

110. See note 47 *supra*. I doubt that the contest over the chairmanship will be drawn simply along North-South lines. Developed countries probably will not dispute that the ITU chairman should come from a developing country; the question will be, which one? The choice is as likely to divide the developing countries as it is to separate them from the developed.

111. See notes 25-26 *supra* & accompanying text.

112. One noteworthy example is the expansion of the IFRB's role in aiding developing countries to select frequencies and register assignments. See note 102 *supra* & accompanying text. Another important new role is to provide assistance in preparing for and organizing future conferences. See WARC DELEGATION REPORT, *supra* note 38, at 95-96.

them to dominate the ITU. The complaint reflects the fact that many developing countries lack sufficient technical expertise to participate fully and effectively in the CCIR. Although the Conference recommended numerous tasks for the CCIR,¹¹³ it was reluctant to entrust the CCIR with major responsibility for making recommendations on important, politically controversial issues.¹¹⁴

The United States has every reason to support a stronger IFRB which has the trust of the Third World and which therefore can exert a positive influence in resolving interference conflicts and in promoting accommodation of interests among ITU countries. The United States supported measures taken at the 1979 WARC to expand the IFRB role in assisting developing countries in locating and registering frequencies. The United States could support even further expansion of this IFRB assistance role. Technical assistance by the IFRB, however, is only a partial answer to the more general problem, faced in all international negotiations, of providing technical and economic assistance for developing countries.

B. Technical and Development Assistance

For many years, the ITU has operated a relatively modest technical assistance program in coordination with the U.N. Development Programme.¹¹⁵ The issue of expanded technical assistance was raised at the WARC, but it did not occupy a prominent place in Conference deliberations. Consistent with the WARC deliberations generally, the discussion of assistance was quite narrowly focused on spectrum management and other matters that were part of the Conference agenda. The result was a series of resolutions calling for establishment of specialized technical assistance.¹¹⁶ Un-

like debates in other forums over the new international economic order, there was little discussion of general principles of international development assistance. For example, contrary to U.S. expectations, there was no carryover into WARC from the U.N. Conference on Science and Technology for Development, held in Vienna a month before WARC began.¹¹⁷ Similarly there was little apparent fallout from the general, often diffuse discussions about development assistance as part of the new world information order.

The failure of WARC to develop a broad concept of general assistance in the field of communications, and the relatively low priority given to the subject generally, doubtless will disappoint those proponents of greater assistance who hoped WARC would provide the occasion for drawing greater international and U.S. domestic attention to this area. For the United States, however, it is probably fortunate that the Third World did not seek a more ambitious commitment of assistance. While the United States supported the resolutions calling for particular programs, to be supported from UNDP or other voluntary funds, it has been chary about committing any large sum of funds to communications assistance either on a bilateral or multilateral basis.¹¹⁸ Indeed, it has been the source of

Frequency Management), Res. BZ (assistance to developing countries in securing access to HF bands for fixed services), and Res. CG (technical cooperation in study of propagation in tropical zone). A complete list is provided in WARC Final Acts, *supra* note 48.

None of the resolutions and recommendations establish any financial commitment to the projects. In general, most of the funding for ITU technical assistance is provided by UNDP, which appropriates such funds only after it has approved the specific project plans submitted by the country requesting assistance. See INTERNATIONAL TELECOMMUNICATION UNION-UNITED NATIONS DEVELOPMENT PROGRAMME, *supra* note 115, at 34-40.

117. The Deputy Secretary-General of ITU had attended that Conference and had discussed the importance of the ITU's satellite communications activities to the Programme of Action of the Conference. See Report of the U.N. Conference on Science and Technology for Development, U.N. Doc. A/CONF.81/16/Corr.1 (1979).

118. U.S. policy has been to channel multilateral technical assistance through the UNDP, to which contributions are voluntary, rather than through the U.N. specialized agencies which are supported by payments assessed to all members according to a prescribed formula. In exceptional cases, however, the United States has supported technical assistance by the specialized agencies where it is tied closely to their operational mission. See *Authorizing Appropriations for Fiscal Years 1980-81 for the Department of State, the International Communication Agency, and the Board for International Broadcasting: Hearings Before the Subcomm. on International Operations of the House Comm. on Foreign Affairs*, 96th Cong., 1st Sess. 67-68 (1979) (statement of C. William Maynes, Assistant Secretary of State for International Organization Affairs). In authorizing appropriations for 1979, Congress, on the initiative of Senator Jesse Helms (R.-N.C.), directed that U.S. dues payments to the United Nations and its specialized agencies should not be used to fund technical assistance. The United States thereupon was obliged to seek assurance from the United Nations and its agencies that no part of U.S. dues would be so used. Failing to obtain such

113. See *id.* at 96. The recommended CCIR studies run the gamut of subjects from the study of climatic zones for purposes of calculating propagation to transmission of electric power from a solar power satellite.

114. For example, the IFRB was chosen to carry out the technical preparations for the important and controversial future space services planning conference. See note 112 *supra*. The CCIR is directed to carry out preparatory studies and to provide the conference with technical information, but the IFRB expressly was given the main responsibility. Otherwise, the developed countries, through the CCIR, might have created a bias in the outcome by introducing technical reasons why planning was not feasible.

115. See INTERNATIONAL TELECOMMUNICATION UNION-UNITED NATIONS DEVELOPMENT PROGRAMME, TELECOMMUNICATION AND DEVELOPMENT (Booklet No. 22, 1978).

116. The Conference adopted some fifteen resolutions and recommendations endorsing technical cooperation and assistance in various areas. Almost all of them deal with highly specific technical subjects relating to radio frequency usage and management. The following are illustrative: WARC Final Acts, *supra* note 48, Res. AD (development of National Radio

some embarrassment that the United States in the past has been looser with its promises than with its purse strings.¹¹⁹

In preparing U.S. positions for WARC, and for earlier UNESCO and U.N. discussions of the new world information order, an effort has been made to develop a more ambitious and coherent program of economic and technical assistance in the field of communications and information activity, including, but not limited to, activities related to the use of radio spectrum. The result of these efforts, though perhaps not negligible, was altogether modest.¹²⁰

assurance, the United States was forced to withhold payment of U.N. dues—a cause for some embarrassment on the eve of the 1979 WARC, where the issue of assistance was expected to be raised. See *id.* at 74-82. Fortunately, the fiscal 1979 stricture was not carried forward to future appropriations and was repealed for fiscal years 1980 and 1981. Department of State Authorization Act, Fiscal Years 1980 and 1981, Pub. L. No. 96-60, § 110, 93 Stat. 395 (1979).

119. A noteworthy example was the U.S. promise, made at the 1976 UNESCO General Conference in Nairobi, to assist Third World countries in developing mass media capabilities. Two years later, when preparations for the 1978 UNESCO General Conference were in the final stages and WARC preparations were in the mature stage, the promise had produced no appropriated funds for the purpose, nor even a coherent plan for developing a program. This was not the first time that pledges of assistance in this area had produced no tangible results. Prior to the 1976 UNESCO General Conference in Nairobi, the Secretary of State had pledged assistance to developing countries in connection with satellite communications and sensing programs. Address by Secretary of State Henry Kissinger before the Fourth Ministerial Meeting of the U.N. Conference on Trade and Development at Nairobi (May 6, 1976), reprinted in 74 DEP'T STATE BULL. 657, 667 (1976). An essentially similar pledge was repeated by the President after the Nairobi conferences. Address by President Jimmy Carter before the Permanent Council of the Organization of American States, 13 WEEKLY COMP. OF PRES. DOC. 523, 525 (Apr. 18, 1977). As of late 1978, little had come of any of these pledges. ACADEMY FOR EDUCATIONAL DEVELOPMENT, *supra* note 9, at 5-6. Fortunately, a modest (\$24 million over a six-year period) AID program to assist in the development of satellite service to rural areas was rescued from virtual oblivion in time to be announced at the 1978 UNESCO Conference. For a description of the project, see Agency for International Development, AID Rural Satellite Program (internal memorandum, Sept. 14, 1979). As of the end of 1979, however, no applications of the program had been approved.

120. See note 119 *supra*. A 1978 internal AID survey of AID projects with communications components showed a total of some \$28.3 million in assistance for fiscal year 1978; however, \$16.6 million of this amount was for security-supporting assistance in the Near East and cannot qualify as development assistance. Agency for International Development, Survey of AID Projects with Communications Components (internal memorandum, Oct. 5, 1978). A description of the types of programs is given in ACADEMY FOR EDUCATIONAL DEVELOPMENT, *supra* note 9, at 138-53.

The modest results reflect an overall U.S. assistance policy in which communications and information technology and services rank near the bottom of aid priorities. Within the current policy framework of targeting aid programs on basic human needs—food/nutrition, population/health, and education/human resources development—it has been difficult to find a place for funding aid programs to develop communications or information systems. The basic human needs orientation reflects the essential character of the so-called “new directions” in aid policy mandated by Congress in 1973. See, e.g., SENATE COMM. ON FOREIGN

One proposal addressing this general aid problem, as well as the lesser-included question of assistance in the field of communications, has special relevance to WARC. It has been suggested that if there ever is to be a redressing of the economic imbalances among nations, the developing countries must be able to commit themselves with their annual budgets beyond the vicissitudes of foreign assistance policies and the like.¹²¹ One method of funding would be an excise tax on international activities such as transportation, commerce, and communications, with funds from the tax distributed into a special development fund for the benefit of the Third World.¹²² Of interest in the present context is the suggestion that a tax be levied on the use of international resources, such as orbital positions for satellites and frequency allocations in the radio spectrum.¹²³

There is a precedent of sorts for such a concept in the Draft Convention on the Law of the Sea, which contains an agreement in principle to a tax on deep seabed mining.¹²⁴ One can extrapolate

RELATIONS, INTERNATIONAL DEVELOPMENT ASSISTANCE ACT, S. REP. NO. 95-161, 95th Cong., 1st Sess. 6-14 (1977).

Even accepting the general philosophy of meeting basic human needs as a first priority of development assistance, it does not automatically follow that low priority should be given to communications and information systems. In fact, communications has an obviously important role to play in almost any scheme for meeting human needs. One need not suppose that possession of a radio or television set is itself a basic human need to recognize that these are important instruments of information with which to meet these needs. Consider, for example, food as a basic human need. I take it that aid which went for the purchase of plows would be deemed consistent with meeting this basic human need. Why not a television set? You cannot eat a television set, of course, but you cannot eat a plow either. A radio will not till the fields, but a plow will not provide information on weather, soil conditions, agricultural methods, etc. Information is the necessary, if not sufficient, condition for advancement. Recognition of that simple reality is providing the impetus for a new world information order as a special construct in the struggle for international fairness.

The problem of communications assistance is part of a larger question about the future direction and level of development assistance generally. Given the popular disenchantment with past economic assistance programs, U.S. foreign aid faces an uncertain future. Such general uncertainty will make it difficult to establish a strong role for development assistance in fields where it previously has not existed. Therefore, assistance for communications and information programs faces a not very promising future.

121. See generally INDEPENDENT COMMISSION ON INTERNATIONAL DEVELOPMENT ISSUES, NORTH-SOUTH: A PROGRAM FOR SURVIVAL (1980) (also known as the Brandt Commission Report).

122. See *id.* at 244-45; H. CLEVELAND, THE THIRD TRY AT WORLD ORDER 67-68 (1977); E. STEINBERG & J. YAGER, NEW MEANS OF FINANCING INTERNATIONAL NEEDS 26-38 (1978).

123. See E. STEINBERG & J. YAGER, *supra* note 122, at 27-28.

124. See Draft Convention on the Law of the Sea (Informal Text), art. 153 & Annex III, art. 13, U.N. Doc. A/CONF.62/WP.10/Rev.3 (1980) [hereinafter cited as Draft LOS Conven-

from this precedent a position that, in one form or another, use of the radio spectrum or geostationary orbit positions should be taxed on the principle of paying for and sharing the benefits derived from a commonly owned international resource.

There are a number of practical issues that must be addressed in evaluating the tax concept. Three basic questions immediately come to mind. First, how would the tax be assessed and the revenues be distributed among the countries?¹²⁵ Second, would the distributed revenues be earmarked for the special purpose of communications development, or could they be used for any purpose by the individual countries?¹²⁶ Third, how would the taxing mecha-

tion] (providing for various fee and profit-sharing arrangements between individual mining entities and the International Seabed Authority).

For the U.S. position on this aspect of the Draft LOS Convention, see U.S. Dep't of State, Office of the Law of the Sea Negotiations, U.S. Delegation Report, Resumed Seventh Session of the Third United Nations Conference on the Law of the Sea, Aug. 21-Sept. 15, 1978, at 9-14 (undated).

The mechanism adopted for exploitation of the deep seabed could establish a model for other international arrangements relating to the development of common global resources, including the radio spectrum. See *Oceanography Miscellaneous—Pt. 2: Hearings on the Law of the Sea Conference Briefings Before the Subcomm. on Oceanography of the House Comm. on Merchant Marine and Fisheries*, 95th Cong., 1st & 2d Sess. 109, 124 (1977-1978) (remarks of Rep. Breaux); *id.* at 137 (statement of Richard G. Darman); Breaux, *The Diminishing Prospects for an Acceptable Law of the Sea Treaty*, 19 VA. J. INT'L L. 258, 261, 277 (1979); Darman, *The Law of the Sea: Rethinking U.S. Interests*, 56 FOREIGN AFF. 373, 387 (1978).

125. Presumably the tax on domestic uses would be levied on governments, but the selection of a tax base still would have to be determined. Would all uses be taxed, or only those registered with the ITU? Would the tax be levied on the basis of number of assignments or bandwidth? Would all frequencies (whatever the unit) be taxed at the same rate? Would international users be taxed the same as domestic? secondary users the same as primary? passive the same as active? None of these problems would be impossible to resolve if there were agreement on the basic concept, but the difficulty of reaching international accord on some of these issues should not be underestimated.

Apart from how the tax is collected, the distributional issue is a difficult one. Insofar as the main purpose of the tax is international wealth redistribution, special shares presumably ought to go to developing countries. Cf. Draft LOS Convention, *supra* note 124, arts. 140, 144, 148, 150, 153, 160 (implying that "special needs" of developing countries demand special distributional shares of seabed mining benefits for them). Such a general principle leaves open a fair range of possible distributional arrangements.

126. One rationale for an earmarked tax would be that the tax is payment for the benefits derived by users specifically for a well-developed system of communications. On this basis, an earmarked tax, at least in theory, serves economic efficiency better than a general revenue tax because it gives the user the ability to determine how much of that benefit should be "purchased" by adjusting the demand for the taxed good. See Buchanan, *The Economics of Earmarked Taxes*, 71 J. POL. ECON. 457 (1963). In addition to this theoretical consideration, earmarking may be an important form of control over the application of tax revenues in the absence of an international mechanism for overseeing expenditures. See E. STEINBERG

nism, including the tax rate, be established and controlled: on the basis of equal voting rights for each country (as for example, in U.N. specialized agencies and the U.N. General Assembly), or by weighted voting according to, say, use of the resource (as in INTELSAT)?¹²⁷

From the U.S. perspective, the tax concept would involve a re-orientation of U.S. foreign policy which generally has opposed mandatory international levies for economic assistance programs.¹²⁸ One can, of course, distinguish this particular tax from such levies on the ground that it is merely an equitable sharing of the benefits of an international resource. As a political matter, however, it almost certainly would be perceived simply as a form of foreign development assistance, and, as such, one that is at odds with traditional policy.

C. Planning Spectrum Distribution

As a scheme of wealth distribution, the tax proposal appeals in part to the notion that all nations should share equitably in the benefits derived from using a global common property resource. Implicit in this appeal is an assumption that the benefits of present use of the resource are not distributed equitably. Whether or not anything ever comes of the tax proposal, the underlying premise is almost certain to have a significant influence on the international spectrum allocation policies. This was apparent at the 1979 WARC. The theme of wealth redistribution not only per-

& J. YAGER, *supra* note 122, at 182-92.

127. In the Draft LOS Convention, *supra* note 124, the issue of institutional control was one of the major unresolved problems. The developing countries insisted on equality of voting rights for all members of the International Seabed Authority, whereas the developed countries insisted on some form of weighted voting power corresponding to their greater stake in seabed mining. See *Oceanography Miscellaneous*, *supra* note 124, at 146-49 (remarks of Richard G. Darman); Breaux, *supra* note 124, at 278-81; Smith, *The Seabed Negotiation and the Law of the Sea Conference—Ready for a Divorce?*, 18 VA. J. INT'L L. 43, 48 (1977).

The solution adopted by the Law of the Sea Conference embodies part of each approach. An Assembly is to consist of all members of the Authority, with each member having one vote. Each State which is a party to the LOS Treaty will be a member. The Assembly then will select a Council of thirty-six members charged with many of the duties of the Authority. Membership on the Council is determined by a complex quota system which requires seats to be set aside for developing countries, countries with the largest investments in the seabed mining field, and other countries with special interests. Each member of the Council will have one vote. Draft LOS Convention, *supra* note 124, arts. 159-162.

128. See note 118 *supra*.

vaded the atmosphere of negotiations, but it also motivated many of the specific allocations decisions and the debate over planning.¹²⁹

The planning issue—i.e., whether and how to allocate frequencies in advance of need—is too complex to deal with here in detail. Some elaboration, however, is needed to understand this controversy, which has been and will continue to be among the most important and divisive problems faced by the ITU. The discussion will focus on the fixed-satellite service¹³⁰ because that service is likely to be the focal point of future space-services planning conferences.

Allotment plans make a one-time distribution on the basis of present needs and predicted future requirements, thus replacing the present ad hoc methods of assignment. One of the main difficulties with constructing such plans is that each country has an incentive to overstate its requirements, and there are few accepted or objective criteria for evaluating each country's stated need. In fact, the individual country itself may have only the dimmest perception of its needs over the time period for which the plan is to be constructed. This is a problem particularly with the new satellite services, with which most countries have had little domestic experience. Under these circumstances, it is easy to make a case that allotment plans are not only difficult to construct, but when constructed will lead to a waste of resources as frequencies and orbit positions are "warehoused" to meet future, indeterminate needs. The warehousing problems could be alleviated either by allowing frequency allotments to be transferred to another country or by imposing a condition of use within a specified period of time.

As to transferring allotments, it suffices here to say that under current plans, frequency allotments are not in a form which could be transferred except perhaps to closely adjacent countries. To create transferable rights would require a different planning scheme than any now in use or in contemplation.¹³¹ The possibility of cre-

ating a different scheme, based on spectrum property rights transferable through an international spectrum market, is considered below.

A condition of use within a specified period of time can avoid waste, but there remains the problem of how to redistribute unused frequencies. Fidelity to the planning approach requires that unused frequencies be redistributed according to a plan. Dealing with unused frequencies is part of the more general problem of modifying the plan to conform to changing circumstances. Herein lies the basis for the main criticism of allotment plans: They lack the flexibility required to adjust quickly and easily to changes in requirements and, equally important, to technological changes. The problem is especially acute where radio technology is changing rapidly, as is the case with satellite communications. An allotment plan constructed on the basis of present technology quickly can become obsolete with changes in both satellite and earth terminal requirements.¹³²

The case against planning is easy to make, but also easy to overstate. International plans for some services, notably the maritime and aeronautical services, long have been an accepted feature of ITU practice, as has regional planning of domestic broadcasting.¹³³ Similarly, plans for the broadcast-satellite service at 12 GHz were established by the ITU in 1977,¹³⁴ a decision which the U.S. initially opposed but now has accepted.¹³⁵ Finally, virtually all countries accept planning of domestic allocations. The United States, for example, in allocating broadcasting frequencies, reserves TV and FM channels for specified markets regardless of immediate need.¹³⁶

132. For example, a satellite allotment plan based on a specified minimum separation between satellites is subject to obsolescence with any change in satellite design that narrows the required separation. Such changes are occurring. Illustrative is the fact that, since the 1977 broadcast satellite plan, *see* note 72 *supra*, technological changes have permitted closer spacing between satellites while still retaining the same protection against interference.

133. *See* notes 30-31 *supra* & accompanying text.

134. *See* INTERNATIONAL TELECOMMUNICATION UNION, FINAL ACTS OF THE WORLD ADMINISTRATIVE RADIO CONFERENCE (1977).

135. *See* Dizard, *supra* note 11, at 165.

136. Harvey Levin has contrasted U.S. domestic and foreign attitudes toward planning, and has suggested an approach combining planning with market incentives. *See* H. Levin, Are U.S. Policies at Home and Abroad Consistent? The Case of Spectrum Reservations and Media Balance 5-7 (unpublished paper prepared for the World Communications Conference, Annenberg School, University of Pennsylvania, May 1980) (copy on file with the author).

129. It was most evident in the debate over allotment plans, particularly in the context of setting the agenda for the future space services planning conference. *See* text at notes 84-85 *supra*.

130. *See* text at note 37 *supra*.

131. Present allotment plans specify both transmission points and service areas for each frequency. A country may have, for example, an assigned orbital position from which it can transmit a signal of specified strength to a particular terrestrial location. A property right so defined would be of little use to another country seeking an orbital position and frequency to serve its own territory.

To these arguments, the U.S. rejoinder has been that it does not oppose all planning; its position both in international and domestic practice is that the case for planning must be carefully weighed in each instance based on distinctive efficiency and equity considerations.¹³⁷ If there is a flaw in the U.S. position, it lies not in inconsistency, but in excessive insistence on a purely analytical approach to the efficiency-equity issue. At WARC, the United States and other developed countries that shared its views on planning did not contest the argument that equity was an extremely important principle in resource allocation. They argued instead that equitable considerations did not compel support for planning. On the contrary, an unplanned assignment system would insure better that all future needs would be met because it would conserve over time more of the resource for distribution as needed.¹³⁸ The Third World fears of being preempted by earlier developed-country exploitation actually were belied by experience, because no one could show that there had been any such preemption, despite considerable satellite activity by both developing and developed countries.¹³⁹ The argument that preemption will not happen failed at WARC, and it probably will fail at the future planning conference because it cannot be proved that the perceived problem is not a real one: It cannot be proved that no country will ever be denied reasonable access to the spectrum or orbit. Such proofs are in the realm of religion, not engineering, and the protagonists do not share the same faith.

Despite the gap of trust that separates developing from developed countries in this regard,¹⁴⁰ I expect a settlement will be negotiated at the future space conference. Without attempting to predict the precise outcome of the future conference, I anticipate that

some form of plan will be approved for selected frequencies and orbital slots used by the fixed-satellite service. The parameters of such a plan I will not attempt to imagine; these will be the subject of heated controversy. When the shouting is over, however, I doubt the Third World will insist on a plan that would be rejected by a significant number of the major space powers. The cost of making a political show of strength would be the loss of international coordination of satellite usage—a loss which must work to the relative disadvantage of the Third World *vis-à-vis* the major space powers. Moreover, I expect it will be possible to engineer a limited plan that will substantially, if incompletely, meet the objectives of developing countries and still remain acceptable to the developed countries. The United States undoubtedly will resist planning the entire fixed-satellite service, at least on the conventional pattern of the 1977 broadcast-satellite plan. But there may be acceptable alternatives—for example, in the form of guaranteed options to certain orbit positions, or allotments strictly limited to a few frequencies and positions.¹⁴¹

I do not suggest that the United States should accept any plan merely in the spirit of accommodation regardless of the plan's merits or its impact on U.S. interests. But U.S. interests must have some flexibility. While the United States has a great deal at stake in terms of its use of these resources, it also is better equipped than most countries to adapt technologically to the regulatory constraints of planning. Also, the extensive space requirements of the

137. See Robinson, *The U.S. Faces WARC: The U.S. Position*, J. COM., Winter 1979, at 151, 155. For example, the United States has supported planning of certain HF frequencies, feeder links, and aeronautical services at the 1979 WARC and at other administrative conferences.

138. See WARC DELEGATION REPORT, *supra* note 38, at 78-79 (statement of U.S. spokesman regarding resolution BP).

139. There were reports of administrative difficulties in completing advanced coordination procedures for two domestic systems, Indonesia's Palapa and India's Insat. Some of these difficulties probably stem from the fact that, as a practical matter, the new entrant has the burden of showing compatibility with existing operations.

140. At times during the 1979 WARC it seemed that the capitalist countries were uniquely the objects of Third World distrust. If so, it was probably because the Soviets challenged Third World proposals less often, for the simple reason that the proposals affected them only marginally.

141. For example, under the guarantee option, developed countries occupying orbit positions might agree to time limits on their occupancy or might agree to be "bumped" from their positions if no slots were available within a specified period to accommodate developing country requirements. ACADEMY FOR EDUCATIONAL DEVELOPMENT, WARC 1979: DEVELOPMENT COMMUNICATIONS STRATEGIES—A REPORT TO USAID (H. Hudson ed. 1979). The first option in effect was crystallized in International Telecommunication Union, World Administrative Radio Conference for Space Telecommunications, Res. Spa 2-1 (1971), which provided that registration of assignments for space services should not give permanent priority to the country registering. Resolution Spa 2-1 was replaced at the 1979 WARC with a resolution which provides essentially the same, with some additional elaboration. WARC Final Acts, *supra* note 48, Res. AY. The United States and the ITU interpreted Resolution Spa 2-1 to mean that a registered frequency assignment for a satellite was valid only for the lifetime of the satellite initially launched, and the priority accorded that assignment did not extend to replacement satellites within the system even if the basic characteristics of the system were unchanged. Curiously, however, the 1979 WARC extended the effective lifetime of satellite assignments by limiting the life of the assignment to the satellite lifetime as indicated in the original assignment notice. WARC Final Acts, *supra* note 48, Res. BY. It also provides that this period can be extended to cover replacement satellites having the same basic characteristics as the original. *Id.*

United States give it a basis on which to claim a relatively large allotment of frequencies and space positions. By any distribution criteria that are likely to be acceptable to the major countries, the United States should do as well as any in having its needs met.

D. Allocating By Market

Insofar as any frequency or orbit position assignment fixes rights of priority use, it confers a form of property right, albeit a very limited one because the assignment cannot be transferred and is conditioned on usage in accordance with the table of allocations and related regulations. Allotment plans go a step further than the flexible assignment system in clearly defining and distributing spectrum rights and satellite orbit positions in advance of specific utilization. Nevertheless, the rights conferred in allotment plans are nontransferable and subject to conditions of use.

It has been argued that greater use-efficiency could be realized by allowing free transferability among users or even among different types of use or services.¹⁴² Users then could purchase full property rights through a spectrum market. The concept of a radio spectrum market to allocate radio frequencies is not a new one; proposals to establish an open market or at least market-type mechanisms for *domestic* allocations have become fairly common over the past two decades.¹⁴³ In recent years there even have been signs of possible acceptance of market mechanisms as a vehicle for spectrum allocations in certain instances, though no specific steps have been taken yet to implement such mechanisms.¹⁴⁴

Only recently has any serious attention been given to the possibility of an *international* spectrum market.¹⁴⁵ In terms of eco-

nomic efficiency the theoretical case does not appear to be much different for an international spectrum market than for a domestic market. In both instances, a market mechanism presumably would facilitate distributions that maximized the economic value of each frequency. Indeed, one can argue that the economic efficiency argument is stronger for international than for domestic allocations. In the domestic setting, one can justify some degree of regulatory control as a means to insure that certain social needs are served which would not be adequately served by pure market allocations. The justification may be exaggerated in many instances in the domestic context, but in the international context there is very little basis for arguing the superiority of social over market choice. While the market deficiencies might be the same at the international level as at the domestic level, the regulatory mechanisms for addressing them are not. The ITU is not an international FCC. Only to a very limited degree, and in a very limited sense, does the ITU make allocations decisions based on any studied consideration or weighing of global social needs. In registering assignments to users within broad service classes, the ITU makes no social evaluation of the use at all.¹⁴⁶ Such evaluations are strictly the province of individual nations. One might argue therefore that, at least after a collective choice is made to allocate frequencies to certain services, a market system of distribution could not possibly impair any international social objectives because no such objectives have been defined.

Establishing an international market mechanism would not be a

142. See, e.g., C. Jackson, A Market Alternative for the Orbit-Spectrum Resource (unpublished paper presented at the Sixth Annual Telecommunications Policy Research Conference, Airlie, Virginia, May 11, 1978) (copy on file with author).

143. See Coase, *The Interdepartment Radio Advisory Commission*, 5 J.L. & ECON. 17 (1962); Coase, *The Federal Communications Commission*, 2 J.L. & ECON. 1 (1959). For a review of these proposals and later treatments, see H. LEVIN, *supra* note 51.

144. See C. Ferris, Private Radio: A Feudal System or a Free Marketplace? (Mar. 20, 1980) (address by Federal Communications Commission chairman before the Annual Meeting of the Land Mobile Communications Council).

145. On at least the conceptual level I believe the case for using market processes in domestic spectrum allocation is compelling. See Robinson, *The Federal Communications Commission: An Essay on Regulatory Watchdogs*, 64 VA. L. REV. 169, 240-43 (1978) [hereinafter cited as Robinson, FCC]. I should confess to having once harbored contrary views which I am now at a loss to justify. See Robinson, *Radio Spectrum Regulation: The Administrative Process and the Problems of Institutional Reform*, 53 MINN. L. REV. 1179, 1248-65

(1969). In some instances I doubt that a pure market system would prove feasible or even desirable, but in virtually all instances the use of market mechanisms in aid of bureaucratic decisionmaking seems to be both practicable and desirable. The use of market-type mechanisms would include, for example, the use of "shadow pricing" or market simulation methods which would calculate the value of the spectrum in different uses. For a discussion of such techniques, see H. LEVIN, *supra* note 51, at 117-57.

Apart from using market simulation techniques as an aid to spectrum allocation decisions, the imposition of a variable tax based on the estimated value of the spectrum in different uses could be used to achieve much the same objectives. Such a tax ("fee") was proposed in 1979 as part of a general revision of the Communication Act. H.R. 3333, 96th Cong., 1st Sess. § 414 (1979). Along with many other reforms, the tax/fee proposal did not survive the sharp attacks of industry.

146. The only such evaluation by the ITU is in allocating frequencies to broadly defined services such as broadcasting, radiolocation, and fixed-satellite. Even here the "evaluation" consists principally in making technical assessments of the different national proposals, and attempting to reach a political consensus that does not necessarily rest on any valuation of competing radio uses by the ITU membership.

simple matter. There are practical and technical problems of defining rights so as to ensure easy transferability among different uses having different operating parameters.¹⁴⁷ A system in which frequencies were transferable only within a particular, narrowly defined service or type of use would be much easier to administer than one in which frequencies were transferable across a wide range of services. It should not be inordinately difficult to devise a market system for particular orbit segments for one specific service such as broadcast-satellite service, within a particular region. Presumably such a market is what the equatorial countries contemplate with their claims of sovereignty to that portion of the geostationary orbit that lies above their respective countries.¹⁴⁸ But, of course, their contemplation is that they alone would own the resource.¹⁴⁹ The market therefore would be dominated by a "geostationary OPEC."

In discussing the efficiency of market process in allocating resources so far I have ignored considerations of "equity" or wealth distribution. Much of the objection to implementing a domestic spectrum market appears to rest, explicitly or implicitly, on the notion that it would be unfair to distribute frequencies according to the ability to pay.¹⁵⁰ In a capitalist society where most resources, public as well as private, are distributed through the market, it seems strange to single out the radio spectrum for such an objection. The objection, moreover, is misplaced. Relative wealth is not the only determinant of resource distribution; relative utility and intensity of demand are equally important. Consider, for example,

two communications firms seeking an orbit position. Whether firm A has greater wealth (or expendable income) than firm B is less important than the relative utility and demand functions of the two. Indeed, in the case of competing commercial users their relative "wealth" is largely meaningless as long as they have reasonable access to capital markets. Interests of noncommercial users may require special accommodation, but that is less a concern of equity than of efficiency—whether the social utility of the noncommercial use requires a special regulatory allocation.

In theory these "equity" considerations ought to apply to international as well as domestic allocations. If it would be fair for, say, Satellite Business Systems to buy required frequencies or orbit positions from Western Union, would it be any less fair for that same firm to buy them from Telesat Canada—or, of course, vice versa?

Whether a market approach to spectrum allocation would be "fair" depends considerably on how the resource is distributed initially. A distribution which would give satellite orbit positions to a handful of subadjacent equatorial countries, must be rejected as unfair because such countries could not advance any credible basis on which they should be so favored.¹⁵¹

One approach would be to make an initial distribution by auction. After the rights had been appropriately defined according to technical or other parameters (such as limitations as to class or

147. See H. LEVIN, *supra* note 51, at 85-115. For an analysis of how the problems associated with free transferability of frequencies and orbit positions could be handled, see C. Jackson, *Technology for Spectrum Markets* (1976) (unpublished Ph.D dissertation on file in Michigan Institute of Technology Library).

148. See note 46 *supra*. Colombian representatives at WARC denied that this was the motive for the claim and instead insisted that the claim was made to preserve its future right of access to the orbit. The two motives are not inconsistent. The sovereignty claim is plenary and includes not only a right of future access by the equatorial countries, but also the right to specify the terms on which other countries could use unoccupied space.

149. This applies only to segments of the orbit directly above the territory of the respective equatorial countries. Orbit segments above the open sea beyond national jurisdictions, under the Bogotá Declaration, *supra* note 46, would be the "common heritage of mankind" and now subject to national sovereignty claims. Gorove, *supra* note 46, at 451.

150. See, e.g., Anthony, *Towards Simplicity and Rationality in Comparative Broadcast Licensing Proceedings*, 21 STAN. L. REV. 1, 101-02 (1971) (raising the objection in the specific case of broadcast licenses). For rebuttal argument, see Robinson, *FCC*, *supra* note 145, at 242-43.

151. For a list of arguments and counterarguments, see Gorove, *supra* note 46, at 451-53. Most of the arguments deal with whether the geostationary orbit can be regarded as outer space within the meaning of the Outer Space Treaty of 1967, which precludes sovereignty claims to outer space. Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, art. II, opened for signature Jan. 27, 1967, 18 U.S.T. 2410, T.I.A.S. No. 6347, 610 U.N.T.S. 205. A central argument of the Bogotá Declaration signatories is that the orbit depends on the gravitational pull of the earth and so is not outer space. But the same argument could be applied to the moon, to which even the Bogotá signatories do not lay claim. Moreover, in any event the gravitational influence is a function of the entire mass of the earth, to which the equatorial countries contribute negligibly. Thus, if gravitational influence is the touchstone, countries such as the United States, Canada, People's Republic of China, and the Soviet Union would have more substantial claims than the equatorial countries.

Even if one were to consider that the orbit is not outer space and thus not governed by the Outer Space Treaty, it still would not follow that subadjacent countries have preemptive claim to it. At bottom, the sovereignty claim rests on nothing more sophisticated than an extreme application of the ancient maxim of English common law, *cuius est solum eius est esque ad coelum*. Some application of this principle is implicit in the concept of territorial sovereignty, but there is no basis in international law or custom for applying it without limit. Finally, in terms of simple "fairness," the case for a monopolistic claim by a bare handful of equatorial countries is hard to square with conventional formulations of equity.

service), an auction might be conducted under ITU auspices, with each country competitively bidding for such rights. Such an approach, whatever its theoretical merit on efficiency grounds, is unlikely to be accepted on grounds of equity: Third World countries would see this as merely another manifestation of their economic "subordination" to a handful of rich countries. On the other hand, their perception might be altered significantly if, instead of an auction, an initial distribution of property rights were made on some "equitable" basis that did not require payment. This would sacrifice the efficiency of an auction, but it would preserve the more important efficiency of allowing subsequent sale or exchange of rights. The trick here is to formulate an initial distribution that would be acceptable as "equitable."

An equal distribution, based on the notion of sovereign equality among all countries, might commend itself on the grounds of simplicity but on no other ground. The fact that Upper Volta and the United States have an equal vote in the U.N. General Assembly does not dictate that each have an equal share of the radio spectrum. It is difficult to formulate any principle of "natural justice" that would warrant such egalitarianism among countries with widely disparate populations and other economic and social conditions. At the same time it is difficult to formulate any other obviously fair bases for distribution. As a practical matter, the best solution might be simply to determine a distribution based on ad hoc, negotiated bargains with respect to discrete areas of the spectrum. Essentially this is the process now used to develop allotment plans except that such plans do not recognize or permit transfers of allotments among users. Such plans may not conform to any theoretical mode of equity, but they provide a basis on which a fair bargain could be struck. The principal problem with such plans is not inequity, but inefficiency.¹⁵² Were such plans reconstructed to permit at least limited transfer of allotments among different countries they would be enormously more responsive to efficiency interests while remaining reasonably faithful to the equity considerations.

One need not imagine a total overhaul of the present system to speculate on the possibility of introducing market processes in some parts of it—for example, in those cases where an allotment plan exists or is proposed. To simplify the technical aspects, the

market could be limited to transfers to a specific class of service with defined operating parameters.

Despite the foregoing, I do not look for any significant movement toward introducing market processes in the immediate future. And in the context of present domestic policies there is little basis on which to recommend U.S. initiative in this direction at this time. I cannot imagine any major country, the United States included, proposing such a scheme for international consumption before at least experimenting with domestic application. So far as I am aware, no country outside the United States seriously has contemplated introducing market processes in the area of spectrum management. Even within the United States, where serious proposals have been advanced, *official* interest largely has been confined to acknowledging that such proposals exist.¹⁵³ More than that will be required before anything can come of proposals for an international market. The possibility of limited experimentation ought to be studied, for if the trend towards fixed allotment plans persists, a market scheme allowing transfer of allotments would provide the flexibility needed to make efficient use of such allotments.

E. Future Conferences

Some of the major issues at the 1979 WARC were postponed to a series of specialized regional WARC's to be held throughout the 1980's.¹⁵⁴ Such specialized conferences are not new, but the scheduling of a series of such conferences by a general WARC is unique, setting out a new pattern of ITU activity. Thus, during the next twenty years a continuing series of smaller conferences will deal with specific parts of the spectrum where technological and other changes mandate revision of the radio regulations. It may be that another general WARC authorized to make decisions on the entire spectrum will not be convened for the indefinite future.¹⁵⁵

153. *But see* C. Ferris, *supra* note 144 (advocating use of the marketplace as a means of allocating use of the domestic spectrum).

154. For a list of conferences recommended at WARC 1979 or previously scheduled on the ITU agenda, see WARC Final Acts, *supra* note 48, Rec. XM. This list includes: a plenary conference; world administrative radio conferences for space services, HF broadcasting, and mobile services; six regional conferences (principally planning conferences dealing with individual services); and two subregional planning conferences.

155. *But see* WARC Final Acts, *supra* note 48, Rec. XP (recommending that the Administrative Council "consider as from 1990" whether it may be necessary to convene another

152. *See* text at notes 131-32 *supra*.

As a practical matter there is probably no compelling reason to have another conference of a scope comparable to the 1979 WARC. Successful as this Conference was, one could not pretend that such big events are the best way to negotiate and implement changes in a well-defined, functioning regulatory system. There certainly appeared to be no efficiencies of scale in bringing together separate problems of radio frequency allocations at the 1979 WARC. For example, the problems of finding new allocations for the fixed-satellite service obviously was not helped by contemporaneous consideration of the problem of HF frequency allocations. One might suppose, of course, that joinder of such different tasks might make sense if negotiating tradeoffs among participants were possible with regard to, say, HF broadcasting and fixed-satellite uses. The nature of the forum and the traditions of the ITU, however, have not promoted a negotiating flexibility that is conducive to making "deals" involving widely disparate frequency allocation problems. Perhaps it is easier to make common cause with parties on a particular issue, such as HF broadcasting, if one also has a common interest in others, for example, fixed-satellite service. But if that is true, so also is the converse: Conflicts on one issue may spill over to another, aggravating the problems of settlement. The wider the range of different problems, the greater the number of conflicts, and the more likely the possibility that a hostile environment will preclude consensus. The fact that the 1979 WARC was able to surmount these problems should not lead to an endorsement of larger over smaller conferences. The success of the 1979 WARC is merely a testament to the underlying strength of an organization which achieves international agreement by focusing on highly specialized problems, and not on general political issues. The ITU should continue its practice of "thinking small," and it is most likely to do that by emphasizing routine continuous negotiation and small specialized conferences, as opposed to "big events" such as the 1979 WARC.

V. CONCLUSION

Despite some of the pre-WARC warnings that the ITU was be-

coming a forum for political confrontation,¹⁵⁶ the ITU survived the 1979 Conference quite well as a forum for rational negotiation. Certainly, there is no reason for the United States to reconsider its commitment to the ITU as some suggested, before WARC, that we might have to do.¹⁵⁷ On the contrary, the United States has every reason to continue to regard the ITU as an effective organization for reaching essential international agreement on the radio spectrum usage. Not all of the debate and discussion at the Conference was sensible, but particularly measured against current standards of national and international political discourse, the dialogue at WARC proved on the whole to be quite dispassionately rational and constructive.

Whether dominated by big events or characterized by more or less continuous processes of negotiation, the problems of international communications policy have a future that is rich in complexity and large in importance. The ITU can play a significant role in addressing those problems. If it maintains the same attention to tangible objectives and disdain for rhetorical posturing as it did in the 1979 WARC, the ITU indeed can be a model for international negotiation generally.

156. See note 14 *supra* & accompanying text.

157. See 125 CONG. REC. S9311, S9313 (daily ed. July 12, 1979) (Report on U.S. Preparations for the World Administrative Radio Conference of 1979, prepared by the Congressional Research Service for the Senate Committee on Commerce, Science, and Transportation) (noting the suggestion by others of withdrawal from ITU, but rejecting it as a practical option).

general WARC). Recommendation XP was adopted in the late hours of the Conference when virtually no one considered it worthwhile to debate the issue. Since the recommendation is cast in such tentative terms, it must be regarded as essentially meaningless.

The Post-WARC Frequency Situation in Central Europe

KLAUS OLMS

Abstract—This paper discusses the results of WARC-79 from the standpoint of a frequency manager in Central Europe. In this part of the world, extensive use is made of radio communication, and it is in close proximity to other regions with different communications needs and regulatory philosophies. Both of these factors make frequency management difficult. The paper discusses the most important decisions of the Conference as well as their impact on Central European frequency management. The bands below 30 MHz, 30–1000 MHz, 1000 MHz–40 GHz, and above 40 GHz are treated. It is concluded that WARC results, in general, are acceptable in Central Europe, although not all requirements for this region have been met. An orderly development of radio services is envisaged that will satisfy needs of the area over the next twenty years.

I. INTRODUCTION

A FREQUENCY MANAGER in Central Europe finds himself in a difficult situation. Considerable economic activity in this northern part of ITU Region 1 demands a highly developed telecommunications infrastructure. In the south this area borders on the less economically developed African continent where the improvement of telecommunications is of great importance. In the eastern part, an entirely different political and economic society leads to divergent priorities in frequency

management. Only in Northern and Western Europe, are there few problems with neighboring countries. In the western part of Central Europe itself, the difficulties decrease from the center to the edges: for example, the situation in the Federal Republic of Germany is much more difficult than in Ireland or Turkey. After all, the Federal Republic of Germany is the only country in the world which borders on as many as nine countries. Difficult coordination problems arise from this situation in the VHF, UHF, and SHF bands. Problems in the fields of short-wave, geostationary orbit, or with intercontinental services, can only be solved on a worldwide basis. Therefore, the increasing frequency demands of industry, Administrations, and the various armed forces cooperating in Western Europe require the more extensive and intensive application of new technologies on the one hand and of highly sophisticated coordination procedures on the other.

II. EXPECTATIONS OF WARC

The difficulties outlined above led to an early and thorough preparation for the conference throughout Europe. The views of Western European telecommunications administrations were discussed within the “Conférence Européenne des Administrations des Postes et Télécommunications” (CEPT) since 1975. The most important subject was the Table of Frequency Allocations itself. In the HF bands, additional re-

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quirements of the Broadcasting service and the Maritime-Mobile service were in conflict with the continuing needs of the Fixed service, mainly for noncivilian uses. In the VHF and lower UHF bands, the expanding Land-Mobile service collided with the powerful Broadcasting service. In the upper UHF and in the SHF bands, additional requirements of the space services were in conflict with terrestrial needs.

The discussions, frequently very controversial, were guided by the view that WARC would have to reallocate bands in order to meet future frequency requirements of various services. The principle of long to very long transfer periods was accepted to allow for modifications. Different priorities in the several European countries did not permit a complete agreement to be achieved. The different opinions, however, were sufficiently reconciled by 1978 to allow a common European view to be expressed in deliberations with telecommunications organizations in Africa, Eastern Europe, and America. Above all, the discussions with developing countries showed clearly that, most probably, not all European requirements could be met and that it would be necessary to find compromises.

III. CONFERENCE RESULTS AND CONSEQUENCES

In retrospect, the role of the 1978 Special Preparatory Meeting of the CCIR for the WARC (SPM) was helpful. In addition to the technical material contributed by the Administrations, regional organizations, and the CCIR, many conclusions were arrived at at the meeting itself that advanced the work of the WARC when it met subsequently. The participation of developing countries in this SPM was, however, not active enough. Their participation might have been increased by holding a technical meeting at the beginning of the WARC itself instead of a special technical meeting of only CCIR members held many months before the Conference.

The objective to reduce drastically the number of Footnotes to the Table of Frequency Allocations was not achieved. Moreover, a considerable number of unclear Footnotes still exist, many of which are open to different interpretations. This was inevitable, in those instances when long and controversial discussions had to be concluded by a compromise. Therefore, it was possible to solve some of the difficulties in the old Radio Regulations, but others were introduced. In view of the enlarged number of Radio Regulations, however, the increase in the number of Footnotes should be considered moderate. In the following sections, some highlights of the WARC are discussed and their consequences outlined.

A. Frequency Bands Below 30 MHz

The proposals of broadcasting authorities to allocate the 255–285-kHz band exclusively to the Broadcasting service was only partially met by downgrading the Aeronautical Radio-navigation service to “permitted” status. In many parts of Europe it is impossible to transfer, in a short time, existing assignments of nondirectional beacons to other frequency bands. The extension of 1.5 kHz at the lower edge of the long-wave broadcasting band will permit better receiver designs. For the same reason, an extension of the medium-wave broadcasting band 525–1605 kHz by 1.5 kHz at its upper end was also welcomed.

The proposals for meeting additional European broadcast-

ing requirements in the HF bands collided with the continuing needs of the Fixed service both in Europe itself and in other parts of the world. Although, the use of HF is decreasing in European PTT networks, it is still very important for other governmental applications, especially in the Federal Republic of Germany. Even though other European telecommunication administrations would have welcomed a further reduction of Fixed service allocations, this was not possible in view of the demands of the less developed countries for HF frequencies for their Fixed services.

The extension of the broadcasting bands around 9, 11, 15, 17, and 21 MHz and the new allocation at 13 MHz was welcomed, although more allocations were proposed below 10 MHz, but not accepted. The agreed transfer procedure for existing assignments in the Fixed service together with the “cleaning-up” of the International Frequency List (IFL) was generally supported by European administrations. Thus later developments are possible which may take into account acknowledged needs of various services. The HF Broadcasting planning conference scheduled for the beginning of 1983¹ will need substantial preparation within the CCIR, especially in view of the necessary standardization of the single-sideband system. Also European administrations would have preferred additional allocations below 10 MHz for the Maritime-Mobile service for teleprinter and telephone purposes. But such allocations on the exclusive basis were only possible above 10 MHz. To employ these additional allocations for this service, there is an urgent need for worldwide agreement on regulations governing their use. The ITU took account of this need by scheduling a Mobile conference for March, 1982.

In conclusion, not all European expectations were met below 30 MHz, especially for the bands between 3 and 10 MHz. However, in compromising divergent views of developing and industrialized countries, the basis was laid for an orderly evolution of radio services over the next 15 years. Thus the conference results are acceptable in this region of the spectrum.

B. The Frequency Bands Between 30 and 1000 MHz

In this part of the spectrum, the demands of the Mobile services, especially of the Land-Mobile service, for additional allocations collided with the increasing requirements of the Broadcasting service. In Europe and Africa, the use of the VHF and UHF bands for sound and television broadcasting is governed by agreements some of which date back to 1961. These agreements are based on systems and standards which are even older. Improvements seem possible, but the introduction of more frequency-economic frequency plans must take into account the enormous investments made by the public for the receiving equipment. Long transfer periods, therefore, require early decisions. We think that all existing coverage requirements could be met in the frequency band 470–790 MHz, if an advanced technology and improved planning methods were applied. To that end, it is necessary to have the whole band available without gaps. This need was satisfied by an exclusive primary allocation to the Broadcasting service in

¹ Dates of some future ITU Conferences have been changed. See Urbany, this issue, pp. 322–326.

Region 1. All existing other services maintained only time-limited allocations or were downgraded to lower than primary status (secondary or permitted). With this decision, the introduction of the Land-Mobile service on a "permitted" basis into 47-68 MHz and 174-230 MHz was adopted making possible the start of a long-term transfer. Shared use of the same frequency bands by the Broadcasting and the Land-Mobile services is difficult, if not impossible in Central Europe. This is due to the fact that the spectrum is fully occupied by the Broadcasting service and stations are operated in accordance with concise rhombic network planning principles, which leave no space for Land-Mobile operations. Nevertheless, investigations are planned within the CEPT to find whether limited shared use is possible, and under what conditions. The WARC was able to agree on an important improvement for the sound-broadcasting service by extending the allocation around 100 MHz upwards to 108 MHz. Use of the band 87.5-100 MHz in the European broadcasting area is governed by an agreement dating to 1961. An agreement for the band 100-104 MHz was worked out in 1971 for 16 European countries but there is no plan for the band 104-108 MHz. It is, therefore now necessary to replan the whole band 87.5-108 MHz in Europe in order to satisfy demands for its early use. The WARC resolved that a planning conference should be held to revise the existing plans in Region 1, the first session of which will begin in August 1982. Some countries in Central Europe will, to a certain extent, be forced to an earlier usage of this band, but such use however, cannot prejudice the conclusions of the 1982 planning conference.

In Central Europe, the "classical" frequency bands for Land-Mobile service (68-87 MHz, 146-174 MHz, 440-470 MHz) are presently seldom used for the Fixed service. It is envisaged that the frequency demand for civilian applications within the Land-Mobile service will be met in these bands through 1990. From that time on, frequency bands in the 900-MHz range will be necessary for the Land-Mobile service. Unfortunately, it was not possible for the WARC to allocate the band 790-862 MHz to the Land- and Maritime-Mobile services in all European countries. Nevertheless, it succeeded in allocating the band 862-960 MHz to these services on a primary basis, while ensuring protection to Broadcasting services in Africa. Thus the necessary provisions for an orderly expansion of Mobile activities have been made. In order to direct these activities and with the aim of standardization, preliminary discussions were held in Europe concerning the Mobile services at 900 MHz. The departure point for this discussion was a plan, in which land-mobile and maritime-mobile applications would be integrated and which would comprise up to 1000 channels, each 25 kHz wide, for duplex operation ($dx = 45$ MHz). At least parts of such a plan should be internationally harmonized as well. Initial views foresee two times 12 MHz out of two times 25 MHz for such an internationally standardized system. In addition, up to 2 MHz between 933 and 935 MHz should be earmarked for low-power personal radio applications with very reduced service ranges. It is expected that the provisions of the Radio Regulations will permit the orderly development of other national Land-Mobile services

besides those described in the frequency band between 862 and 960 MHz. It must be noted, however, that this implies the transfer of existing stations in the Fixed service, now operating in the 900-MHz band, into higher frequency bands. In conclusion, the WARC has largely responded positively to the needs of services in the bands between 30 and 960 MHz. Long-time evolution and transfer procedures have been initiated, which, in general, meet the requirements of administrations in Central Europe.

C. The Frequency Band Between 1000 MHz and 40 GHz

In this area of the spectrum, the needs of the Fixed-Satellite service, the Space Research service, and the question of feeder links in broadcasting satellites posed the main problems. The Conference results reflected only to a limited extent the requirements of European countries. However, their active contribution in the search for a compromise led to acceptable results. The need to implement active and passive sensors for the benefit of space-research projects was satisfied by appropriate allocations. Development is now possible and will be funded in the framework of supranational research programs at the European level.

The almost complete sharing of all frequency bands usable by the Fixed service and space services was necessary to satisfy the growing demand of the space services. The increased coordination difficulties arising therefrom may necessitate restrictions on radio-relay operations. These operations may have to be transferred to cable or other means as a consequence. New requirements for radio-relay systems can only be met in the future with severe constraints on those systems.

Special difficulties in Central Europe arise through the use of the frequency bands 3.4-3.7 GHz and 4.5-4.8 GHz. Some countries cannot authorize the use of these bands by the Fixed-Satellite service and have announced that intensive terrestrial use of these bands will lead to rejection of any coordination demand for a station in the space services. Other Administrations see limited possibilities for applications in the space services, when the number of Earth stations is kept to a minimum. In general, it seems that the prospects for the space services are a little better in the band 4.5-4.7 GHz than in the band 3.4-3.6 GHz, which is now used extensively for terrestrial applications.

The operation of space systems with small Earth stations is possible and will be carried out in Central Europe in two 250-MHz allocations to the Fixed-Satellite service at 12.5 and 14 GHz. Later, possible additional requirements may be satisfied in two corresponding 500-MHz allocations at 20 and 30 GHz.

The question of feeder links for the Broadcasting-Satellite service, which has been controversial for a very long time, has been resolved by a compromise, which foresees the use of the band 17.3-18.1 GHz for this purpose throughout Europe. The use of the 11-GHz band for feeders is impossible in most cases due to extensive terrestrial usage. Neither could a 14-GHz allocation be made in Europe.

The attitude of Administrations at the forthcoming planning conferences has to be awaited. In coordinating uplink

requirements, account has to be taken not only of one's own orbital position but also of the neighboring ones as well as the requirements for telecommand purposes in the same frequency band.

D. Frequency Bands Above 40 GHz

At the WARC, almost all frequency bands were already allocated on a shared basis to maintain maximum flexibility. It was, however, the majority view in Europe that, in principle, exclusive allocations would provide greater freedom in developing new radio systems without constraints due to sharing considerations, thus supporting the transfer of broadband systems in particular to higher frequency bands, which are little used. It remains to be proved that greater flexibility serves the same purpose. The shared allocations, however, permit operation of multipurpose satellite systems which provide several services and need the corresponding terrestrial services for system design.

IV. CONCLUSION

Not all provisions in the Table of Frequency Allocations in the new Radio Regulations fulfill spectrum requirements in Europe. This, of course, is no surprise, since the European telecommunications administrations were informed of other views long before the Conference, knew that compromises would have to be made, and were ready to do so. This was especially true in view of the understandable efforts of the developing countries to obtain allocations for their somewhat different requirements: a goal which European countries, by and large, wholeheartedly supported. But even in the discussions with the other industrialized countries it was not possible to win acceptance of European views. Many problems had to be deferred to later conferences where they will then again undoubtedly give rise to lively discussions. Nevertheless, the WARC-79 results are basically acceptable on the whole. They allow an orderly evolution of radio telecommunications over the coming two decades.

WARC Allocations and Some of their Impacts on Japan and in Asia

SHINZABURO TANAKA

Abstract—This paper describes certain decisions made at the World Administrative Radio Conference (WARC) held in September 1979 which will have great impact on the utilization of radio in Japan and throughout Asia and Oceania. This paper concentrates on the table of frequency allocations adopted at the conference. It also outlines some of the problems expected at the forthcoming WARC for high-frequency broadcasting (WARC-HFBC) and on the space services planning conferences.

I. INTRODUCTION

IN ORDER TO cope with worldwide development of radio communication services over the next 20 years, WARC-79 revised both frequency allocations (Art. N7/5) and technical

standards as well as the regulations on coordination, notification, and registration of frequencies, all of which are included in the Radio Regulations (RR) of International Telecommunication Union (ITU). It also resolved to hold several World Administrative Radio Conferences over the next decade to help plan the use of particular services.

While some decisions made at WARC-79 will open up many new opportunities for the utilization of radio waves, others will involve some loss to Region 3 countries (including Japan) which, for example, must make changes in frequency assignments for aeronautical radio beacons. The new opportunities which could develop, include the allocation of frequency bands to feeder links for 12-GHz broadcasting satellites, allocations of various frequency bands to mobile-satellite services, and allocations of frequency bands above 40 GHz to terrestrial services.

In this paper, we will concentrate on the new frequency

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allocations that are of primary concern to Japan and to other countries of Region 3 (Asia and Oceania) and describe some of their effects.

II. ALLOCATIONS BELOW 4 MHz

A. Long-Wave Broadcasting in Region 1, and Aeronautical Radio Beacons in Region 3

In the frequency band 160–285 kHz, allocations have long been different from ITU Region to Region. In Region 1, this band is used for long-wave broadcasting, while in Regions 2 and 3, it is used mainly for aeronautical beacons. At the ITU Regional Administrative LF/MF Broadcasting Conference (Geneva, Switzerland, 1975) a frequency-allocation plan for long-wave broadcasting in Region 1 was drawn up. This plan contemplated the construction of many new stations and increases in the transmitting power of existing stations. Implementation of this plan, however, was suspended pending the decisions of WARC-79, for fear that interference might be caused to aeronautical radio beacons in Region 3. At WARC-79, the problem of interference from long-wave broadcasting stations was pointed out by the countries of Regions 2 and 3, and objections were raised against implementation of the plan. Nevertheless, WARC-79 approved the implementation of the long-wave broadcasting plan for Region 1.

This decision imposes considerable constraints on the assignment of frequencies to aeronautical beacon stations in Region 3. In order to alleviate this situation, the allocation table was revised as shown below with regard to the aeronautical radio navigation service in Region 3:

In the 190–200-kHz, 285–315-kHz, and 315–325-kHz bands, the aeronautical radio navigation service was upgraded from a secondary basis to a primary or permitted basis.

The 415–495-kHz band, which had been allocated exclusively to the maritime mobile service, is now allocated in several countries of Region 3 to the aeronautical radio-navigation service on a permitted basis.

The 510–526.5-kHz band, which had been allocated to the mobile service (including the maritime-mobile service), is now allocated to the aeronautical radio-navigation service on a permitted basis.

The 1606.5–1800-kHz band, which had been allocated to the fixed and mobile services, is now also allocated to the radio-navigation service. The countries of Region 3 must find new frequencies in these bands for their aeronautical radio beacons. This will be a difficult task, since it would require frequency changes to existing stations.

In addition, WARC-79 resolved that the carrier frequencies of all stations involved in the LF Broadcasting Plan should be reduced by 2 kHz so that they become multiples of 9 kHz, the channel spacing of the Plan, in the hope that this might lessen mutual interference in LF broadcasting in Region 1.

Because of this decision, carrier frequencies of long-wave broadcasting stations in Region 1 will be changed in the following three steps:

- from Channel 1 to 5 on February 1, 1986;
- from Channel 6 to 10 on February 1, 1988;
- from Channel 11 to 15 on February 1, 1990.

As these changes are introduced, existing aeronautical beacon stations will also have to change frequencies to avoid interference from long-wave broadcasting stations.

B. Allocation of the 1606.5–2000-kHz Band

Frequency allocations made in the 1606.5–2000-kHz band by WARC-79 are complicated. In Region 1, the 1606.5–1800-kHz band is now allocated to the maritime-mobile service which takes priority over other services, except 1625–1635 kHz which is allocated to the radiolocation service. In Region 2, the 1605–1705-kHz band is allocated to the broadcasting service, and the 1705–1800-kHz band to the fixed, mobile, radiolocation, and aeronautical radionavigation services. In Region 3, the 1606.5–1800-kHz band is allocated to the fixed, mobile, radiolocation, and radionavigation services. However, this band is also allocated to the broadcasting service on a secondary basis in Australia, Indonesia, New Zealand, the Philippines, Singapore, Sri Lanka, and Thailand. Thus this frequency band can be used for various services depending on the Region and the country. In Japan, it will be used for the maritime-mobile service, radio fishing buoys, "Decca High Fix," aeronautical beacons, and the public information system. But as Japan's neighbors start to use the band for different services, the possibility of interference will arise.

In order to avoid such a situation, national frequency allocations may have to be adjusted to take account of the use of these bands in neighboring countries. Accordingly, it will become necessary to introduce radio equipment which will permit such changes during its lifetime.

Allocations in the 1800–2000-kHz band also differ from Region to Region. In Region 3, this band was allocated to a multiplicity of unrelated and potentially incompatible services: amateur, fixed, mobile, radio-navigation, and radiolocation. However, in Region 1 the 1810–1850-kHz band was allocated to the amateur service and this band could thus be established as an amateur band to be used throughout the world. At present, several countries of Region 3 operate Loran-A in the 1825–1875-kHz band. Loran-A, however, is obsolescent worldwide. Thus in the future, the 1810–1850-kHz band could be used only by amateurs. Then, the 1850–2000-kHz band could be allocated primarily to the mobile service.

III. 4–27.5 MHz

A. Allocation Changes from the Fixed Service to the Maritime-Mobile, Broadcasting, and Amateur Services

The role of the short-wave band in long-distance, fixed communications is gradually diminishing with the increased reliance being placed on communication satellites, submarine cables, and microwave networks. However, the demand for that particular band is still on the increase in the maritime-mobile, broadcasting, and amateur services. Taking this into consideration, WARC-79 decided that allocations to the fixed service should be reduced and reallocated to the services mentioned above.

An additional 800 kHz of bandwidth was allocated to the maritime-mobile service on an exclusive basis plus 158 kHz of bandwidth on a shared basis with the fixed service. The new exclusive bands represent a gain of 21 percent over existing exclusive allocations (3850 kHz of bandwidth). The specific

band assignments are:

Additional Allocations on an Exclusive Basis	Increased Bandwidth
12230-12330 kHz	100 kHz
16360-16460 kHz	100 kHz
17360-17410 kHz	50 kHz
18780-18900 kHz	120 kHz
19680-19800 kHz	120 kHz
22720-22835 kHz	135 kHz
25110-25120 kHz	100 kHz
26100-26175 kHz	75 kHz
Total	800 kHz

Additional Allocations on a Shared Basis	Increase in Bandwidth
4000-4063 kHz 8100-8195 kHz	158 kHz

Plans for the 4- and 8-MHz bands, to be allocated on a shared basis, will be made at a Mobile services WARC which is to be held in March, 1983.¹ Plans for bands allocated on an exclusive basis will be made at the next competent World Administrative Radio Conference.

An additional 780 kHz was allocated to the broadcasting service, an increase of 33 percent over the existing allocation of 2350 kHz as shown below:

New Allocations	Increase or Decrease of Bandwidth (kHz)
5950-6200 kHz (5950-6200 kHz)*	0
7100-7300 kHz (7100-7300 kHz)	0
9500-9900 kHz (9500-9775 kHz)	+125
11650-12050 kHz (11700-11975 kHz)	+125
13600-13800 kHz	+200
15100-15600 kHz (15100-15400 kHz)	+150
17550-17900 kHz (17700-17900 kHz)	+150
21450-21850 kHz (21450-21850 kHz)	+100
25670-26100 kHz (25670-26100 kHz)	-70
Total 3130 kHz	780 kHz

* Existing allocations are shown in parentheses.

The 10-, 18-, and 25-MHz bands were allocated to the amateur service in addition to the existing bands at 7, 14, 21, and 28 MHz which are harmonically related.

Band	Status
7000-7100 kHz	exclusive
7100-7300 kHz	shared, Region 2
*10100-10150 kHz (150 kHz)	shared (secondary)
14000-14350 kHz	exclusive
*18068-18168 kHz (100 kHz)	exclusive
21000-21450 kHz	exclusive
*24890-29990 kHz (100 kHz)	exclusive
28000-29700 kHz	exclusive

* Newly allocated bands.

Existing stations in the fixed service which operate in the

¹ Dates of some future ITU Conferences have been changed. See Urbany, this issue, p. 322-326.

bands newly allocated on an exclusive basis for the maritime, broadcasting, and amateur services have been requested by Resolution 8 to make frequency changes to other bands in the fixed service by the following dates:

July 1, 1989—for frequencies above 10 MHz.

July 1, 1994—for frequencies below 10 MHz.

Arrangements for these changes will be made by the International Frequency Registration Board (IFRB) of the ITU.

To facilitate these arrangements, each Administration has been requested (under Resolution 9) to examine its national assignments as recorded in the International Frequency List (IFL), and to submit the results to IFRB by March 31, 1981. They should: a) delete from the List any entries no longer required, and b) classify the remaining entries of the fixed service with the use of the following symbols:

- A assignment for regular operational use which is not provided by another satisfactory means of telecommunication;
- B assignment for use as a stand-by to some other means of telecommunication;
- C assignment for occasional use on a reserve basis and not requiring internationally recognized protection from harmful interference.

Similar classification by symbols was also adopted for the notification of frequency allocations to stations in the fixed service in the 3000-27 500-kHz band by RR 4280.

In judging the notifications submitted by each administration, the IFRB will apply a higher criterion of protection to services under Symbol A than to those under Symbol B. Possible interference with those under Symbol C will be neglected (RR 4298A). These measures will make it possible to delete a considerable number of assignments from the IFL or downgrade them to Symbols B and C. Consequently, congestion of short-wave frequencies may be eased, and urgent requests from developing countries for the use of short waves can largely be met.

B. Standard Frequency and Time Signal Service

Standard Frequency and Time Signals (SFTS) are useful for the calibration of frequency-measuring instruments and as an accurate standard of time. Such SFTS stations are now under construction in various countries in Asia. At present, 2.5, 5, 10, 15, 20, and 25 MHz are allocated to the SFTS service.

With the increase in the number of SFTS stations in recent years, more mutual interference has been reported. To improve the situation, the adoption of offset frequencies at $f_0 \pm 4n$ kHz ($n = \pm 1, \pm 2$) has been studied, but this is reported to cause beats in the standard frequency signals and to lower the reception accuracy because of distortion to waveforms. In order to avoid interference between SFTS stations in neighboring countries, different frequency bands are needed. At WARC-79, allocation of 4-, 8-, and 16-MHz bands, each with ± 5 kHz bandwidth, were made to the SFTS service on a shared basis with the fixed service. This allocation will help to eliminate interference between SFTS stations. It is hoped that fixed stations in these frequency bands can be shifted to other bands over a period of years.

IV. 27.5-960 MHz

A. Some Aspects of the Broadcasting Band

Allocations to the broadcasting service differ not only from Region to Region but also to some extent from country to country. At WARC-79, efforts were made to eliminate regional differences in the frequency allocation table. Consequently, considerable unification may be observed in the allocations for Region 1. In Region 3, however, unification of the frequency allocation table is only apparent, since new allocations were made on the basis of footnotes which maintained existing allocations.

Furthermore, in Region 3 there is no plan for the broadcasting service in the VHF and UHF bands. In the allocation table, frequencies for the broadcasting service are shared with the fixed and mobile services, except in the 100-108-MHz band. Adjacent countries, therefore, may suffer from possible interference between their services. This led to a Resolution for the opening of a Region 3 Radio Conference that would establish sharing criteria between different services. To prepare for the conference, the CCIR was requested to undertake technical studies.

The need may also arise within a set of national allocations for the broadcasting service to share frequencies with the land-mobile service so as to ease the current congested situation of land-mobile service frequencies. In order to facilitate the possible sharing of frequencies between the broadcasting service and the land-mobile service, new land-mobile communication techniques should be studied. The allocations made at WARC-79 to the broadcasting service and to the fixed mobile services on a shared basis in Region 3 should provide impetus for this study.

B. Utilizing the 470-960-MHz Band for the Mobile Service

The lower part of the 470-960-MHz band is allocated to the broadcasting service worldwide on an exclusive basis, but in Region 3 it is newly allocated to the fixed and mobile services on a primary basis. In Region 2, the 470-512-MHz band is allocated to these services on a secondary basis.

The lower part of this frequency band which is preferable to the upper part both from the propagation standpoint and because it requires less expensive equipment, will be used for the mobile communication service as well.

Near 900 MHz, the 862-960-MHz band is allocated worldwide to the fixed and mobile services. This band has been in use for the land-mobile service in a few countries, and its use will increase considerably in the future. It is expected that this band will also be used for international public correspondence in the maritime-mobile and aeronautical-mobile services. Because of the nature of these services, a unified frequency band should be used for both on a global basis. The establishment of a specific band for international services is urgently required before the 900-MHz band becomes more congested.

WARC-79 failed to designate new frequency bands for such international mobile services as the maritime public correspondence system. However, it drew special attention to the importance of maritime and other international mobile public correspondence systems in the UHF band, and advised in Recommendation 310 that suitable bands for these services

should be designated. It also requested the CCIR, as a matter of urgency, to consider the designation of suitable bands for international mobile services such as an integrated and automated maritime- and land-mobile system. This band is allocated to the mobile-satellite service, and the subject will be discussed further in section V-A below.

V. 960 MHz-36 GHz

A. Allocations to the Mobile-Satellite Service

To pave the way for future development of satellite communication with vessels, frequency allocation have been made to the maritime-mobile-satellite services (MMSS); 19 MHz for uplink use, and 14 MHz for downlink use. In this allocation, 11.5 MHz has been added to the existing uplink allocation and 6.5 MHz to the downlink allocation. The existing spacing of 101.5 MHz between the uplink and downlink frequencies was maintained.

For the aeronautical-mobile-satellite service (AMSS); 14 MHz was allocated for both uplinks and downlinks, which represent a reduction of 2 MHz from the existing allocation.

For distress and safety operations using satellite communications, 1 MHz is allocated to the uplink and downlink, respectively, near the allocations of the AMSS and MMSS. These allocations are exclusive on a worldwide basis. The specific frequency bands are as follows:

Maritime-Mobile-Satellite Service

1535-1544 MHz (space-to-Earth)	(19 MHz)
1626.5-1645.5 MHz (Earth-to-space)	(14 MHz).

Aeronautical-Mobile-Satellite (R) Service

1545-1559 MHz (space-to-Earth)	(14 MHz)
1646.5-1660 MHz (Earth-to-space)	(14 MHz).

Mobile-Satellite Service (Distress and Safety Operation)

1544-1545 MHz (space-to-Earth)	(1 MHz)
1645.5-1646.5 MHz (Earth-to-space)	(1 MHz).

These allocations will prove useful for the modernization of current commercial maritime and aeronautical communications, which depend largely on short waves. They will also contribute to the establishment of a system of search and rescue operation using Emergency Position Indicating Radio Beacons (EPIRB) transmitting to satellites.

Several allocations were made to the mobile-satellite service for land operation. The main frequency bands are as follows:

Band	Status
235-322 MHz	(all Regions)
335-399.9 MHz	(all Regions)
806-890 MHz	(Region 2, Region 3, Norway, Sweden)
942-960 MHz	(Region 3, Norway, Sweden)
2500-2535 MHz	(space-to-Earth, Region 3)
2655-2690 MHz	(Earth-to-space, Region 3)
7250-7375 MHz	(space-to-Earth, all Regions)
7900-8025 MHz	(Earth-to-space, all Regions)
19.7-21.2 GHz	(space-to-Earth, all Regions)
29.5-31 GHz	(Earth-to-space, all Regions)

Since each frequency band listed above is also allocated to the fixed service, the mobile service, or to the broadcasting service, the problem to be solved is the shared use of these frequencies with these terrestrial services. With current satellite technology, it is difficult to narrow the beam coverage of a satellite antenna in the band below 900 MHz. Therefore, frequency coordination will be required among these services operating in neighboring countries. However, in this case it will be possible to use a simple antenna mounted on a terrestrial mobile unit. On the other hand, beam confinement is easier above 2.5 GHz, thereby reducing the problem of frequency coordination with terrestrial services. In that event, use of small parabolic antennas will be necessary. The bandwidth available for the mobile-satellite service below 2.6 GHz is not wide enough to allow the use of several channels per mobile unit; but the bands above 7 and 8 GHz can be used for high-capacity mobile-satellite communications.

B. Extension of the Broadcasting Satellite Band at 12 GHz and Designation of Frequencies for the Feeder Link

At present, the band 11.7–12.2 GHz is allocated to the broadcasting-satellite service in Region 3. An orbital and frequency allotment plan was established at the WARC for broadcasting-satellites in 1977. This plan was based on the requirements submitted by various countries for satellite broadcasting using individual reception. Satellite broadcasting for individual reception requires high transmitting power. It will thus be difficult to cover a wide area due to limitations on the output power available from satellite transmitters. In large countries, therefore, the use of broadcasting satellites for community reception over wide areas may be established until direct broadcasting satellites become practicable. In response to this demand, the new table includes an allocation at 12.5–12.75 GHz to the broadcasting-satellite service in Region 3 (with a limit on power flux-density of -111 dBW/m²). This frequency band is also allocated to the FSS (space-to-Earth) so that this band could be used for the relay and distribution of TV programs to terrestrial broadcast stations.

The bands 14.5–14.8 GHz and 17.3–18.1 GHz have been allocated in Region 3 for feeder links (Earth-to-space) for broadcasting satellites operating in the band 11.7–12.2 GHz. The use of these two frequency bands in each country must be based on a plan which is expected to be adopted at some future WARC. Frequency bands, including 14–14.5 GHz, allocated to the fixed-satellite service (Earth-to-space) could also be used on a coordinated basis according to Resolution 101. The band 14–14.5 GHz in particular could be used for feeder links to broadcasting satellites as well, if they are placed in orbital positions which will not conflict with the use of the same frequencies for the fixed-satellite service.

C. Passive Sensors and the Fixed and Mobile Services used on a Shared Basis

In the new frequency allocation table, a number of frequency bands are allocated to the passive sensors of the Earth exploration-satellite service. Passive remote sensing means receiving the electromagnetic waves that radiate naturally from the Earth by radiometers on board the satellites. The most promising of the allocated frequencies are the 10.6–10.7-GHz and 18.6–18.8-GHz bands.

At WARC-79 the 10.6–10.7-GHz band was allocated to the Earth exploration-satellite service (passive), to the space research service (passive) on a primary basis, and to the radio-astronomy service and the fixed and mobile services (10.6–10.68 GHz). At the same time, operational restrictions were imposed on both active services for the protection of the passive service. Under these restrictions effective isotropically radiated power (EIRP) in the terrestrial service must be kept below 40 dBW, and the power delivered to the antenna below -3 dBW. Use of the 10.68–10.7-GHz band for the fixed and mobile services is allowed only for those facilities that will be in operation by January 1, 1985. This means that fixed and mobile services in this band will have to be moved to other bands. From this discussion, it appears that the band 10.6–10.7 GHz is intended primarily for the passive service. Every country, therefore, should make its national assignment bearing this principle in mind.

The 18.6–18.8-GHz band, in the central part of the 17.7–19.7-GHz band, is allocated to the fixed and mobile services as well as to the fixed-satellite service. If this 2 GHz is used for radio-relay systems, it will be difficult to also use it for remote sensing. In Japan, a 400-Mbit/s radio-relay system is already in operation, using 3.5 GHz of bandwidth in the 17.7–21.2-GHz band as permitted by Footnote 3800. EIRP limits to protect passive sensors would make it difficult to operate such radio-relay systems. For these reasons, passive sensors were allocated on a secondary basis in Region 3 with a footnote stating only that the antenna input power and EIRP from the stations in the fixed-satellite service and the fixed and mobile services (except for the aeronautical mobile) should be limited as far as possible, to lessen interference to passive sensors.

Recommendation 706 of the WARC requests the CCIR to study the question of frequency sharing among passive sensors and the fixed-satellite, fixed, and mobile services (except for the aeronautical mobile). As for the 19.7–21.2-GHz band, the number of countries given an allocation for the fixed and mobile services increased from one (Japan) to 46 at WARC-79. This indicates that more countries will introduce radio-relay systems using this 3.5-GHz-wide band. In view of this, the early establishment of sharing criteria is desirable.

VI. ABOVE 36 GHz

A. Allocations to the Terrestrial Services Above 36 GHz

Allocations above 40 GHz were first made at WARC-ST in 1971, but they were limited to the space services. In the years that followed, radio technology has made remarkable progress. In Japan, picture-transmission systems and radio-relay systems have been developed, and the 60-GHz band has been used in an experimental system for auto-traffic information transmission. Allocations of the frequency band above 40 GHz to the terrestrial services made at the WARC-79 will lead to the rapid utilization of this band.

In this band, a gain of about 40 dB can be achieved using a 30-cm-diameter parabolic reflector. Direct attachment of a transmitter-receiver to the back of such a reflector enables the equipment to be easily installed on rooftops, providing economical service.

Japan has already established a frequency-assignment plan for the terrestrial services in the 36-39.5-GHz band and this is now in force. Because of the difficulty of sharing between the fixed-satellite service and the mobile service, Japan has avoided the use of the 37.5-39.5-GHz band, for the mobile service. The 36-37.5-GHz band can also be used for the mobile service, including picture transmission, but the lower segment, 36-37 GHz is shared with other services including passive sensors.

The 39.5-40.5-GHz band has also been allocated to the mobile-satellite service and will not be used in Japan for terrestrial services to permit the future development of the former service.

The 40.5-42.5-GHz band allocated to the broadcasting-satellite service can also be used for terrestrial services, because it will be some time before broadcasting satellites will be developed there. Moreover, the spectrum used by any one country will be only a small portion of the 2-GHz bandwidth available. These bands, therefore, can be used for the mobile service, for electronic news gathering, and for the terrestrial broadcasting service.

Frequencies near 50 or 60 GHz can be widely used for short-distance communications such as building-to-building communications and private intrafactory communications, as well as for high-speed data communications with vehicles. Development of such systems is now under way.

B. Allocation of Frequencies above 36 GHz to the Fixed-Satellite Service

Considerable improvements have been made to the allocation of frequencies above 40 GHz to space services. Allocations to the fixed-satellite service are as follows:

Downlinks	Uplinks
37.5-40.5 GHz	42.5-53.5 GHz 49.5-50.2 GHz 50.4-51.4 GHz
81-84 GHz	71-71.5 GHz
102-105 GHz	92-95 GHz
149-164 GHz	202-217 GHz
231-241 GHz	265-275 GHz

As shown above, there has been an increase of bandwidth from 1 to 3 GHz in the 40-50-GHz band, and the newly allocated 81-GHz band will permit further development. In this band, circuit capacity provided by satellite will be considerably increased through the use of spot beams, thus making the most of limited capacity of the orbit. Propagation losses due to rain, which are inevitable in this frequency band, occur only locally in most cases, and the consequent circuit interruptions may be overcome by proper use of microwave satellite systems. Japan has already developed a satellite that makes use of the 31-34-GHz band and will continue the development of satellites that will utilize millimetric waves.

VII. FUTURE WARC'S

A. WARC for the Planning of HF Bands Allocated to the Broadcasting Service

A WARC for the planning of HF broadcasting bands will be held in two sessions: the first in 1983, for 5 weeks; the second in 1984, for 7 weeks.

In the first session, technical parameters for planning and governing principles for the HF broadcasting bands will be established, and principles and methods of planning will also be decided. The second session will decide how to carry out the planning in accordance with the principles and methods adopted at the first session.

Planning will be done on the basis of double-sideband (DSB) emissions. The gradual introduction of a single-sideband (SSB) system will also be considered. The bands allocated to short-wave broadcasting, including newly added bands (an increase of 33 percent over the existing allocations, but not usable until the fixed service starts using other frequencies) will still not be enough to eliminate current congestion in short-wave broadcasting unless an SSB system is adopted. SSB broadcasting is capable of reducing the required bandwidth by one-half, and requires only one-fourth the transmitting power used by DSB systems. SSB will thus contribute to the lessening of short-wave broadcasting congestion and the improvement of reception conditions.

WARC-79 requested the CCIR to accelerate the study of the problem of introducing SSB into short-wave broadcasting, and to develop specifications for a suitable SSB system. According to a study conducted in Japan, there will be no problem in manufacturing receivers, whichever SSB system is adopted. It is hoped that the WARC-HFBC will provide frequency bands to facilitate the introduction of SSB, and will decide on the time of their coming into use.

B. WARC Actions on the Use of the Geostationary Satellite Orbit and the Planning of Space Service Utilizing It (First session: March 12, 1984; second session: not later than 18 months after the first session).

The purpose of these two WARC's is to secure equal access by every country to the geostationary satellite orbit and to the frequency bands allocated to space services. The first session will decide on the space services and the frequency bands, which are the subjects of planning, together with the principles, technical parameters, and criteria for those bands. The second session will implement the decisions made at the first session. At the 35th Session of the Administrative Council, it was decided that the coming conference would also deal with the planning of feeder links to broadcasting satellites in the 12-GHz band.

From a practical viewpoint, it is difficult to plan the orbit and frequencies for every space service, nor is there much need to do so. The services to be considered in the planning may be the fixed-satellite and the broadcasting-satellite services. However, it may be difficult for Administrations to establish

the requirements for frequencies and orbits for the fixed-satellite service at this time, since it will take many different forms of utilization with the development of space technology in the future.

As part of the preparatory work for the coming WARC, the

CCIR is conducting technical studies. In parallel with these studies by the CCIR, it is also necessary to examine whether the designation of orbits and frequencies on a country-by-country basis, as was done for 12-GHz broadcasting satellites, is a good idea or whether there is a better way.

The WARC-79 and Papua New Guinea

GEORGE HUGH RAILTON

Abstract—This paper briefly describes Papua New Guinea, a newly independent country, its telecommunications facilities, and its proposals to the 1979 World Administrative Radio Conference (WARC-79), and selected WARC-79 results. The importance of the high-frequency (HF) band is emphasized. It is concluded that most of the requirements of Papua New Guinea regarding the Table of Frequency Allocations were met—although some were not met in the way in which they were first proposed.

THE COUNTRY

PAPUA NEW GUINEA is a newly independent country lying north of Australia and east of Indonesia. It is a tropical country of some 470 000 km² with mountains rising to over 5000 m in a central cordillera that runs through the center of the large island which forms Irian Jaya and the mainland of Papua New Guinea. There are extensive swamp lands and many islands as well as high mountains. In this land of contrasts, some 80 percent of the population live in rural areas with very few roads. Aviation forms a major means of transport because of the lack of alternatives. Around the coastline and between the islands, shipping also supplies a valuable service using both conventional as well as traditional craft.

TELECOMMUNICATION FACILITIES

Despite the extensive development of a terrestrial microwave telecommunications network which links all the major urban areas, most of the population can only be reached by using HF radio. At present, there are some 1500 HF stations working through 11 base stations for interconnection to the public network. There are also some 300 Papua New Guinea-

registered ship stations as well as numerous ships of other nations using the HF Coast Radio Stations.

Because of the extremely high central cordillera, aircraft often have to fly through high mountain passes to reach their destinations, many of which are grass airstrips in jungle clearings or on sides of mountains. There are over 400 registered landing strips, the highest being at 2500 m above sea level. While the major airports are served by VHF air-ground services, HF radio will be for many years to come the major system for air-ground communications. Therefore, the major area of importance to Papua New Guinea at the International Telecommunication Union (ITU) World Administrative Radio Conference in 1979 (WARC-79) was regarding the allocation of frequency bands to services operating in the 3-30-MHz (HF) band.

PAPUA NEW GUINEA PROPOSALS TO WARC-79

As with all countries, technology is rapidly developing and, consequently, the interest of Papua New Guinea was not restricted only to the HF band, and therefore the Papua New Guinea proposals covered the bands from 9 kHz to 21.2 GHz. Prior to the drawing up of proposals, opinions were canvassed from as many sectors as possible. In October 1978, the first draft was widely circulated within Papua New Guinea and also given to some 50 ITU Administrations for comment. The Papua New Guinea submissions to the WARC contained what was seen at the time as being the national future requirements for the next 20 years. Some proposals were also made in support of other Administration's proposals, while other proposals were based on supporting the findings of the CCIR Special Preparatory Meeting (SPM) held in late 1978 [1].

In drawing up the Papua New Guinea proposals, three principles were used as overall guidance. They were:

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1) The Radio Regulations should be simplified and made easy to read.

2) The resulting Final Acts of WARC-79 should reflect the development needs of all countries over the next 20 years.

3) All provisions in the Radio Regulations should be kept as flexible as possible to allow for the rapidly changing spectrum requirements in developing countries.

On reflection, it is obvious now that the WARC was not wholly successful in meeting these three principles. It is doubtful whether the new Radio Regulations [2] will be easier to read; since, overall, they are more complex and voluminous than the 1959 Radio Regulations. However, in some Articles, considerable effort was made to simplify and standardise the text. As far as principle 2) is concerned, this author believes that the most apt quotation came from a delegate of Norway who stated that "while it was not possible to make everybody happy, it may be possible to make everybody equally unhappy" and that, in many areas, was achieved. The extensive use of Footnotes to the Table of Frequency Allocations to reflect each nation's different requirements do indeed reflect the attempt to achieve principle 2), though not necessarily in a well-engineered manner or with any rational technical basis. Principle 3) was not tackled by the Conference in any depth, with the consequence that in a few short years the whole process will have to be carried out again. In fact, one delegation presented a document to allow for another general WARC in 10-years time. However, it did not obtain sufficient support. This did indicate, however, that there was some disquiet with the results achieved.

This author, therefore, concludes that as far as the three basic principles used by Papua New Guinea in drawing up its proposals are concerned, WARC-79 was not an unmitigated success. In detail, however, the WARC did go a long way to meet the national requirements of Papua New Guinea.

THE WARC-79 TABLE OF FREQUENCY ALLOCATIONS

LF Allocations

The major requirement for the LF bands in Papua New Guinea was for the extension of Aeronautical Radionavigation service bands for use by nondirectional beacons (NDB's). The decision of the WARC to give extensions to this service on a primary basis in Region 3, along with the decision to exclude LF broadcasting in the Region, has resulted in ample spectrum being made available for this service.

MF Allocations

Experience with LF NDB's has shown that under some geographical circumstances, reflections occur in the LF bands causing bearing errors. To overcome this problem, NDB's in the 1605-1705-kHz band have been used with some success. Papua New Guinea had proposed that the 1606.5-1705-kHz band be allocated to the Radionavigation service for use by radiobeacons on an exclusive basis. The Conference decided differently and allocated the band 1606.5-1800 kHz to the Fixed, Mobile, Radiolocation, and Radionavigation services, with a Footnote allowing the Broadcasting service on a secondary basis in some countries.

While this allocation does allow NDB's to be used in the 1606.5-1705-kHz band, some problems with interference are expected to occur, since the Radiolocation systems that may use this band are undefined and could be incompatible with the operation of the Aeronautical Radionavigation service, as well as problems that could arise with the Broadcasting service. (Who ever heard of broadcasters accepting a secondary status?)

HF Allocations

As stated earlier, the thrust of the Papua New Guinea proposals was towards the allocations to be made in the HF band. Since the Conference resolved to hold additional specialized conferences to discuss the Broadcasting and Mobile services, not all proposals were fully considered. The major interest of Papua New Guinea was in the HF bands below 10 MHz, where extensive use of the HF Fixed and Mobile services exists today.

HF Fixed and Mobile Service Allocations

While it is possible that some of the HF Fixed service usage will be replaced by satellite systems in the years to come, it is expected that usage of HF Fixed services will increase along with the Mobile services. In many applications, HF networks consisting of Fixed and Mobile stations are required, and the general inclusion of Mobile services in the Fixed service allocations has gone a long way towards bringing the new Radio Regulations in line with current practice.

HF Tropical Zone Broadcasting

Extensive use is made of Tropical Zone broadcasting in Papua New Guinea and the "no change" situation has at least allowed status quo in this regard. The inclusion of a power limitation in this service should assist in orderly development. The extensions sought for Tropical Zone broadcasting in the 9- and 11-MHz bands was not achieved, however, this will be able to be reviewed at the proposed forthcoming HF Broadcasting conference. Thus for the most part, the WARC has allowed for the continued operation and some small extensions for HF Broadcasting used for national purposes.

HF Maritime-Mobile Service Allocations

The very small increases made for the Maritime-Mobile services will be of significant consequence to all nations relying on the Maritime-Mobile service for trade and development. Indeed, the Conference did very little to alleviate the 6-MHz maritime-mobile congestion problem and this will have an effect on all maritime nations. One of the reasons for this situation occurring was the lack of guidance on the sharing possibilities between the Maritime-Mobile service and other services, and it is this author's view that the stance adopted by developed nations at the CCIR SPM was the root cause.

In Papua New Guinea and throughout the Pacific, extensive use is made of the 6-MHz maritime-mobile bands since the occurrence of tropical noise [3] makes the 2-MHz bands less useful. The failure of the Conference to provide a solution to allocating more spectrum at 6 MHz for the Maritime-Mobile service will mean increasing interference in this area over the next 20 years.

Transitional Arrangements for HF Services

The transition arrangements for the Fixed services that will be displaced by the new Broadcasting and Maritime-Mobile allocations should prove to be satisfactory because:

- a) There are only small sections of spectrum involved.
- b) There is adequate time allowed for the transition.

HF Safety Communications

Papua New Guinea had proposed that three small bands be set aside for safety services. This was an attempt at providing a service for highly economical emergency communications for use mainly in rural areas. What was proposed was the world-wide allocation of small bands at around 2, 4, and 8 MHz. The Swiss delegation, however, proposed that frequencies in the Amateur bands be used for this purpose. The resulting Resolution 640 thus opens up the way for the Amateur fraternity to assist in this task. However, this will only be achieved if the relevant action is taken by the amateur organizations. In particular, the International Amateur Radio Union should address this subject with some urgency.

HF Aeronautical-Mobile Allocations

The status quo situation in the Aeronautical-Mobile (R) service allocations has allowed for a continuation of the expansion of this service through the provisions of the Final Acts of the 1978 WARC for the Aeronautical Mobile (R) Service which doubled the number of available telephony channels by converting from double sideband to single sideband. It is, therefore, expected that there will be sufficient spectrum for the future needs of the Aeronautical-Mobile (R) service in this part of the world.

The inclusion of the allocation for the Mobile, except Aeronautical Mobile (R), service in the band 5730-5950 kHz is a step forward to allow integrated air-to-ground and ground-to-ground operations on the same frequency. This type of service in this frequency range has long been needed for development projects where an integrated communications system is needed to assist in the overall operations.

VHF Allocations

The big problem in the VHF bands is in the variety of bands used by the various users of television broadcasting throughout the Region. The continued allocation of the lowest TV channel in the 44-52-MHz frequency range is unfortunate since propagation by the E-layer in particular, means that the relatively high-power TV stations can cause interference at large distances. Obviously, with the huge amounts of capital involved already in TV systems using these bands, no major move could be expected. It is indicative of a future trend, however, that only Australia and New Zealand are persisting with TV in the 44-47-MHz band.

In the bands above 200 MHz, Papua New Guinea has a continuing need for allocations for aeronautical distance measuring equipment (DME) and the Footnotes, as well as the Frequency Table entries, cover this need. The continued allocation of Fixed and Mobile services to large portions of the VHF

bands was seen by Papua New Guinea as being of very high importance, and the Conference also concurred with this assessment. The creation of a new band for Broadcasting (216-230 MHz) will support two new 7-MHz-wide TV channels, making it possible, in the long run, for countries to change from the 44-52-MHz band.

UHF Allocations

The prime requirement in this frequency range was for Fixed and Mobile services. The sharing of Fixed, Mobile, and Broadcasting services introduced throughout the band 470-960 MHz will go a long way towards solving this problem.

Generally, the sharing possibilities included in the new Frequency Table give considerable choice to national Administrations as to how they will develop these bands. It is, therefore, considered that the UHF allocations are in line with the needs of Papua New Guinea over the next 20 years.

SHF Allocations

The requirements for Papua New Guinea in these bands were to protect the existing terrestrial 2-GHz networks (including tropospheric scatter systems) from constraints by the possible introduction of new space services in the band 1700-1900 MHz, to provide more spectrum for satellite services in the 4- and 6-GHz bands, and to provide Fixed-Satellite down-link capacity in the band 12.2-12.5 GHz. All these objectives were achieved at the Conference.

Summary

In the work at the Conference on the Table of Frequency Allocations [4], most of the requirements sought by Papua New Guinea were met, though some were not met in the way in which they were first proposed.

OTHER ARTICLES

Definitions

Papua New Guinea had made proposals on most of the other Articles of the Radio Regulations. However, the major work was directed at Article 1 (Definitions). Because of the confusion that has sometimes occurred when using the 1959 Radio Regulations, this Administration sought to clarify terms and definitions and to re-sort them into a more logical order. It was quickly noticed, however, that some Administrations strongly resisted any change, possibly because the confusion that exists enables them to get their way with countries who do not speak one of the official ITU languages. In particular, the concepts of "Service Area" and "Coverage Area" were not treated adequately at the Conference, and the international radiocommunications community now has to put up with the growing ambiguity that will surround these terms for the next 20 years.

On reflection, the entire area of definitions was far from adequately treated, and this will possibly lead to further confusion in ITU texts. The consideration of Article 1 by four sub-committees was not the appropriate method of work, as now there are some inconsistencies that were not in the original text of the 1959 Radio Regulations. Considering these factors,

The new Article 1 has come through reasonably well, however, it could have been very much better.

Equipment Standards

In Article 5 (Technical Characteristics of Equipment) and the associated Appendices 7 and 8 (Frequency Tolerances and Spurious Emission Power Levels), Papua New Guinea had followed the findings of the CCIR SPM in this area and had proposed some editorial changes to make the subject clearer.

Inasmuch as the format of the new Appendix 8 is based on Papua New Guinea proposals, the Conference accepted this work. It should be noted that the Papua New Guinea proposals were suggestions on how the subject should be approached. The technical values were drawn directly from the SPM. Without the SPM guidance on this subject it is unlikely that such a good result would have been achieved. In this area, and in many other areas, the SPM played a valuable role in giving technical guidance and, therefore, was a worthwhile exercise.

Amateur Service

Proposals were also made by Papua New Guinea on many other Articles of the Radio Regulations, however, most were based on supporting other Administration's ideas. One proposal of particular interest, however, was in Article 2 on the changing of the Morse code requirement for Amateur operators using the bands above 144 MHz. This provision was changed to extend the exception to bands below 30 MHz, thus bringing the ITU Radio Regulations into line with current Papua New Guinea practice.

SUMMARY

As an individual Administration, Papua New Guinea's requirements were met for the most part by the Conference;

however, it was obvious to us at the time that the needs of many countries were severely compromised in the spirit of achieving the production of a Conference Final Acts. This will, no doubt, lead to the need for another conference in about 10 years time rather than the 20 years previously anticipated.

One of the reasons for this is that the Conference was attempting too much, and small delegations had to seriously restrict their areas of work to just the vital issues. There is some merit in having the next Conference in two parts. The first part could set up the "framework" (i.e., definitions, technical provisions, and administrative provisions), and then the second part of the Conference would carry out the Frequency Table work within the "framework" decided by the first part of the Conference. In this way, the huge number of Footnotes to the Table of Frequency Allocations could be decreased to a workable level while still providing for each nation's needs.

Certainly we now have a Final Acts of the 1979 World Administrative Radio Conference [4]; however, the "good" points and "bad" points of this great document have yet to be discovered. If nothing else, WARC-79 has shown the world that the ITU can produce an extraordinary amount of paper.

REFERENCES

- [1] ITU, "Technical Bases for the World Administrative Radio Conference in 1979," Report of the Joint Meeting of CCIR Study Groups Special Preparatory Meeting for the WARC-79, International Radio Consultative Committee, International Telecommunication Union, Geneva, Switzerland, 1978.
- [2] ITU, "Radio Regulations Edition of 1982 Including Additional Radio Regulations, Appendices, Resolutions and Recommendations," International Telecommunication Union, Geneva, Switzerland, 1982 (in preparation).
- [3] CCIR, "World distribution and characteristics of atmospheric radio noise," Rep. 322, International Radio Consultative Committee, International Telecommunication Union, Geneva, Switzerland, 1964.
- [4] ITU, "Final Acts of the World Administrative Radio Conference, Geneva, 1979," International Telecommunication Union, Geneva, Switzerland, 1980.

Impact of WARC-79 on the Studies of the International Radio Consultative Committee (CCIR)

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Abstract—The CCIR provided the main technical bases for the World Administrative Radio Conference, 1979, including terminology; technical bases for allocation, regulation, and for the provision for new services; characteristics of equipment and emissions; radio wave propagation and noise data. The WARC specified CCIR studies to be carried out for a number of future radio conferences to be held in the 1980–1986 time period, including a conference in 1983 to plan satellite broadcasting in the region of the Americas and a world conference in 1984/1986 concerning the geostationary satellite orbit. Additional studies set out for technical radio regulations included, for example, determination of coordination area around an Earth station in the bands from 1 to 40 GHz shared between space and terrestrial services, and other technical criteria for frequency band sharing. Over the next few years, because of the intense schedule of ITU administrative radio conferences, CCIR studies related to frequency sharing and other radio regulations will increase markedly.

INTRODUCTION

THE MAIN SUBSTANCE of the Final Acts of the World Administrative Radio Conference (1979) is the allocation of frequency bands to the various services (services are defined by radio regulation, as for example, broadcasting service, maritime mobile service, etc.) in different regions of the world, together with technical regulations for the use of frequencies and intricate procedures for notification and coordination of frequency assignments to establish the right to international protection from harmful interference. There are also operational provisions for certain services, and finally, a compendium of resolutions and recommendations to guide planning, progressive changes in spectrum utilization, and studies for future development.

The International Radio Consultative Committee (CCIR) is the permanent organ of the International Telecommunication Union (ITU) set up to study technical and operating questions in radiocommunications and to issue recommendations. The CCIR's two main areas of activity concern the technical aspects of spectrum utilization and standards for performance and compatible interworking of radio systems in international telecommunications. The work is carried out in thirteen Study Groups (see Table I). Recommendations and questions for study are approved by the Plenary Assembly held every three to four years. Administrations, recognized private operating agencies, scientific and industrial organizations comprising some 1200 delegates from some 40 countries usually participate.

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TABLE I
CCIR STUDY GROUPS

Study Group 1	Spectrum Utilization and Monitoring
Study Group 2	Space Research and Radioastronomy
Study Group 3	Fixed Service at Frequencies below About 30 MHz
Study Group 4	Fixed Service Using Communication Satellites
Study Group 5	Propagation in Non-Ionized Media
Study Group 6	Propagation in Ionized Media
Study Group 7	Standard Frequencies and Time Signals
Study Group 8	Mobile Services
Study Group 9	Fixed Service Using Radio-Relay Systems — Frequency Sharing and Coordination Between Systems in the Fixed Satellite Service and Radio-Relay Systems
Study Group 10	Broadcasting Service (Sound)
Study Group 11	Broadcasting Service (Television)
CHTT	Transmission of Sound and Television Broadcasting Signals Over Long Distances
CHV	Vocabulary

CCIR recommendations and reports provide the main technical bases for ITU administrative radio conferences. CCIR propagation data, for example, suggest appropriate frequency bands for various service requirements as long-range navigation, sound and television broadcasting, Earth-space links, etc. Certain detailed propagation prediction methods become an integral part of the coordination of frequency assignments laid down by regulation. CCIR's radio astronomy studies led to a recommendation for protection of certain frequency lines of natural (resonance) origin. Recommendations and reports dealing with modulation techniques, protection ratios, antenna performance, and frequency tolerances serve to guide the regulatory provisions for bandwidth and orbit utilization, and coordination criteria. In some cases, as for satellite broadcasting, CCIR studies provided the technical basis for detailed planning of frequency assignments and orbital utilization to establish an international plan for satellite broadcasting.

The information provided to the WARC-79 was given in a report by the CCIR 1978 Special Preparatory Meeting (SPM) entitled, "Technical Bases for the World Administrative Radio Conference, 1979." This report covered:

- 1) terminology;
- 2) classification and designation of emissions;
- 3) technical bases for allocation and regulation of spectrum utilization by terrestrial and space services, including considerations of band sharing;
- 4) technical basis for provision for new services and for bands not yet allocated;
- 5) technical aspects of optimum use of the spectrum;

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- 6) technical characteristics of equipment and emissions, including frequency tolerances and spurious limits;
- 7) radio-wave propagation and noise data relevant to frequency allocation, regulation, and sharing.

In addition, CCIR proposals to the Conference were the basis for adoption of a new system of classification and designation of emissions and for changeover from GMT to Coordinated Universal Time (UTC) in international telecommunications usage.

The WARC-79, besides using much of the CCIR material in preparing the new regulations, referred to CCIR recommendations in many of the provisions of these regulations. It also adopted resolutions and recommendations requesting further studies which have a considerable bearing on the future work program of CCIR. Conclusions of the SPM in the areas of transmitter frequency tolerances and spurious emission limitations were mostly adopted with little change.

TECHNICAL STUDIES REQUIRED FOR FUTURE ADMINISTRATIVE RADIO CONFERENCES

The WARC-79 set the stage for a number of further World and Regional Administrative Radio Conferences to deal with problems of specific services.

Resolution 3 provides for a world space conference relating to the use of *the geostationary satellite orbit and the planning of the space services using it*. The objective is "to guarantee in practice for all countries equitable access to the geostationary satellite orbit and the frequency bands allocated to space services." The Resolution invites CCIR to carry out preparatory studies to provide the first session (1985) with technical principles, criteria, and parameters, including those required for planning space services. A paper by Withers (this issue, pp. 00-00), chairman of CCIR Interim Working Party 4/1 covers the CCIR studies in detail. Results are expected to deal with 1) techniques for increasing the efficiency of using orbit/spectrum, 2) technical aspects of coordination of space services and frequency sharing between different space services, 3) the limitations on space services to insure frequency sharing with terrestrial services, 4) description of fixed satellite networks of the present and future, and 5) a summary of the technical aspects of operation of the space services (propagation considerations, space satellites, etc.). A major problem is considered to be the future expansion of fixed satellite services. Broadcasting satellites are assigned specified frequencies and orbital positions according to conference decision, and there is no provision for expansion. The 1985 conference must initially consider all satellite services, including mobile, meteorological, etc.

Resolution 202 sets up a *world conference for the mobile services*, to be held in March 1983, which will revise the radio regulations to harmonize some provisions for aeronautical, maritime, and land mobile services, to improve distress and safety provisions, and to take account of new technology and systems. The conference will consider, among other things, channeling plans for high-frequency maritime mobile radio-telephone service in bands affected by decisions of the WARC-79, distress and safety communication, digital selective calling,

temporary technical and operational provision for maritime mobile satellite service, the remaining aspects of a new system for station identification which was adopted by the WARC-79, maritime radio beacons, emergency position indicating radio beacons, and the development of future ship telemetry, telecommand, and data exchange systems. The CCIR has been asked to prepare the technical and operational basis for this conference, and Study Group 8, leading this effort, began its work in November 1980. It will hold a further special meeting in September 1981. Its preliminary report covers technical and operational recommendations for distress and safety communication, digital selective calling, radiotelephony connected to the telephone network, direct printing telegraphy (teleprinter, telex operation on radio circuits), and draft new recommendations on numerical identification of ship stations.

Resolution 508 foresees a conference (now to be held in January 1984) *to plan the use of HF bands allocated to broadcasting*. The first session will consider the power appropriate to HF broadcasting, the needs of each country for national and international service, the maximum number of frequencies to be used for one program to one zone, and the introduction of a single sideband (SSB) system for future HF broadcasting. These topics have been studied for a long time by CCIR Study Group 10, which has set up an Interim Working Party to finalize recommendations on protection criteria, channel spacing, minimum signal-to-noise ratios, directional antennas, specification of a suitable SSB system for progressive introduction. The CCIR Plenary Assembly will approve in February 1982 the material to be provided for this conference.

A conference of considerable interest to countries in the region of the Americas (ITU Region 2) concerns the *planning of the broadcasting satellite service in the 12-GHz band*. A detailed frequency assignment and orbital position plan will be drawn up. This conference, initiated by WARC-79 Resolution 701, is scheduled to be held for five weeks beginning June 13, 1983. CCIR has been asked to carry out the necessary technical studies, as it did for the satellite broadcasting conference of 1977 which drew up plans for Europe, Africa, Asia, and Oceania (ITU Regions 1 and 3). CCIR Study Groups 10 and 11 have set up a joint Interim Working Party under the chairmanship of Dr. C. Siocos, Canada, to prepare this work. The report will cover terminology, system technology for broadcasting satellites, radio-propagation factors, Earth-receiving antennas and receivers, frequency-sharing considerations, and techniques for orbit and frequency planning. The Working Party's first meeting was held in Ottawa, Canada, April 28-May 1, 1981.

A number of other conferences are also engaging CCIR technical preparations. Following the expansion of the *VHF broadcasting band* in ITU Region 1 to 87.5-108 MHz (formerly the upper limit was 100 MHz), the broadcasting station plan will be revised by a regional conference for Region 1 in 1982, set up by Resolution 510. The technical preparations which CCIR has been asked to carry out include sharing criteria between sound and television broadcasting, protection ratios, and minimum required field strengths for FM mono- and stereophonic reception, optimum channel spacing, antenna and polarization characteristics, and compatibility with aero-

nautical radionavigation operating in the adjacent band above 108 MHz. Additional CCIR work is underway in preparation for the *VHF/UHF Broadcasting Conference in Africa* (Resolution 509) and concerning the planning of *feeder links to broadcasting satellites* (Resolution 101).

CCIR STUDIES FOR TECHNICAL RADIO REGULATION

In view of the relatively infrequent occurrence of WARC's for general revision of the radio regulations, and the continuing rapid development of radio communications, WARC-79 referred to CCIR a number of technical matters bearing directly on radio regulation. Frequently the phrase "in accordance with the relevant CCIR Recommendation" is used, or some equivalent. Certain WARC-79 resolutions or recommendations request specific studies by CCIR with a view to use of the information by a future WARC for revision of the radio regulations.

Some selected examples of reference in the radio regulations to relevant CCIR recommendations are cited:

"Technical Characteristics of Stations. . .

- 302. To the maximum extent possible, equipment to be used in a station should apply signal processing methods which enable the most efficient use of the frequency spectrum in accordance with the relevant CCIR Recommendations . . .
- 305. In the absence of . . . specified maximum permitted power levels [for out of band emission] transmitting stations shall, to the maximum extent possible, satisfy the requirements relating to the limitation of the out-of-band emissions specified in most recent CCIR Recommendations . . ."

"Standard Frequency and Time Transmissions. . .

- 2772. In selecting the technical characteristics of standard frequency and time signal transmissions, administrations shall be guided by the relevant CCIR Recommendations . . ."

"Terrestrial Radiocommunication Services Sharing Frequency Bands with Space Radio Communication Services Above 1 GHz

- 2501. Sites and frequencies for terrestrial stations, operating in frequency bands shared with equal rights between terrestrial radiocommunication and space radiocommunication services, shall be selected having due regard to the relevant CCIR Recommendations with respect to geographical separation from earth stations . . .
- 2509.1 . . . and limits concerning inter-Regional interference which may appear in CCIR Recommendations should, as far as practicable, be observed by administrations . . ."

These provisions, cited from among perhaps a hundred such references, give a flavor of the role of the CCIR recommendations relevant to radio regulations, and the studies underway to improve and update them. A major task before the XVth

Plenary Assembly is the precise identification for each mention in the radio regulations, of the "relevant CCIR Recommendation" and, in many cases, the relevant parts.

A series of resolutions of the WARC-79 requires special attention of CCIR to particular topics of radio regulation. A few are outlined below.

Resolution 60 invites the CCIR to continue to study *propagation data concerned with the determination of coordination area* around an Earth station in bands from 1 to 40 GHz shared between space and terrestrial services, with a view to direct insertion of the new material into the relevant parts of Appendix 28 of the Radio Regulations upon acceptance by Administrations. This portion of Appendix 28, based originally on CCIR material, covers radio climatic zones, methods for taking into account attenuation due to distance, atmospheric water vapor and oxygen, and rainfall. A contentious aspect of the revision is the occurrence and effect of propagation ducts. Study Group 5 is responsible for this work and, in June 1980, produced a draft revision of Report 724 on the subject.

Resolution 63 asks CCIR to study, in collaboration with IEC and CISPR, *radiation from industrial, scientific, and medical (ISM) equipment* in the entire radio spectrum in order to insure adequate protection against interference to radio communication services. Recommendations are sought as soon as possible on any limits that might be imposed on radiation from ISM equipment both inside and outside the bands designated for its use in the radio regulations. An Interim Working Party for this purpose has been set up with the participation of CISPR representatives.

Another Recommendation (705) asks CCIR to study urgently the sharing criteria to be applied to *frequency sharing between the sound broadcasting satellite service and the terrestrial television broadcasting service* in the band 620-790 MHz and to prepare a recommendation on limitation of power flux densities for broadcasting satellites in this band to replace provisional limits set out in the radio regulations.

Recommendation 708 sets out comprehensive CCIR studies relating to *sharing of frequency bands between space services and between space and terrestrial services*, including antenna patterns for earth stations and satellites, cross-polarization factors, interference criteria for the various services, the necessary limits of power flux density incident at the Earth's surface by satellite transmitters, and the possibility of establishing a technical criterion for expressing the efficiency of use of the geostationary satellite orbit.

Resolution 66 concerns division of the world into geographical regions for the purpose of frequency allocation and asks the CCIR to study the technical and operational basis for a possible revision of the present division. A joint Interim Working Party, under the chairmanship of Mr. O. Lediju, Nigeria, began meeting in May 1981 for study of this question.

Three resolutions concern maritime mobile radiocommunication and are under study by Study Group 8. Resolution 200 concerns the use of SSB reduced and suppressed carrier emission (R3E and J3E) for maritime and aeronautical distress and safety use on the international distress frequency of 2182 kHz. Present regulations require use of double sideband or full-carrier SSB. Resolution 310 asks CCIR to advise on bandwidths and data formats for future implementation of

ship movement telemetry, telecommand, and data exchange systems in the maritime service. Such short-range service at frequencies about 10 GHz was suggested by the CCIR Special Preparatory Meeting for the WARC-79. Resolution 311 anticipates completion of CCIR studies for a digital selective calling system for the maritime service with a final recommendation for its technical and operating characteristics, probably to be approved at the next Plenary Assembly.

Resolution 505, anticipating a sound broadcasting service by satellite at some frequency in the range 0.5-2 GHz, encourages experiments and asks CCIR to study the technical characteristics for a satellite sound broadcasting system for individual reception by portable or automobile receivers and the feasibility of such a service sharing a band with a terrestrial service.

The table of allocations contains many situations where two or more services share the same band of frequencies with equal rights. Typical of such sharing cases are fixed with mobile, fixed with broadcasting, and broadcasting with mobile. Space services share with other space services, as well as terrestrial services. Many new sharing situations were created by the WARC-79 to satisfy the demands of most services for greater allocations. Only in some cases do the regulations provide technical criteria for sharing, as for example, between satellite fixed service and the terrestrial fixed (microwave radio relay) service. In most cases, sharing criteria are unspecified and CCIR is expected to provide recommendations for technical criteria or other conditions of operation which would permit the services to operate without harmful interference. Thus studies of required protection ratio, antenna characteristics, geographical separations, and other factors relating to criteria or conditions for band sharing are a major part of CCIR studies for both space and terrestrial services. This work increases significantly with the number of sharing situations represented in the new frequency allocations.

GENERAL TECHNICAL STUDIES

Besides regulation-related topics, the WARC adopted a number of resolutions and recommendations urging CCIR study of questions concerning future planning of radiocommunications, development of frequency management, or topics of special interest to developing countries. A few typical areas are outlined below.

Resolution 5 and Recommendation 68 concern radio-wave propagation. The resolution urges developing countries in tropical regions to institute national radio propagation studies, including propagation measurements and collecting appropriate meteorological data in accordance with CCIR methods, and to contribute the information to CCIR studies. The recommendation asks CCIR to encourage and assist radio propagation studies where not already well established, to continue its general studies of radio propagation and noise, to coordinate the results of studies carried out in different countries, and to give particular attention to those studies which can assist in further refinement of the International Frequency Registration Board (IFRB) technical standards. Resolution 61 relates to the division of the world into climatic zones for the purpose of calculation of propagation parameters. Emphasis is placed on the effects of rainfall and on

studies of sand and dust storms. The objective is to revise the present classification of the world into climatic zones. Recommendation 505 requests expediting of studies on rainfall attenuation in tropical regions, in relation to satellite broadcasting at 12 GHz, and to specify, as soon as possible, the attenuation values necessary for ensuring a satisfactory broadcasting-satellite service.

Recommendation 3 concerns the transmission of electric power at radio frequencies from a spacecraft (solar power satellite) and asks the CCIR to study all aspects of the effect of such transmission on telecommunication services and to consider ecological and biological implications. Study Group 2 is continuing studies begun several years ago and has established contact with other relevant international organizations.

Recommendation 1 asks continued study of the standard specification and preferred frequencies for transportable Earth stations for use in natural disasters and for compatible mobile and transportable fixed communications in relief operations.

Recommendation 60 asks CCIR to expedite all phases of the program of studies which will assist the IFRB in further refinement of its technical standards.

A handbook for computer-aided techniques for radio-frequency management (Recommendation 31) is to be prepared by CCIR by 1982. It is intended to describe approaches that have been taken already and to give practical guidance to all Administrations for establishing various levels of computer-aided frequency management, including aspects involving international cooperation. A draft of this handbook was prepared by Study Group 1 in June 1980.

Of particular interest is Recommendation 65, relating to technology for new spectrum sharing and band-utilization schemes. It is recognized that advances in technology, particularly digital radio, and new encoding, modulation, and access schemes, are making practical new sharing techniques that offer economical as well as technical advantage for increasing the efficiency of spectrum utilization. CCIR is requested to study the new techniques, as for example, packet radio, spread spectrum, and multiuser concepts. CCIR is asked to develop new concepts for time sharing of frequencies and to recommend criteria and specifications for efficiency, compatibility, and interworking of such systems, as well as criteria for spectrum management of these new systems.

More than two dozen additional such recommendations request CCIR studies on topics such as:

- 1) protection ratios and minimum field strengths;
- 2) terminology and definitions;
- 3) frequency tolerances;
- 4) equipment characteristics, e.g., bandwidths, selectivity;
- 5) lightning protection for radio installations;
- 6) automated UHF maritime mobile communications;
- 7) aeronautical satellite communications;
- 8) spurious emissions from satellite and other stations.

CONCLUSION

Spectrum utilization questions have always been an important element of CCIR studies. But it is likely over the next few years, because of the intense schedule of administrative

radio conferences to 1986, that regulatory-related, conference-preparatory, and frequency-sharing studies will strongly dominate the CCIR activities. This program will not only burden the resources of national Administrations, but it will also strain the normal organizational arrangements of CCIR. The study groups are established to facilitate work on a service-by-service basis. The regulatory and conference questions, and studies of frequency sharing, with their many interservice aspects, will require an unprecedented degree of information exchange, coordination, and cooperation among the study groups. Besides establishing a "lead role" in certain topics for certain study groups to coordinate and consolidate studies, a number of special and joint working parties are being established. The meetings program will increase.

For several of the activities, as for preparation for the geostationary satellite orbit conference and the Region 2 satellite broadcasting conference, the participation of a number of countries which have not been participating normally in study

group work will be important. Such participation (85 countries) was an important factor in the wide support of the Report of the CCIR SPM for the WARC-79. In this connection, certain regional telecommunications organizations could provide valuable collaboration. In some topics, close liaison with other international organizations, as with the Intergovernmental Maritime Consultative Organization and the International Maritime Satellite Organization in maritime matters, and with the International Electrotechnical Commission and the International Special Committee on Radio Interference in matters relating to equipment standards.

Meantime, CCIR's regular program concerned with the performance and interworking of systems, including new telecommunication services, must continue unabated. These topics include such examples as the maritime mobile satellite service, the development of new broadcast still image, teletext and data services, and the development of standards for digital microwave radio relay links.

WARC-79 Changes to the Technical Radio Regulations

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Abstract—The WARC-79 met to revise and reorder the International Radio Regulations. This encompassed consideration of some 1300 pages of text over a two and one third month period by approximately eighteen hundred people. Approximately fourteen thousand proposals were presented. Technical proposals were considered within Committee 4 which was chaired by N. Morishima of Japan. This paper will identify those sections of the Radio Regulations considered in the Technical Committee, the important changes, and the implications thereof.

I. INTRODUCTION

THE WARC-79 considered many technical items during the update and revision of the Radio Regulations. This work, which formed the basis for many of the other decisions made throughout the conference, was assigned to the Technical Committee which consisted of three Working Groups: 1) Technical Definitions and Related Matters, 2) Spectrum Sharing by Space and Terrestrial systems, and 3) All other technical matters, e.g., Designation of Emissions, Spurious Emission Limits, etc. Table I identifies the specific portions of the Radio Regulations assigned to the technical committee.

The Working Group on Technical Definitions covered a broad range of items. Agreement was reached on a group of items that will allow unambiguous terminology to be used in the context of the Radio Regulations. This is important be-

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TABLE I
RADIO REGULATIONS CONSIDERED IN TECHNICAL COMMITTEE

Article/Appendix*	Subject
1 (N1)	Terms and Definitions
2 (N2)	Nomenclature of the Frequency and Wavelength Bands Used in Radiocommunication
4 (N3)	Designation of Emissions
5 (N4)	Technical Characteristics of Stations
18 (N16)	Interference
19 (N17)	Tests
Appendix 7 (3)	Table of Transmitter Frequency Tolerances
8 (4)	Table of Maximum Permitted Spurious Emission Power Levels
6 (5)	Additional Characteristics for the Classification of Emissions; Determination of Necessary Bandwidths Including Examples for their Calculation and Associated Examples for the Designation of Emissions
27 (N25)	Terrestrial Radiocommunication Services Sharing Frequency Bands with Space Radiocommunication Services Above 1 GHz
28 (N26)	Space Radiocommunication Services Sharing Frequency Bands with Terrestrial Radiocommunication Services Above 1 GHz
29 (N27)	Special Rules Relating to Space Radiocommunication Services
35 (N33)	Radiodetermination Service and Radiodetermination-Satellite Service
Appendix 28	Method for the Determination of the Coordination Area Around an Earth Station in Frequency Bands Between 1 GHz and 40 GHz Shared Between Space and Terrestrial Radiocommunication Services
Appendix 29	Method of Calculation for Determining if Coordination is Required Between Geostationary-Satellite Networks Sharing the Same Frequency Bands.

*Designator in () are numbers used prior to WARC 79

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cause of the international nature of the regulations, language differences, and the regional use of terms that can lead to confusion and misunderstandings.

Discussions regarding Spectrum Sharing of Space and Terrestrial Systems provisions of the Radio Regulations were detailed and resulted in several changes. Specifically, changes were introduced in Articles and Appendices concerning Space System Coordination, limits and restrictions related to Space and Terrestrial System Sharing in Bands Above 1 GHz, and Special Rules Relating to Space Radio Communication Services.

The last Working Group made significant and extensive modifications to Articles and Appendices containing standards and limits for Emission Designators, Spurious Emission levels, and Transmitter Frequency Tolerances. Adoption of these standards and limits will provide a uniform base for system design and promote more effective use of the radio spectrum.

In addition, each of the Working Groups considered a large number of existing and new Resolutions and Recommendations which can affect an administration's telecommunication planning activities.

II. APPENDIX 28

This Appendix contains a method used to determine the coordination area around an *Earth station* that shares frequency bands with terrestrial radiocommunication services. The requirement for such a procedure is obvious, i.e., transmitting Earth stations can cause interference, and receiving Earth stations can receive interference. This uniform approach to the introduction of compatible space and terrestrial service in shared bands forms the basis for procedures and automated programs used by the United States and other Administrations in their domestic and international activities. Appendix 28 is used in one form or another around the world.

At WARC-79, numerous changes were made to the Earth station coordination procedures contained in Appendix 28. These included sections concerned with propagation, receiving station protection contours, consideration of very narrow-band receiving stations, coordination based on mobile-station service area, and procedures for modifying propagation data after future International Radio Consultative Committee (CCIR) Plenary meetings.

Propagation data and coordination limits were adopted that significantly reduced the maximum coordination distances for Mode 1 (great circle mechanisms as opposed to rain scatter) propagation. The effect of these changes will be particularly noticeable for Zone A propagation paths (over land), since the maximum coordination distances in and near the direction of the mainbeam were arbitrarily truncated.¹ To deal with the uncertainties of these changes, and other associated propagation factors, Resolution 60 (originally designated AJ) was adopted. This Resolution is significant in that it provides a means for regular review and updating after each CCIR Plenary meeting. If the CCIR concludes that changes are technically justified and appropriate, then the International Telecommuni-

cation Union (ITU) Administrative Council can place these proposals on the agenda of the next scheduled World Administrative Radio Conference (WARC) as an extraordinary item. This allows timely modification of the propagation portions of this Appendix as new data and findings are developed.

New provisions also allow the notification of receiving Earth station coordination contours which provide reduced protection over those normally developed using Appendix 28. An Administration can use any procedure it wishes to calculate a coordination contour to protect transmissions to its Earth stations provided that the coordination contour is smaller than that using normal Appendix 28 calculation methods. This will provide Administrations the option to reduce coordination requirements and associated complexities and delays when they feel that adequate protection from interference will be provided. It is, however, necessary to identify the nature of the departure from Appendix 28, and to recognize that future changes that result in increased protection are effective only from the associated new International Frequency Registration Board (IFRB) publication date. In addition, Administrations have the option to provide a set of receiving station contours for Earth stations that receives both broadband and very narrow-band transmissions (e.g., single channel per carrier SCPC). By providing these contours, along with relevant technical data used in their determination, and information on frequency segments used for these transmissions, the coordination process could be enhanced through the early identification of problem areas and conflicts with terrestrial systems.

The growing use of mobile-satellite systems was recognized by the Conference as well as the need to determine the coordination area associated with the operation of mobile Earth stations.

A new provision in Appendix 28, Section 7, allows for the coordination of mobile (except aeronautical) Earth stations. This provision is based on the procedures of Appendix 28 and allows for coordination of a mobile Earth station service area rather than for a specific location. By precoordinating a service area, the mobile Earth station can be deployed and operated within it without entering into the time-consuming coordination process with each move.

A U. S. proposal to establish "protection areas" for mobile Earth-station operation was *not* accepted. Using this concept, areas within a coordination area would be determined based on detailed knowledge of the location and characteristics of radio-relay systems within the coordination area. Once protection areas had been defined, mobile stations could operate anywhere outside those regions with no danger of causing (or receiving) interference, without further coordination or notification. This concept requires information on changes in radio-relay characteristics or station locations and additions (to prevent this service from becoming, in effect, a secondary service). While a method of determining protection areas was not added to Appendix 28, it will be possible for Administrations to use the concept under a bilateral agreement.

In summary, there have been several changes in Appendix 28 that affect procedural aspects of the coordination process, required and optional data input and their application, and the update of propagation data. Although there is no direct

¹ Maximum coordination distances are now 200 and 375 km for interference criteria of 1 and 0.001 percent of the time, respectively, with intermediate distances for percentages of time between those values.

one-for-one tie to equipment-design requirements, system designers and operators should be aware of the basic coordination process and the associated technical aspects and concerns as reflected in the regulations.

III. APPENDIX 29

Appendix 29 contains procedures for determining when coordination between *satellite networks* sharing the same frequency bands is needed. Appendix 29 procedures are an essential part of a process to assure the orderly introduction and compatible operation of space systems using the geostationary orbit. Recognizing that Appendix 29 is basic to this process, it is evident that changes can significantly affect procedural matters, space telecommunication system design, and space/telecommunication systems planning.

The basic measure that determines the need for coordination is a predetermined increase in the "equivalent satellite link noise temperature" caused by a proposed system. The WARC increased the threshold or percentage increase in equivalent noise temperature ($\Delta T/T$) from 2 to 4 percent. This was consistent with efforts to reduce the number of situations where coordination is required between systems; however, it is anticipated that this will make little practical difference since the calculated $\Delta T/T$ is normally either considerably under or over the criteria (coordination trigger level).

An optional procedure for the use of polarization isolation in determining coordination requirements was introduced. If Administrations involved consent and have notified the system's polarization characteristics, then levels provided in Appendix 29 can be used. The isolation levels are modest (see 2.2.3 of Appendix 29) but certain implications are associated with this procedure. First, it implies that if polarization isolation is to be used as an effective means to reduce coordination, then more attention must be given to the design of spacecraft and Earth terminal antennas with regard to out-of-main-beam polarization purity and isolation. This also implies that use of polarization isolation beyond that associated with a single spacecraft could complicate space system network architecture, e.g., flexibility in applying frequency reuse through polarization diversity on a single spacecraft could be affected. In general, detailed consideration of polarization isolation factors should not play a significant role in the Appendix 29 process, but they should be given more detailed attention, as appropriate, during the coordination process.

Interference from slowly swept TV carriers into certain narrow-band (SCPC) carriers has been recognized for some time. In lieu of including a special calculation method within Appendix 29, consideration of this has been left to the initiative of Administrations. Specifically, Administrations using SCPC carriers that are registered as a result of a prior coordination, or are under coordination, may inform an Administration notifying new frequency assignments of this use. This would allow the notifying Administration to consider avoiding FM TV transmission on these channels, thereby eliminating one particularly troublesome interference interaction. In addition, Administrations introducing new systems using SCPC transmissions may seek information from other Administrations on their FM TV transmissions. The development of techniques

and methods that reduce the interference potential between these two types of signals would enhance orbit utilization, capacity, and reduce the complexity of the coordination process.

New reference antenna patterns for D/λ less than and greater than 100 were adopted. These patterns provide new values for the area between the main beam and the first sidelobes. The remainder of the reference pattern is the same as the existing pattern for $D/\lambda \geq 100$, and as recommended by the CCIR Special Preparatory Meeting (SPM) for $D/\lambda < 100$. It can be expected that interest in antennas which have sidelobe levels lower than these reference patterns will continue.

IV. ARTICLES 27 (FORMERLY N25) AND 28 (FORMERLY N26)

The increased use of space services to satisfy world communications requirements was recognized with the addition of new satellite service allocations and increases in sharing between space and terrestrial services. Both Articles are concerned with space and terrestrial system sharing above 1 GHz. The provisions of these articles are important in that they limit the maximum Effective Isotropically Radiated Power (EIRP) of terrestrial fixed-service systems, fixed-service antenna pointing restrictions toward the geostationary orbit, maximum Earth station EIRP towards the horizon, and power-flux density limits at the Earth's surface produced by space stations. For the most part, both articles have remained unchanged.

In Article 27 (formerly N25), the question of having terrestrial system pointing restrictions for systems that operate above 15 GHz was raised. For the bands above 15 GHz, no pointing restrictions for the Fixed and Mobile Services were adopted. However, a footnote provision states that when the CCIR has made a Recommendation as to the need for restrictions above 15 GHz, all systems introduced after January 1, 1982 should, as far as possible, meet such restrictions. This subject was referred to the CCIR for study and, if necessary, development of subsequent recommendations. The January 2, 1982 date is dependent on completion of CCIR studies by this date.

The power-flux density limits in Article 28 (formerly N26) are designed to assure compatible operation and frequency sharing between space and terrestrial systems. Any major change, either up or down, directly affects compatibility, space and terrestrial system design, and the range of telecommunication applications available to the designer, e.g., large/small Earth stations, interference margins, etc. The limits in Article 28 (formerly N26) were aligned with new allocations and increased in only one band, i.e., between 2.5 and 2.655 GHz. The Fixed Satellite Service (FSS) was aligned to that of the Broadcast Satellite Service (BSS) which produced a 2-dB increase at low angles and a 7-dB increase at high look angles to the satellite. This will allow common design between BSS and FSS applications and allow the unambiguous use of interactive services that could be considered either a BSS or FSS type of service.

In both Articles, the subject of inter-Regional interference

acceptable interference, and protection ratio. In addition, twelve new definitions were adopted that deal with emission designations and equipment characteristics, including terms for radiation, emission, class of emission, single-sideband emission, out-of-band emission, and unwanted emission. Regarding technical terms relating to space, new definitions were adopted: active sensor, passive sensor, and geostationary satellite orbit; and some terms were modified, such as passive satellite which became reflecting satellite and the definition of a geostationary satellite in general. Definitions for service area, coverage area, and channel could not be agreed on. Recommendations for CCIR study of these terms were passed.

VIII. OTHER

Articles 18 (formerly N16) and 19 (formerly N17) deal with provisions concerning Interference and Tests to which minimal changes were made. Similarly, Article 35 (formerly N33) which deals with interference protection to Aeronautical Radiobeacons was considered in the technical committee. A requirement to increase the protection ratio for aeronautical radiobeacons operating in the LF/MF range was identified by the International Civil Aviation Organization (ICAO). In practice, these beacons had been protected at a 15-dB level instead of the 10-dB level indicated in the Radio Regulations. At the ICAO Communications Divisional Meeting in the Spring of

1978, it was unanimously agreed that the Radio Regulations should be changed to provide a protection ratio of 15 dB, and the WARC agreed.

The Radio Regulations contain a large number of resolutions and recommendations. Those that had direct technical implications were reviewed within the Technical Committee, and others were developed to address newly defined needs. Many of the existing resolutions and recommendations were retained with little or no change. Most of the new resolutions and recommendations adopted were primarily directed to the CCIR asking for further study.

IX. CONCLUSION

The WARC-79 reviewed all of the existing Radio Regulations, many of which generated considerable debate; but in general, the regulatory provisions assigned to the Technical Committee were not highly controversial. This was due, in large part, to the preparatory work done within the CCIR and specifically by the SPM. There remain many areas requiring further study set forth in Recommendations and Resolutions of the WARC. In addition, several of the forthcoming Regional and Specialized Administrative Radio Conferences scheduled for the next several years, as well as the continuing CCIR meetings, could have a significant effect on the technical sections of the Radio Regulations.

The Impact of the 1979 World Administrative Radio Conference on the Fixed-Satellite, Inter-Satellite, and Mobile-Satellite Services

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Abstract—The Fixed-Satellite service (FSS) is the most heavily used and still the fastest growing of the seventeen space radio communications services recognized by the International Telecommunication Union (ITU). To provide the additional spectrum needed for continued growth in both domestic and international satellite networks, the ITU's 1979 World Administrative Radio Conference (WARC-79) more than doubled the bandwidth allocated to this service in most parts of the spectrum. The Inter-Satellite service (ISS) is an "auxiliary" service whose allocations are intended to provide inter-satellite links between the space stations of other services. Although not yet implemented in commercial systems, such links are expected to be used extensively in future FSS networks. To permit the introduction of the ISS earlier and at lower cost than would be possible with the existing allocations above 50 GHz, WARC-79 allocated two 1-GHz-wide bands to the ISS at 23 and 33 GHz. The Mobile-Satellite

services (MSS) include land, maritime, and aeronautical components. WARC-79 left the Aeronautical-Mobile Satellite allocations essentially unchanged, created new possibilities for development in the Land-Mobile Satellite service, and essentially doubled the spectrum that will be available to the Maritime-Mobile Satellite service. WARC-79 made only minor changes to the regulatory procedures for gaining access to the various space service allocations. However, in response to the concerns of developing nations about equitable access to the spectrum and the geostationary satellite orbit for future satellite systems, WARC-79 resolved to convene another World Administrative Radio Conference in two sessions scheduled for 1984 and 1985 (WARC-84/85).¹ This Space Conference would consider the use of the geostationary satellite orbit and the planning of the space services using it with the objective of guaranteeing in practice for all countries equitable access to the orbit. This paper provides a detailed description of the WARC-79 allocation actions affecting the FSS, ISS, and MSS and provides background on the decision to convene WARC-84/85.

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¹ Note added in proof: Sessions 1 and 2 of this Space Conference were rescheduled to 1985 and 1987, respectively, at the June 1981 meeting of the Administrative Council of the ITU.

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I. INTRODUCTION

THE CHANGES in the international radio regulations enacted by the 1979 World Administrative Radio Conference (WARC-79) will affect to varying degrees all of the radiocommunication services identified by the International Telecommunication Union (ITU) [1]. The impact of these changes will be especially strong in the case of the space services—i.e., those services that include radio transmitters and/or receivers located on spacecraft. None of the space services existed prior to 1963 and some of them were not defined or provided with frequency allocations until 1971 [2]. Today, the ITU distinguishes some 17 space services (although some of these represent special categories of others), but this paper will consider only the six that are of greatest interest to commercial point-to-point and mobile telecommunications: the Fixed-Satellite service (FSS), the Inter-Satellite service (ISS), the Mobile-Satellite service (MSS), and its three components, the Land-Mobile, Maritime-Mobile, and Aeronautical Mobile-Satellite services.²

The changes in the Radio Regulations that affect these services will be described for each of the three categories around which WARC-79 was organized:

Frequency Allocations: The specification of how the radio frequency spectrum is to be divided among the communication services for each of the three geographic Regions³ of the world identified by the ITU.

Technical Regulations: The technical standards and design constraints imposed on systems in the various services to encourage efficient use and equitable sharing of the frequency spectrum and the geostationary satellite orbit.

Regulatory Procedures: The formal steps that countries must take to obtain international recognition for the assignment of frequencies to and the deployment of specific systems in certain services.

In the case of the six space services under consideration, WARC-79 did not make substantial changes either in the technical regulations or in the regulatory procedures applicable over the next few years. However, WARC-79 did adopt major changes in the frequency allocations for the FSS, ISS, and MSS, and did agree to hold a future World Administrative Radio Conference that could drastically change the way in which countries obtain frequencies and orbital positions for their space services. Indeed, this future WARC could formulate plans of orbital position and frequency allotments to countries for the FSS, MSS, and other space services that would be similar in principle to the Plan adopted in 1977 for the BSS in the 12-GHz band [3], [4]. In view of this, the major emphasis in the sections that follow will be on the changes to the Allocation Table for the selected space services and on the issues surrounding the future Space WARC.

² The other eleven satellite services are: Broadcasting, Earth Exploration, Space Research, Meteorological, Space Operation, Amateur, Radiodetermination, Radionavigation, Aeronautical Radionavigation, Maritime Radionavigation, and Standard Frequency and Time Signal.

³ Region 1 includes Europe, Africa, USSR, and Mongolia; Region 2 includes The Americas and Greenland; Region 3 includes Asia (except USSR and Mongolia), Australia, and the Southwest Pacific.

II. FREQUENCY ALLOCATIONS

A. Introduction

To provide a direct indication of the allocation actions taken by WARC-79, the pre-WARC and post-WARC allocations are shown side-by-side for the FSS, ISS, and MSS in Tables I-III, respectively. The Broadcasting-Satellite service (BSS) allocations are shown in Table IV for reference [5]. In these tables, all frequencies are in gigahertz (except megahertz in Table IV below 10 GHz) and the following abbreviations are used: 1: Region 1; 2: Region 2; 3: Region 3; n: not allocated; u: uplink; d: downlink; b: bidirectional; f: footnote allocation; (): secondary allocation; r: see footnote; t: TV only; c: community reception only; B: EPI beacon only; D: Distress/Safety only; C: Canada; N: Norway; S: Sweden;]: paired bands. Table Ic is provided to show the post-WARC-79 allocations to the FSS on a linear frequency scale with allocations to services sharing these bands also shown. In this table upper case indicates a primary allocation; lower case indicates a secondary allocation. The following abbreviations are used:

Abbreviation	Service
B	Broadcasting
F	Fixed (e.g., radio relay)
M	Mobile
MxA	Mobile, except Aeronautical Mobile
FS	Fixed-Satellite
IS	Inter-Satellite
BS	Broadcasting-Satellite
MS	Mobile-Satellite
MMS	Maritime-Mobile Satellite
AMS	Aeronautical-Mobile Satellite
EES(p)	Earth Exploration Satellite (passive)
RNS	Radionavigation Satellite
SFTSS	Standard Frequency and Time Signal Satellite
MetS	Meteorological Satellite
SR(ds)	Space Research (deep space)
SR(p)	Space Research (passive)
RA	Radio Astronomy
RL	Radiolocation (radar)
RN	Radionavigation (e.g., Loran-C)
↑	Earth-to-space (uplinks)
↓	Space-to-Earth (downlinks)
↑↓	Bidirectional
↔	Space-to-space

The pre-WARC allocations given in Part a of these tables are included not only as a basis for comparison with the revised allocations shown in Part b, but also because they will remain in effect until the Final Acts of WARC-79 come into force in January 1982.

In all of the tables, the allocated bands are listed in order of increasing frequency. The commonly used shorthand designation of certain bands is indicated to the left of the frequency range for the band, and any restrictions on the direction of transmission and/or the Regional extent of the allocation (if less than worldwide) are shown on the right side of the frequency range. The normal pairing of uplink (Earth-to-space) and downlink (space-to-Earth) bands is also indicated by square brackets on the right side of the frequency ranges.

Except for Table Ic, the allocation listings in the tables given

here do not show two features of great practical importance to the operational use of the bands: namely, the other services to which the bands are allocated and the text of the footnotes associated with certain bands in the complete Table of Allocations. The footnotes can specify additional or alternative allocations in particular countries and often impose a variety of restrictions on how the band in question is to be used by the authorized services (see [5, sec. III-B1]). For example, nearly every space service allocation below 40 GHz is shared with at least the terrestrial Fixed and Mobile services, and nearly all FSS downlink allocations below 11.7 GHz are subject to power flux density (pfd) limitations to protect these services.

The proposals for allocation changes submitted to WARC-79 showed that most nations recognized a need for substantial increases in the amount of spectrum allocated for use by commercial FSS systems in the vicinity of the present 6/4- and 14/11-GHz band pairs, for Maritime Mobile-Satellite systems in the neighborhood of 1.6 GHz and for domestic Broadcasting-Satellite and Fixed-Satellite systems in the 12-GHz band in Region 2. In addition, there was a widely recognized need to provide FSS uplink allocations on a dedicated basis for use with the 12-GHz BSS allotments in the 1977 WARC Plan for Regions 1 and 3 and for the corresponding Region 2 Plan that is to be developed at the 1983 Regional Administrative Radio Conference (RARC-83). The final decisions of WARC-79 on how to satisfy these needs for the space services in question are summarized below for each service in turn.

B. Fixed-Satellite Service

In comparing the post-WARC allocations to the FSS shown in Tables Ib and Ic with the pre-WARC allocations of Table Ia, the following changes are worthy of note:

1) *2500 MHz or "S"-band*: The band 2.535–2.690 GHz was newly allocated (in Region 2 only) to the FSS in the space-to-Earth direction in order to allow the existing S-band BSS allocation 2.5–2.69 GHz (see Table IVa) to be used optionally in the FSS; for example, to provide interactive return links in various public service broadcasting applications. The pfd limit on the FSS that previously applied in the 2.5–2.535-GHz band has been replaced by the existing BSS limit in order to facilitate the use of small Earth stations in FSS applications. Note that, above 2.655 GHz, the FSS allocation is bidirectional. Additional uplink frequencies for use with both FSS and BSS S-band downlinks are available in the 6.425–7.075-GHz extension to the pre-WARC 6-GHz FSS uplink band.

2) *6/4-GHz Bands*: In the case of the 6/4-GHz band pair, there was comparatively little disagreement, either on deletion of the unused pre-WARC 4.4–4.7-GHz uplink allocation or on how to augment the 6-GHz half of the band pair. Besides extending the upper band limit by 650 MHz, the pre-WARC Region 1 and 3 allocation, 5.85–5.925 GHz was made worldwide, and its utility in the FSS increased by reducing the Radiolocation service to secondary (noninterfering) status, thus yielding a contiguous worldwide uplink allocation of 1225-MHz bandwidth.

In contrast, final agreement on footnotes affecting the use of extensions to the 4-GHz band was not reached until the last week of the WARC. The controversy centered on the status of the Radiolocation service in the 3.4–3.6-GHz portion of

TABLE I
FIXED-SATELLITE SERVICE ALLOCATIONS

a. Pre-WARC			b. Post-WARC		
Band	Freq. Range	Restrict.	Band	Freq. Range	Restrict.
S	2.5–2.535	1n, 2d, 3d	S	2.5–2.535	1n, 2d, 3d
	2.655–2.690	1n, 2u, 3u		2.535–2.655	1n, 2d, 3n
	3.4–3.7	d		2.655–2.690	1n, 2b, 3u
4	3.7–4.2	d	4	3.4–4.2	d
	4.4–4.7	u		4.5–4.8	d
	5.725–5.85	1u, 2n, 3n		5.725–5.85	1u, 2n, 3n
6	5.85–5.925	1u, 2n, 3u	6	5.85–7.075	u
	5.925–6.425	u		7.25–7.75	d
	7.25–7.75	d		7.9–8.4	u
8	7.9–8.4	u	11	10.7–11.7	1b*, 2d, 3d
	10.95–11.2	1b, 2d, 3d		11.7–12.3	1n, 2d, 3n
	11.45–11.7	d		12.5–12.7	1b, 2n, 3d
12	11.7–12.2	1n, 2d, 3n	12	12.7–12.75	1b, 2u, 3d
	12.5–12.75	1b, 2u, 3d		12.75–13.25	u
	14.0–14.5	u	14	14.0–14.5	u
20	17.7–21.2	d		14.5–14.8	u*
	27.5–31.0	u		17.3–17.7	u*
30	40–41	d	20	17.7–18.1	b*
	50–51	u		18.1–21.2	d
	92–95	u		27.0–27.5	1n, 2u, 3u*
	102–105	d	30	27.5–31.0	u
	140–142	u		37.5–40.5	d
	150–152	d		42.5–43.5	u
	220–230	b		47.2–49.2	u*
	265–275	b		49.2–50.2	u
				50.4–51.4	u
				71–74	u
				74–75.5	u
				81–84	d
				92–95	u
				102–105	d
				149–154	d
				202–217	u
				231–241	d
				265–275	u

* uplink limited to BSS feeder links

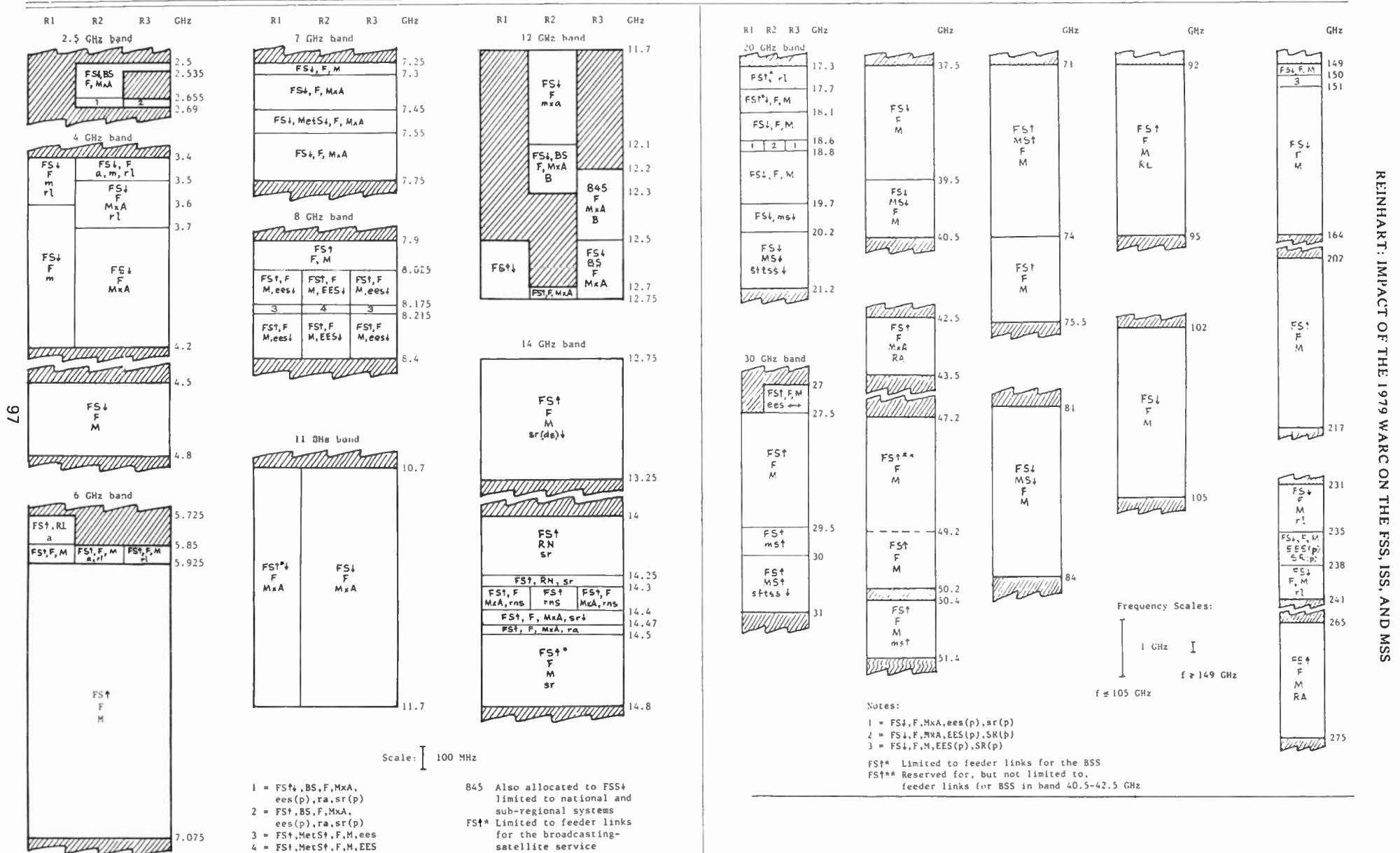
* intended for but not limited to BSS feeder links

the little-used 3.4–3.7-GHz pre-WARC downlink band and on the question of which countries would exclude the FSS from a new downlink band at 4.5–4.8 GHz. In the end, the Radiolocation service became secondary in the Table, but footnotes retained its primary status in Regions 2 and 3 and in certain European countries. The footnotes also urged that radiolocation operations cease by 1985 and that, thereafter, every practicable effort be made to protect the FSS which, in any case, would not be required to coordinate with the Radiolocation service.

Other footnotes excluded certain European countries from the 4.5–4.8-GHz band. However, a Declaration signed by these countries and by the USA, Canada, and Australia pledged that the signatories would not withhold support for INTELSAT's use of either band extension by reason of the footnote restrictions. The net result was a two-part worldwide downlink allocation of 1100-MHz bandwidth. The subband 3.4–3.6 GHz will not be fully available to the FSS for many years in the United States and certain other developed countries, and domestic coordination restrictions are likely to limit the use of both this subband and the 4.5–4.8-GHz part of the allocation to international applications in these countries. Nonetheless, the available bandwidth of the 6/4-GHz band pair was more than doubled in most countries of the world.

3) *8/7-GHz Bands*: The 8/7-GHz band pair, which is used principally for government FSS systems, was retained without change in band limits, but the formerly exclusive subbands at 7.25–7.3 and 7.975–8.025 GHz must now be shared with the

TABLE 1c
WARC-79 ALLOCATIONS TO THE FIXED-SATELLITE SERVICE



terrestrial Fixed and Mobile services and, by footnote, with the MSS (see Table IIIb).

4) *14/11-GHz Bands*: The bandwidth of the 14/11-GHz band pair was exactly doubled by adding new downlink allocations at 10.7-10.95 and 11.2-11.45 GHz and a new uplink allocation at 12.75-13.25 GHz. This created a contiguous downlink band, 10.7-11.7 GHz, and a split uplink band whose two 500-MHz parts are separated by 750 MHz. In the United States, it is expected that domestic coordination restrictions on the downlink band will limit applications to international systems.

5) *12-GHz Band*: In the 12-GHz band, both the upper limit of the 11.7-12.2-GHz FSS downlink allocation in Region 2 and the requirement that this allocation be shared with the BSS were changed. The upper limit was raised to 12.3 GHz, and the BSS allocation was expanded and shifted to the band 12.1-12.7 GHz. The resultant 200-MHz overlap between the FSS and the BSS allocations will remain only until 1983. Then the Region 2 Planning Conference (1983 RARC) will choose a frequency in the range 12.1-12.3 GHz that will become both the new upper limit of the FSS allocation and the new lower limit for the BSS allocation, thus totally eliminating any requirement for arc-segmentation between the two space services. It is expected that the dividing line will be set at 12.2 GHz so that, with the entire orbital arc available to both the FSS and the BSS, the total number of satellites that can be accommodated will be at least doubled in each service.

Another significant change in the FSS downlink allocation was a footnote permitting transponders on FSS space stations to be used for BSS TV transmissions up to a maximum equivalent isotropically radiated power (EIRP) of 53 dBW per channel, provided that these transmissions neither cause greater interference nor require more interference protection than the proposed to permit operational implementation of a satellite service now being tested experimentally in Canada on Anik B. A similar footnote to the 12-GHz Region 2 BSS allocation will permit Region 2 countries to use assignments to broadcasting-satellite stations under the Plan to be established by RARC-83 for transmissions in the FSS (space-to-Earth). Such use must not cause more interference nor require more interference protection than the BSS transmissions operating in accordance with the Plan.

6) *30/20-GHz Bands*: The frequency limits of the 30/20-GHz FSS band pair were not changed, but the exclusive status of the FSS allocation in the subbands 19.7-21.2 and 29.5-31 GHz was ended by a primary footnote allocation of the lower band to the terrestrial Fixed and Mobile services in some 46 developing countries and by allocation of the upper 1 GHz of each subband to the MSS (see Table IIIb).

7) *FSS Bands Above 35 GHz*: At frequencies above 35 GHz, there was a significant increase in the total amount of spectrum allocated to the FSS, as may be seen by comparing parts a and b of Table I. The amount of spectrum involved was increased from 32 to 71.5 GHz, but because each band is now restricted to a single direction of transmission, the amount available for a given direction is increased by only 11.5 GHz in the uplink direction and by 8 GHz in the downlink direction. The uplink band at 47.2-49.2 GHz is intended primarily for feeder links to broadcasting satellites in the band 40.5-42.5

TABLE II
INTER-SATELLITE SERVICE ALLOCATIONS

a. Pre-WARC			b. Post-WARC		
Freq.	Range	Bandwidth	Freq.	Range	Bandwidth
54.25-58.2		3.95	22.55-23.55		1
59-64		5	32-33		1
105-130		25	54.25-58.2		3.95
170-182		12	59-64		5
185-190		5	116-134		18
Total		50.95	170-182		12
			185-190		5
			Total		45.95

GHz, which accounts in part for the fact that the total bandwidth of uplink allocations is 3.5 GHz greater than that for downlink allocations. All allocations are worldwide and must now be shared with terrestrial services.

8) *BSS Feeder Link Bands*: Feeder links to broadcasting satellites must use allocations to the FSS (Earth-to-space). In principle, any of the uplink allocations shown in Table I may, with appropriate intersystem coordination, be used for such feeder links to broadcasting satellites using the BSS allocation shown in Table IV. In practice, however, use of a given FSS uplink band to provide feeder links to all of the broadcasting satellites in a Plan as extensive as that formulated for Regions 1 and 3 at WARC-77 would virtually preclude use of that band to match an FSS downlink band. Accordingly, the problem of which FSS uplink bands should be used for feeder links to 12-GHz broadcasting satellites in the existing Plan for Regions 1 and 3 and in the plan to be made in 1983 for Region 2, received a great deal of attention at WARC-79. As shown in Tables Ib and Ic, three FSS (Earth-to-space) allocations were designated specifically for and limited to this purpose: 10.7-11.7 GHz in Region 1 only, 14.5-14.8 GHz worldwide, except for the countries of Europe, and 17.3-18.1 GHz worldwide. All three of these bands will probably be used at the Region 1 and 3 uplink planning conference called for in a WARC-79 Resolution, but only the 17.3-18.1-GHz band is expected to be used in planning the BSS for Region 2 at RARC-83. For the BSS allocations at 23 and 42 GHz, WARC-79 indicated that the FSS uplink allocations at 27-27.5 and 47.2-49.2 GHz were to be preferred for feeder link use (see Table Ib).

C. Inter-Satellite Service

The pre- and post-WARC allocations to the ISS are displayed in Table II. The principal change is the addition of 1-GHz-wide bands for each direction of transmission at 23 and 33 GHz to permit the introduction of the service earlier and at lower cost than would be possible with the pre-WARC allocations above 50 GHz. Another change was a reduction of the bandwidth of the allocation around 120 GHz from 25 to 18 GHz, leading to a net reduction of 5 GHz in the total amount of spectrum allocated to the ISS. As with the above-35-GHz allocations to the FSS, all of the ISS allocations must now be shared with terrestrial services. This is not expected to be a problem with the ISS bands above 50 GHz which are coincident with atmospheric absorption bands, but sharing criteria may have to be imposed to avoid mutual interference with the Fixed, Mobile, and Broadcasting-Satellite services at 23 GHz and with the Radionavigation service at 33 GHz.

TABLE III
MOBILE-SATELLITE SERVICE ALLOCATIONS

a. Pre-WARC			
Land	Maritime	Aeronautical	Footnote
	240-328.6 bf		308A
	335.4-399.9 bf		308A
	406-406.1 urB		317A
	1535-1542.5 dr		352E
	1542.5-1543.5 dr		352F
		1543.5-1558.5 dr	352G
		1558.5-1636.5 bf	352B
	1636.5-1644 ur		352H
	1644-1645 ur		352I
		1645-1660 ur	352J
		5000-5250 bf	352B
		15.4-15.7 bf	352B
	43-48 b		
	66-71 b		
	95-101 b		
	142-150 b		
	190-200 b		
	250-265 b		

b. Post-WARC			
	121.45-121.55 uFB		3572A
	242.95-243.05 uFB		3572A
	235-322 bf		3618
	335.4-399.9 bf		3618
	405.5-406 uFC		3633A
	406-406.1 urB		3634
	406.1-410 uFC only		3633A
	(608-614 u) 2 only		3670B
	806-890 bf 2,3,N,S only		3662C
	942-960 bf 3,N,S only		3662CA
	1530-1544 dr		3695C
	1544-1545 drD		3695A
		1545-1559 d	
		1610-1626.5 bf	3687
	1626.5-1645.5 u		--
	1645.5-1646.5 urD		3695A
		1646.5-1660.5 u	--
		5000-5250 bf	3687
	7250-7375 df		3764B
	7900-8025 uf		3764B
	(14-14.5 uf)		3794B
		15.4-15.7 bf	3687
	(19.7-20.2 d)		--
	20.2-21.2 d		--
	(29.5-30 u)		--
	30-31 u		--
	39.5-40.5 d		--
	43.5-47 br		3814C
	(50.4-51.4 u)		--
	66-71 br		3814C
	71-74 u		--
	81-84 d		--
	95-100 br		3814C
	134-142 br		3814C
	190-200 br		3814C
	252-265 br		3814C

TABLE IV
BROADCASTING-SATELLITE SERVICE ALLOCATIONS

a. Pre-WARC			b. Post-WARC		
Band	Freq. Range	Restric.	Band	Freq. Range	Restric.
UHF	0.62-0.79	t	UHF	0.62-0.79	t
S	2.5-2.69	c	S	2.5-2.69	c
12	11.7-12.2		12	11.7-12.1	1,3 only
	12.2-12.5	1 only		12.1-12.2	
	22.5-23	3 only		12.2-12.5	1,2 only
	41-43			12.5-12.7	2,3 only
	84-86			12.7-12.75	3 only
				22.5-23	2,3 only
				40.5-42.5	
				84-86	

Mobile Satellite service. The primary application of these bands is expected to be in the Land-Mobile Satellite service.

The bands that are restricted to one or two of the component services are indicated in Tables IIIa and b by shading in the column for the excluded service. In the case of the Maritime- and Aeronautical-Mobile Satellite services, WARC-79 resulted in the readjustment of the allocations primarily to accommodate the growth and increased need for spectrum to serve maritime requirements while maintaining the existing 101.5-MHz separation between uplink and downlink bands. The existing 7.5-MHz allocations to the Maritime-Mobile Satellite service were increased to 19 MHz in the Earth-to-space direction and to 14 MHz in the space-to-Earth direction. The additional 5 MHz in the uplink direction is intended to accommodate the need for a unidirectional high-speed, wide-band data service. In order to accommodate the requirements of the Maritime service, it was necessary to slightly reduce the existing 15-MHz up- and downlink allocations to the Aeronautical-Mobile Satellite service to 14 MHz.

III. TECHNICAL REGULATIONS

A. Introduction

In the technical area, the Radio Regulations deal with the interaction between systems and, in particular, with the characteristics of systems and transmissions and the containment of intersystem interference.

Table V lists the Articles and Appendices pertaining to space services which have predominant or partial technical substance, as they appear in the Final Acts of WARC-79. Table VI lists Recommendations and Resolutions of primarily technical content, relating to future CCIR studies or actions by WARC-79.

B. Articles and Appendices

Detailed discussion of text changes and special provisions relating to these Articles is limited to the most significant changes affecting satellite systems.

*Article 27 (25; Formerly Article 7, Section VII):*⁴ This Article, relating to EIRP and pointing constraints for terrestrial radio-relay systems in bands shared with space services, has had two footnotes of significance added. The first provides for pos-

⁴ The first number is the definitive WARC-79 designation; the letters or numbers in parentheses are the interim designation used during WARC-79 itself.

D. Mobile-Satellite Service

As previously noted, the Mobile-Satellite service (MSS) includes the Land-Mobile Satellite service, the Maritime-Mobile Satellite service and the Aeronautical-Mobile Satellite service. Bands allocated to the MSS in general are shown in Tables IIIa and b as being available to all three of the component services. Many of these allocations appear in footnotes with the major change from the pre-WARC situation being additions at 7/8 and 30/20 GHz. Of particular interest are the bands 806-890 and 942-960 MHz, where a number of countries obtained an additional footnote allocation to permit use of these bands by the MSS, except for the Aeronautical-

TABLE V
TECHNICAL ARTICLES AND APPENDICES

Text Designation		Previous	Title of Text
Definitive	Interim		
Article			
1	1	1	Terms and Definitions.
2	2	2/III	Nomenclature of the Frequency and Wavelength used in Radiocommunications.
3	4	2/I, II	Designation of Emissions.
4	5	12	Technical Characteristics.
16	18	14/Exc. IV	Interference.
17	19	14/IV	Tests.
25	27	7/VII	Terrestrial Radiocommunication Services sharing Frequency Bands with Radiocommunication Services above 1 GHz.
26	28	7/VIII	Space Radiocommunication Services Sharing Frequency Bands with Terrestrial Radiocommunication Services above 1 GHz.
27	29	7/IX	Special Rules Relating to Space Radiocommunication Services.
Appendix			
3	7	3	Table of Transmitter Frequency Tolerances.
4	8	4	Table of Maximum Permitted Spurious Emission Power Levels.
5	6	5	Additional Characteristics for the Classification of Emissions; Determination of Necessary Bandwidths Including Examples for their Calculation and Associated Examples for the Designation of Emissions.
28	28	28	Method for the Determination of the Coordination Area Around an Earth Station in Frequency Bands between Space and Terrestrial Radiocommunication Services.
29	29	29	Method of Calculation for Determining if Coordination is Required between Geostationary Satellite Networks Sharing the same Frequency Bands.
1A	3	1A	Notices relating to Space Radiocommunications and Radio Astronomy Stations.
1B	4	1B	Advance Publication Information to be Furnished for a Satellite Network.

TABLE VI
TECHNICAL RESOLUTIONS AND RECOMMENDATIONS

Designation		Title
Definite	Interim	
Resolutions		
60	AJ	Relating to Information on the Propagation of Radio Waves used in the Determination of the Coordination Area.
506	AP	Relating to the Use, by Space Stations Operating in the 12-GHz Frequency Bands Allocated to the Broadcasting-Satellite Service, of the Geostationary Orbit and No Other.
61	BK	Relating to the Division of the World into Climatic Zones for the Purpose of Calculation of Propagation Parameters.
Recommendations		
68	E	Relating to Studies and Prediction of Radio Propagation and Radio Noise.
73	J	Relating to the Use of the Term "Channel" in the Radio Regulations.
62	K	Supplementing the Additional Characteristics for Classifying Emissions and Providing Additional Examples for the Full Designation of Emissions. Both as Given in Appendix 5.
66	L	Relating to Studies of the Maximum Permitted Levels of Spurious Emissions.
63	M	Relating to the Provision of Formulae and Examples for the Calculation of Necessary Bandwidths.
709	O	Relating to Sharing Frequency Bands between the Aeronautical Mobile Service and the Inter-Satellite Service.
69	P	Relating to the Frequency Tolerance of Transmitters.
705	T	Relating to the Criteria to be applied for Frequency Sharing between the Broadcasting-Satellite Service and the Terrestrial Broadcasting Service in the Band 620-790 MHz.
712	U	Relating to the Interdependence of Receiver Design, Channel Grouping, and Sharing Criteria in the Broadcasting-Satellite Service.
403	V	Relating to the Development of Techniques which would help to Reduce Congestion in High Frequency Bands Allocated to the Aeronautical (R) Service.
102	X	Relating to the Study of Modulation Methods for Radio-Relay Systems in Relation to Sharing with Fixed-Satellite Service Systems.
405	Y	Relating to a Study of the Utilization of the Aeronautical Mobile-Satellite (R) Service.
707	YV	Relating to the Use of the Frequency Band 32-33 GHz Shared between the Inter-Satellite and Radionavigation Service.
706	YW	Relating to Frequency Sharing by the Earth Exploration-Satellite Service (Passive Sensors) and the Space Research Service (Passive Sensors) and the Fixed, Mobile (except Aeronautical Mobile) and Fixed-Satellite Services in the Band 18.6-18.86 GHz.
711	Z	Relating to the Coordination of Earth Stations.
103	ZA	Relating to Carrier Energy Dispersal in Systems in the Fixed-Satellite Service.
506	ZC	Relating to the Harmonics of the Fundamental Frequency of Broadcasting-Satellite Stations.
508	ZD	Relating to Transmitting Antennae for the Broadcasting-Satellite Service.
101	ZE	Relating to Feeder Links for the Broadcasting-Satellite Service.
507	ZF	Relating to Spurious Emissions in the Broadcasting-Satellite Service.
505	ZL	Relating to Studies of Propagation at 12 GHz for the Broadcasting-Satellite Service.
65	ZM	Relating to the Technology for New Spectrum Sharing and Band Utilization Schemes.
708	ZQ	Relating to Frequency Bands shared between Space Radiocommunication Services and between Space and Terrestrial Radiocommunication Services.
72	ZR	Relating to Terminology.

sible EIRP/pointing constraints in frequency bands above 15 GHz as the result of future CCIR action. The second, which provides for inter-Regional adherence to EIRP/pointing constraints for the case in which different Regions have different allocations, is also subject to future CCIR action.

As a result of allocation actions at WARC-79, the paragraphs listing the frequency bands to which the provisions of Article 25 apply have been changed. Noteworthy are the protection extended to the Maritime- and Aeronautical-Mobile Satellite services (1.625-1.66 GHz) against primary Fixed service footnote allocations, the protection afforded the bi-directionally allocated FSS in the bands 10.7-11.7 and 12.5-12.75 GHz, and the protection of the allocation 14.5-14.8 GHz, earmarked for broadcasting-satellite feeder links.

Article 28 (26; Formerly Article 7, Section VIII): This Article deals with emission constraints on space communications systems in bands shared with terrestrial services. Limits are placed on Earth station EIRP in the horizontal plane, on minimum Earth station main beam elevation angle, and on power-flux density due to emissions from space stations. Changes include an inter-Regional footnote of the kind mentioned in the preceding paragraph, and the addition of the frequency range 31-40.5 GHz to the power-flux density section.

Present limiting values were retained, but various space services and frequency bands were added to those to which the provisions applied previously, in accordance with the new Table of Frequency Allocations and its various footnote provisions.

In the band 2.5-2.69 GHz, the power-flux density for the FSS was aligned with that already in existence for the BSS, providing relief for the FSS. No power-flux density penalty was imposed in bidirectionally allocated frequency bands which are also shared with terrestrial services.

Article 29 (27; Formerly Article 7, Section IX): The section relating to control of interference between geostationary space systems formerly gave precedence to any geostationary system over nongeostationary systems in the FSS. It now gives precedence to geostationary fixed-satellite systems over any nongeostationary space system. A special provision was added by which geostationary fixed-satellite systems have precedence over geostationary systems in the Earth Exploration-Satellite service with links to nongeostationary space stations.

The section on longitudinal stationkeeping of geostationary space stations now imposes on the FSS a capability requirement of $\pm 0.1^\circ$ and on other services (excluding the BSS in the band 11.7-12.7 GHz) a capability requirement of $\pm 0.5^\circ$. Space stations in the BSS in the band 11.7-12.7 GHz are subject to the provisions of the new Appendix 30 (29A), which were transferred from the Final Acts of WARC-77.

A "prior rights" provision for "old" satellites (put into service prior to January 1, 1987, and advance-notified prior to January 1, 1982) was added.

In the satellite antenna pointing section, the minimum pointing tolerance was tightened to 0.3° , with an exemption added for broadcasting satellites in the band 11.7-12.7 GHz. Article 29 (27) also contains a provision aimed at minimizing Earth station transmitted out-of-beam EIRP density in the direction of the geostationary orbit.

Appendix 7 (3): The table of transmitter frequency tolerances applicable to space services is shown below:

Frequency Range	Transmitter Frequency Tolerance Relative to Carrier Frequency	
	Space Stations	Earth Stations
4.0 MHz-2.45 GHz	2×10^{-5}	2×10^{-5}
2.45 GHz-10.5 GHz	5×10^{-5}	5×10^{-5}
10.5 GHz-40 GHz	1×10^{-4}	1×10^{-4}

These tolerances apply to new transmitters installed after January 1, 1985, and to all transmitters after January 1, 1990.

Appendix 8 (4): This Appendix provides footnotes specifying maximum permitted spurious emission levels for transmitters, as well as a general table giving permitted levels either by frequency range or by mean (carrier) power level. Spurious emissions include by definition harmonic and parasitic emissions, intermodulation products, and frequency-conversion products, but exclude out-of-band emissions, i.e., spectral components resulting from a modulation process.

Stations in the space services are exempt from the quantitative provisions of Appendix 4 but are exhorted to minimize their levels of spurious emission.

Appendix 28 (28): Appendix 28, which provides for the determination of coordination areas around an Earth station with respect to radio-relay systems operating in the same frequency band, has been substantively changed to reflect up-to-date CCIR documentation as well as changes to the Table of Allocations.

A provision was adopted which allows the coordination area for a receiving Earth station to be smaller than that resulting from the use of values tabulated for that purpose, subject to case-by-case justification. A regulatory provision for the operation of mobile Earth stations was added, outlining a method for determining a coordination area which would protect a service area rather than a single service location. Such protection would allow users of mobile Earth stations to operate anywhere within the service area, subject to successful prior coordination.

Annex I to Appendix 28 reflects an extension of Earth station antenna reference patterns to regions near the main beam including the first sidelobe. Users of antennas with $D/\lambda < 100$ are asked to comply with the reference pattern for $D/\lambda \geq 100$, which is somewhat more stringent.

The auxiliary coordination contours are the subject of a new Annex III. Auxiliary coordination contours may be used by Administrations to resolve certain cases of potential interference without recourse to detailed coordination calculations.

Appendix 29 (29): This Appendix deals with a method for determining whether frequency coordination is required between two geostationary space networks using the same frequency bands. The basic method of the pre-WARC Appendix 29 has been retained, with certain amendments and additions. The most significant amendment changes the "threshold" fractional increase in noise temperature from 2 to 4 percent, while others deal with bidirectional allocations and discretionary polarization isolation provisions.

Revised reference antenna patterns for Earth stations, identical to those adopted in Appendix 28, were also incorporated in Appendix 29.

Appendices 3 (1A) and 4 (1B): These two Appendices con-

TABLE VII
SUMMARY OF WARC-79 ISSUES AFFECTING THE FIXED-SATELLITE SERVICE (FSS)

Issue	WARC-79 Action	Impact
Extend FSS allocation at 2.5 GHz to match BSS allocation and PFD limit	Done in Region 2	Permits greater flexibility in social service applications: small earth stations, interactive links, etc.
Extend existing 6/4-GHz bands and provide additional uplink bandwidth for 2.5 GHz FSS and BSS allocations	Bandwidth more than doubled but with footnote restrictions	Provides capacity for continued growth in requirements, but new bands limited to international service and not fully available in USA and some other countries.
Extend existing 14/11-GHz bands	Bandwidth doubled	Provides capacity for continued growth, but new bands primarily for international service in USA.
Provide more orbit/spectrum for Region 2 FSS at 12 GHz and preclude FSS plan at RARC-83	FSS: 11.7-12.2 → 11.7-12.3 GHz BSS: 11.7-12.1 → 12.1-12.7 GHz RARC-83 to eliminate BSS/FSS overlap and not plan FSS Footnotes permit limited use of FSS satellites for BSS transmissions and vice versa	Provides about three times pre-WARC-79 capacity for future growth of Region 2 FSS DOMSAT's and greater flexibility of use.
Provide more bandwidth above 40 GHz	Total bandwidth more than doubled (32 to 71.5 GHz) but all shared with terrestrial services	Provides even greater capacity for future government and commercial systems after 30/20-GHz band becomes saturated.
Guarantee equitable access to geostationary orbit	Schedule two-session WARC in 1984, 1985	Raises possibility of worldwide or Regional planning of all space services and all bands.

tain significant amendments particularly as they relate to Appendix 29. Appendix 3 (1A) list information to be used as a basis for calculations under Appendices 28 and 29, for coordination between Administrations, and, ultimately, to be submitted for frequency registration by the International Frequency Registration Board (IFRB). Appendix 4 (1B) lists information to be submitted for the advance notification of a space network; such notification is to be the basis for comments by concerned or affected Administrations.

C. Resolutions and Recommendations

WARC-79 generated a large number of Resolutions and Recommendations calling for future action, either to provide lacking information or to test and implement new concepts. Some of these Resolutions and Recommendations were directly aimed at the perceived needs of nonindustrialized nations.

Among the Resolutions and Recommendations of primarily technical content listed in Table VII, several deserve a few comments:

Resolution 60 (AJ): This Resolution establishes a mechanism for remedying shortcomings of the Appendix 28 propagation model and for introducing new propagation data with a minimum of delay, if desirable. It calls for continuous updating of the relevant material by the CCIR. If a CCIR Plenary Assembly concludes that a revision of Appendix 28 is justified, the relevant amendments proposed by the CCIR will be placed, as an extraordinary item, on the agenda of the next WARC.

Resolution 61 (BK): This Resolution calls for intensified studies, by Administrations, and by the CCIR, of propagation above 1 GHz in remote and, so far, relatively unexplored areas of the world, with special emphasis on the effects of sand and dust storms and on the development of a sufficient number of representative "propagation-climatic geographic zones."

Recommendation 66 (L): Space services, which are exempt

from the spurious emission provisions of Appendix 4, are nevertheless perceived as ultimately requiring such bounds in the interest of improved spectrum utilization. Recommendation 66 (L) calls for the urgent study of necessary and acceptable spurious emission bounds above 960 MHz.

Recommendation 705 (T): This Recommendation deals with sharing between the BBS and the Broadcasting service in the frequency band 620-790 MHz. It imposes a provisional pfd limit on broadcasting satellite emissions and calls upon the CCIR for further studies relating to sharing between the two subject services.

Recommendations 712 (U), 506 (ZC), 508 (ZD), 101 (ZE), 507 (ZF), and 505 (ZL): This is a set of Recommendations aimed at the entire field of designing, coordinating, and operating BSS's around 12 GHz. Subsequent to the development of the WARC-77 Region 1 and 3 Plan, there were questions relating to the validity of the assumptions used, and to the planning of uplinks, which had not been undertaken at all at WARC-77. Moreover, since both up- and downlinks need to be considered at RARC-83, Region 2 felt a particular urgency for solving all relevant technical problems prior to that date.

Recommendation 102 (X), 711 (Z), 65 (ZM), and 708 (ZQ): This set of Recommendations is aimed at advancing methods and means by which frequency sharing between space and terrestrial services might be enhanced and assessed.

Recommendation 709 (O): This Recommendation requests the CCIR to carry out studies of sharing between the ISS and the Aeronautical-Mobile service pursuant to allocations at WARC-79 in bands above 40 GHz.

Recommendation 707 (YV): As above, this Recommendation relates to sharing between the ISS and the Radionavigation service in the band 32-33 GHz.

Recommendation 706 (YW): As above, this Recommendation relates to sharing of services using passive spaceborne sensors with the Fixed and Mobile, and the FSS in the band 18.6-18.8 GHz.

TABLE VIII
SUMMARY OF WARC-79 ISSUES AFFECTING THE MOBILE-SATELLITE SERVICES (MSS)

Issue	WARC-79 Action	Impact
Extend existing 1.6-GHz Maritime-Mobile Satellite allocations	Uplink 7.5 → 19 MHz; downlink 7.5 → 14 MHz; aeromobile satellite unchanged	Provides spectrum needed for future growth of maritime-mobile satellites using pre-WARC-79 translation frequency.
Provide spectrum for Land-Mobile Satellite service	Bidirectional footnote; allocations 806-890 MHz and 942-960 MHz in Regions 2, 3, Norway, Sweden	Permits development of Land-Mobile Satellite applications.
Provide mobile satellite allocation in government FSS bands	New 125-MHz bandwidth in 8/7-GHz bands and 1-GHz bandwidth in 30/20-GHz bands	Permits use of mobile and transportable Earth stations in government FSS networks.

IV. REGULATORY PROCEDURES

A. Coordination Procedures

The regulatory procedures for the advance publication, coordination, notification, and registration of space radio-communication services are given in Articles 11 (11) and 13 (13) and underwent only minor changes in three areas:

a) The time periods in which Administrations are to examine the advance publication information on new space radio-communication networks and the requests for coordination between networks or between Earth stations and terrestrial stations.

b) The requirement to submit, for publication, additional reports to the IFRB on the progress in resolving problems in the advance publication and coordination states of implementing a space radiocommunication network.

c) Clarification of various provisions to reflect current practices in the Regulations.

The provisions dealing with the coordination and notification of terrestrial stations in bands shared with the space services underwent similar changes.

A new Article 14 (13A) was adopted introducing a procedure to be followed when a footnote to the Table of Frequency Allocations requires the agreement of another Administration whose services may be affected.

The provisions dealing with the notification and registration of terrestrial services were revised although the concept remains basically unchanged. Many of the existing provisions were revised to clarify and highlight them. For example, the IFRB is to select frequency assignments of countries in need of special assistance. To assist in identifying the source of interference to stations of countries in need of special assistance, and to review Master Register entries which received unfavorable findings so that these entries may be upgraded when the assignments have not caused harmful interference.

To maintain the accuracy of the Master Register, provisions were adopted whereby the IFRB is to periodically review each section by sending to each Administration extracts of its entries for review and necessary revision.

B. Future Planning Conferences

As just noted, the regulatory procedures for the advance publication, coordination, and registration that govern the establishment of new satellite communication systems were

maintained in essentially their pre-WARC form. The principal effect of the rearrangement of the texts adopted at WARC-77 and the changes adopted at WARC-79 was to clarify and somewhat to simplify the procedures. Nonetheless, there was a widespread fear among the developing countries that these procedures would ultimately lead to a situation where certain segments of the geostationary orbit would become so crowded that future systems would be unable to find suitable frequencies and orbital positions.

In response to this fear, a number of countries (India, China, USSR, Iraq, Afghanistan) proposed that a future WARC be convened to plan certain space services in certain parts of the spectrum. However, there was no agreement among them as to which services or bands should be planned. For example, China proposed that only the new allocations to the FSS below 10 GHz should be planned, whereas India proposed that the FSS, including feeder links to the BSS, should be planned in the entire 4/6- and 11/14-GHz bands. The USSR proposal was the most modest, with planning confined only to BSS feeder links. The Iraq proposal was the most ambitious, embracing all space services in all frequency bands.

All of the planning proposals were in agreement that planning should lead to a detailed plan of orbital position and frequency allotments to countries in the fashion of the WARC-77 Plan for the BSS. Nearly all of the proposals justified the need for a plan on the claims that the geostationary satellite orbit was rapidly filling up in the 4/6-GHz band and that the present regulatory procedures, characterized as "first come, first served," would deny equitable access to developing countries in the future.

The developed countries denied these claims, and presented arguments to show that detailed planning was, in their view, totally unsuitable for most space services and especially so for the FSS. They suggested that improvements in the regulatory procedures and/or new dynamic and flexible approaches to planning could be developed to meet the objective of guaranteeing equitable access to all countries. Equally important, these approaches would permit the efficient and economical use of the orbit-spectrum resource that is essential if a sufficient amount of the resource is to be accessible to each user at an affordable price.

After extended debate in the Regulatory Procedure Committee at WARC-79, Resolution 3(BP) was adopted to hold a Space WARC whose principal goal was to guarantee equitable

access to all countries and groups of countries. The Conference would take place in two sessions, with the first session slated for about 1984 and the second session a year to a year-and-a-half later. The first session would decide which, if any, services and frequency bands should be planned, and would be free to decide on the principles of planning to be employed in each case, as well as the criteria and technical parameters for the planning. In the process of deciding where planning may be appropriate, other approaches to meeting the goal of equitable access would be considered, including improved regulatory procedures. The second session of the conference would then carry out the decisions of the first session.

Further details about WARC-84/85 will be found in a different paper in this issue [6].

V. SUMMARY

The key issues at WARC-79 affecting the FSS and the MSS are summarized in Tables VII and VIII, respectively. The tables identify the issues and summarize the actions taken and the potential impact on the services.

ACKNOWLEDGMENT

The material presented in this paper borrows heavily from a Conference presentation [7] by the author and from a joint paper [8] by the author and his colleagues at the Communications Satellite Corporation. In particular, the description of the technical regulations in Section III and of the coordination

procedures in Section IV-A is entirely the work of Hans J. Weiss, who was a member of the U.S. Delegation to WARC-79 and an active participant in the work of the Technical Committee at the Conference.

REFERENCES

- [1] ITU, *Final Acts of the World Administrative Radio Conference, Geneva, 1979*. Geneva, Switzerland: International Telecommunication Union, 1980.
- [2] ITU, *Final Acts, World Administrative Radio Conference on Space Telecommunications*. Geneva, Switzerland: International Communication Union, 1971.
- [3] ITU, *Final Acts, World Administrative Radio Conference for the Planning of the Broadcasting-Satellite Service in the Frequency Bands 11.7–12.2 GHz (in Regions 2 and 3) and 11.7–12.5 GHz (in Region 1)*. Geneva, Switzerland: International Telecommunication Union, 1977.
- [4] R. G. Gould and E. E. Reinhart, "The 1977 WARC on Broadcasting Satellites: Spectrum management aspects and implications," *IEEE Trans. Electromag. Compat.*, vol. EMC-19, no. 3, pt. II, pp. 171–178, Aug. 1977.
- [5] E. E. Reinhart *et al.*, "The impact of WARC-79 on the Broadcasting Satellite Service," this issue, pp. 273–289.
- [6] F. Urbany, "Future ITU radio conferences," this issue, pp. 322–326.
- [7] E. E. Reinhart, "Impact of the 1979 WARC on certain space communications services," in *Conf. Rec., IEEE Int. Conf. on Communications* (Seattle, WA, June 8–12, 1980), vol. 1, pp. 7.6.1–7.6.5.
- [8] C. Dorian, J. B. Potts, E. E. Reinhart, and H. J. Weiss, "The 1979 World Administrative Radio Conference and Satellite Communications," *Comsat Tech. Rev.*, vol. 10, no. 1, pp. 1–26, Spring 1980.

The Effect of WARC-79 on Efficient Use of the Geostationary Satellite Orbit

DAVID WITHERS

Abstract—The Fixed-Satellite and Broadcasting-Satellite services will make heavy use of the geostationary satellite orbit, and efficient use of orbit is a matter of importance in both services. WARC-79 will have direct and indirect impact on orbit utilization efficiency in both services. Of the direct effects, the tightening of certain technical requirements in the ITU Radio Regulations and the designation of specific frequency bands for broadcasting satellite feeder links are the most important. Indirectly, however, it can be foreseen that the pressure for equitable access to the orbit for all countries, which found concrete expression in a resolution to hold a further WARC around 1984/1985,¹ will have a much greater effect on orbit utilization efficiency by providing a strong stimulus for improvement in network characteristics, particularly in the Fixed-Satellite service.

I. INTRODUCTION

THE International Telecommunication Union (ITU) defines 17 different space radio services. Any of them could use geostationary satellites and all of them will probably do so in time. The outcome of the World Administrative Radio

Conference, 1979 (WARC-79) will affect them all to some degree. However, in their very different ways, it is the Fixed-Satellite and the Broadcasting-Satellite services which raise problems of efficiency now in their use of the geostationary satellite orbit, and it is on these services that this paper concentrates.

Section III below reviews the outcome of WARC-79 in as far as it can be expected to affect directly the efficiency of utilization of the geostationary orbit. More important than these direct effects will be the stimulus to increased efficiency that will be generated by another world administrative radio conference which WARC-79 set up, to be held in 1984/1985. The possible course of that process of stimulation is considered in Section IV. However, it may be useful to look first at the reasons why the orbit utilization which is currently foreseeable is less efficient than it might be, and Section II provides a brief survey of these factors.

II. SOURCES OF INEFFICIENCY IN ORBIT UTILIZATION

On an ideal planet, the stationary satellite orbit would be utilized rationally by systems with optimum parameters; its capacity would be enormous. In the more interesting world

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¹ Note added in proof: Now scheduled for 1985 and 1987 by action of the ITU's Administrative Council, June, 1981.

we live in,

a balance has to be found between the varying demands of over 150 nations for both domestic and international satellite services;

operational requirements and technical options only a few years ahead are often rather unpredictable;

spectrum has to be shared between space and terrestrial services, and sharing places constraints on both;

competition from terrestrial networks places economic constraints on space systems.

However, even accepting these limitations of the real world, the number of satellites that will be able to use the geostationary orbit could be greatly increased by changes in present practices.

If the orbit is not used for such noncommunications purposes as solar power satellites, the use that can be made of it for communication satellites will be limited by interference between communications networks using the same frequency bands. The minimum acceptable angular separation between satellites and the feasibility of admitting new satellites to the orbit without excessive interference will be influenced by the following main factors:

a) Satellite east-west movement. Prior to WARC-79, the east-west station-keeping tolerance imposed by the ITU Radio Regulations was $\pm 1^\circ$; this wastes orbit.

b) Earth station antenna off-beam radiation level and sensitivity to interference. Two main aspects arise, the side-lobe response of the antenna and the design of the network as a whole, including, for example, the forward gain of the Earth station and satellite antennas.

c) Satellite antenna radiation level and sensitivity as seen at places on Earth outside the required service area. Satellite attitude control tolerance is clearly one aspect of this factor.

d) Permitted internetwork interference level. The International Radio Consultative Committee (CCIR) recommends that this interference level should be as measured in working communication channels; typically, the current recommendations say that total interference noise should not exceed 20 percent of the channel noise from all sources under normal operating conditions.

e) Transmission techniques. The choice of modulation method and the multiple-access method which is adopted will determine the spectral distribution of interference energy and the spectral pattern of sensitivity to interference. Uniformity in spectrum goes with minimum satellite separations.

f) Homogeneity. The more uniform the characteristics of the networks of adjacent satellites sharing a frequency band are, the less will be the minimum necessary separation between them.

g) Internetwork coordination. Collaboration between the organizations operating satellite networks can lead to adjustments of network characteristics to minimize incompatibilities. Harmonization of the frequency plans in frequency-division multiple access system can also be used with considerable effect to reduce the minimum spacing required between satellites, although this may lead to a disadvantageous rigidity of the facilities available with each network. Flex-

ibility as to the location of satellites in orbit will be a very important factor in providing orbital places for new networks. Efficient coordination is more difficult to achieve when a satellite uses several frequency bands, since the best satellite location may be different in each band.

h) A disciplined and systematic use of frequency bands is necessary if the maximum use is to be obtained from the spectrum.

Concern for these factors involves effort, technical difficulty, and cost, but that is the price of adequate total usable capacity in the geostationary orbit.

III. THE DIRECT IMPACT OF WARC-79 DECISIONS ON ORBIT UTILIZATION EFFICIENCY

A. Technical Standards

It is mainly through the CCIR rather than the Radio Regulations that the ITU exercises its detailed influence over technical standards used in radio systems, but such standards have greater international authority when, having been approved by an administrative radio conference, they are included in the Radio Regulations. WARC-79 modified two technical standards as follows:

a) Subject to various exemptions, the east-west station-keeping tolerance for all satellites making use of frequencies allocated to the Fixed-Satellite and Broadcasting-Satellite services was tightened from $\pm 1.0^\circ$ to $\pm 0.1^\circ$ relative to the nominal position [1]. In addition, 12-GHz broadcasting satellites were required to have their orbital inclination limited to 0.1° [2].

b) The error in the pointing direction of satellite beams, relative to nominal, was required to be kept within 10 percent of the half-power beamwidth or 0.3° , whichever is less [3]. The previous tolerance was 10 percent of beamwidth or 0.5° , whichever was less. Exceptionally, the tighter tolerances required of broadcasting satellites operating at 12 GHz by the WARC in 1977 (namely 0.1° regardless of beamwidth [4]) were embodied in the Radio Regulations for those satellites.

The effect on orbit utilization efficiency of this change in station-keeping tolerance should be substantial. The benefit for the Fixed-Satellite service from the beam-pointing tolerance change may not be great until many more high-gain high performance satellite antennas are in use, but undoubtedly the adoption of stringent conditions for beam-pointing and out-of-beam radiation at the Broadcasting-Satellite WARC in 1977 was one of the factors that allowed a high yield of usable channels to be obtained in the plans produced at that conference.

B. Additional Allocated Bandwidth

The bandwidth allocated for the Fixed-Satellite service was increased in several parts of the spectrum [5]. Thus the bandwidth at 6 and 4 GHz was increased effectively to 1100 MHz in each direction of transmission. Some sharing problems remain in the new bands at 4 GHz but these are not likely to diminish seriously the value of the additional bandwidth in the long term. A further 500 MHz for each direction was added for the Fixed-Satellite service at 13 and 11 GHz.

In ITU Region 2 (North and South America), an additional 500 MHz was allocated jointly for satellite broadcasting and

fixed-satellite downlinks near 12.5 GHz, making 1000 MHz there in total, and prepared the way for rationalization of the use of this bandwidth by the two services. In addition, a new satellite broadcasting band was allocated for that region at 22.5-23.0 GHz.

In ITU Region 3 (Australasia, and Asia east of the Persian Gulf, but excluding USSR) an additional band was allocated for the Fixed-Satellite services at 12.2-12.5 GHz, and the Broadcasting-Satellite service was added to an existing Fixed-Satellite allocation at 12.5-12.75 GHz.

This additional spectrum allocated by WARC-79 for these busy services will clearly permit heavier use of the geostationary orbit, in proportion to the expansion of bandwidth. It will not in itself provide for more efficient use. However, the creation of new fixed-satellite bands with no satellite networks already using them offers the possibility of action to reduce inhomogeneity of band utilization through specialization of application. For example, a preference might be established by international agreement for using the new frequency bands for networks using high power flux density and for using the old bands for low power flux density networks. If this opportunity is grasped, an improvement in efficiency of orbit utilization should eventually follow.

C. Broadcasting-Satellite Feeder Link Bands

The WARC in 1971 allocated 11.7-12.5 GHz for satellite broadcasting in Region 1 (Africa, Europe, USSR-in-Asia, and the Middle East west of the Persian Gulf). In Region 3, the allocation was 11.7-12.2 GHz and in Region 2 the same band was shared by satellite broadcasting and fixed-satellite downlinks. The uplinks to broadcasting satellites, now called feeder links, are part of the Fixed-Satellite service. WARC-71 made no special allocation for feeder links serving these broadcasting-satellite bands and there has been an alarming possibility that the usefulness of a part of fixed-satellite frequency bands, probably the 14- and 11-GHz bands, would be gravely diminished by an invasion of the uplink band by assignments for broadcasting-satellite feeder links. Fixed-Satellite networks might be totally excluded from a pair of bands by the use of the uplink band for a feeder link frequency allotment plan to match a satellite broadcasting allotment plan like the one agreed at the WARC in 1977.

WARC-79 went far to solving the problem by allocating additional fixed-satellite uplink bands specifically for broadcasting satellite feeder links [6]. The situation is complicated, but it is sufficient for the present purpose to say that ample additional uplink bandwidth has been allocated at 11, 15, and 18 GHz to provide for feeders for all the 12-GHz broadcasting-satellite facilities. In addition, there is enough fixed-satellite uplink bandwidth allocated at 7, 15, 18, 27, and 48 GHz in excess of the corresponding fixed-satellite downlink bandwidth to provide for feeders for broadcasting satellites operating in the 2.6-, 23-, and 41-GHz bands.

D. Equitable Access to the Geostationary Orbit

Under the existing ITU Radio Regulations, a new fixed-satellite network is coordinated with already-established net-

works and planned new networks for which formal notification has already been provided to ITU before it is admitted to the International Frequency List, thus obtaining international recognition [7]. This process usually takes the form of a series of bilateral discussions between the managers of the new network and the managers of other networks using the same frequency bands and the same part of the orbit. These discussions have the purpose of determining whether interference from either network as envisaged to the other will exceed acceptable levels, and if so, to agree what should be changed in the networks to reduce the interference sufficiently. In accommodating newcomers, much may depend upon the good will of the negotiators in adjusting system plans and parameters to facilitate coordination.

A major concern of many delegations at WARC-79 was to amend the procedures regulating access to orbit and spectrum to ensure that all countries wishing to use space for communication would be able to do so on an equitable basis. Some delegations locked on the Fixed-Satellite service in the same light as the Broadcasting-Satellite service, and would have welcomed the establishment of orbit-spectrum allotment procedures for both services. Other delegations drew a distinction between these two services. WARC-77 had drawn up satisfactory plans for satellite broadcasting at 12 GHz in Regions 1 and 3; this had been feasible because orbit/spectrum allotments could be associated with specific and substantially unchanging requirements, geographical and technical. These latter delegations considered that the Fixed-Satellite service differed from this pattern in many significant ways, for example:

- 1) Some networks are national, others international, even global.
- 2) The technical characteristics of networks often vary greatly across the spectrum and differ markedly from those of other networks with which they may interfere.
- 3) The coverage, the traffic flows, and the technical characteristics of networks change from year to year, sometimes in fundamental though unpredictable ways.

The allotment of orbit/spectrum on a national basis would be appropriate for only some networks, and these latter delegations considered that the impossibility of forecasting requirements and technology accurately would make inefficient the application of this technique even to those networks.

No solution to the problem of equitable access to orbit/spectrum was agreed on at WARC-79, but a Resolution was adopted, setting up another WARC by 1984 which would have as its task the finding of a solution to that problem [8]. It has since been decided that the first session of this WARC will start in March 1984, to decide which space services should be planned, and how, and what other procedures might be used to achieve equitable access. The second session would start in November 1985, to implement the decisions made at the first session.

This forthcoming WARC could have great influence, good or bad, on the efficiency with which the geostationary orbit is utilized for space services, particularly for the Fixed-Satellite service.

IV. THE INDIRECT IMPACT OF WARC-79 ON ORBIT UTILIZATION EFFICIENCY, THROUGH WARC-1984/1985

A. A Stimulus for Technical Improvements

Whatever the outcome of WARC-1984/1985, users of the Fixed-Satellite service have been put very clearly on notice of the need to utilize the geostationary orbit efficiently, so that there is enough capacity for all. Much could be done to achieve this purpose through technical means. There are four main technical areas where progress is needed, and the CCIR must play an important part in each. The four areas are

- Earth-station antenna sidelobe gain envelope;
- satellite antenna gain in directions not required for service;
- permissible internetwork interference levels and methods of aggregating the individual entries when calculating acceptable satellite separation distances;
- improved transmission techniques and carrier energy dispersal.

Foreseeable progress in each of these independent areas could increase the capacity of the orbit several-fold. Altogether it seems reasonable to assume that capacity could be increased by 20 or 30 times relative to present-day technology. This would not be done without cost, but quite large benefits might be obtained without unacceptable cost additions provided that the process of raising technical standards is carried out widely and long-sightedly. Action is most urgent on Earth-station antenna sidelobes, since low-standard antennas built now may still be wasting orbit at the end of the century. Present-day satellites have shorter working lives, but their design and procurement cycle is long; here again quick action on antenna characteristics is desirable. The need for early action is less acute in the other two areas, since changes in transmission techniques and parameters can be made, with greater or less difficulty, at any time in the life of a network.

Progress is being made in all four areas in industry, in systems, and in CCIR.

B. Earth-Station Antenna Sidelobes

There has developed a better understanding in recent years of the importance of designing the feed/subreflector assembly of symmetrical Cassegrain Earth-station antennas so as to minimize subreflector overspill. Big main reflectors with good profile accuracy are now available. Small- and medium-sized antennas with offset geometry are also commercially available. These techniques reduce sidelobe gain dramatically, but there is a cost penalty. This cost penalty may be accepted readily by a new network as the price of getting started; it is more painful to an established network, already equipped and often with nothing to gain but new neighbors in orbit, possibly competing systems.

If progress is to be made, the incentive may have to take the form of insistence on better performance by government authority, backed by international regulations, recommendations, or agreements. The time factor is important. Such

measures should take account of the need to allow antennas, once built, to complete a reasonable working lifetime before they are scrapped unless their performance is much worse than the agreed standards. It will usually be necessary to arrange for a market demand to be generated for better new antennas early enough and large enough to encourage manufacturers to develop good products and offer them at an acceptable price. At its meeting in October/November 1980, CCIR Study Group 4 took the first steps in that direction by beginning the draft of a recommendation on sidelobe performance of new antennas, with the ultimate prospect of performance standards for all operational antennas at some time in the future [10]. Hopefully, this draft recommendation will be completed and approved at the next CCIR Plenary Assembly in 1982.

C. Satellite Antenna Radiation Patterns

In many current fixed-satellite situations there is little benefit to the satellite system in making the footprint of the satellite antenna conform closely to the service area, with a rapid rolloff of gain outside it. Such an antenna is likely to be bigger and heavier than a simpler antenna, the improvement in efficiency of power distribution is quite small, and the limitation of overspill may deny the system unforeseen but interesting revenues. Nevertheless, good geographical control of radiation could greatly facilitate coordination between satellites serving limited areas, particularly where there is marked inhomogeneity between them. The CCIR has been studying the out-of-beam radiation of satellite antennas for some years, with a view to determining recommended reference radiation patterns, a possible way of stimulating an improvement in the performance of systems, but the problem is technically awkward and progress is slow [11].

However, other influences are at work. WARC-77 imposed rigorous satellite antenna out-of-beam radiation patterns on the satellite-broadcasting systems it planned for, in order that the largest feasible number of programs could be made available to each country [12]. Shaped beams generated by multiple feeds illuminating a common reflector, designed for reduced out-of-beam gain in order to permit frequency reuse within the network, were developed for INTELSAT IV A satellites, and more ambitious beam shaping is being introduced for INTELSAT V. Thus the technology is being stimulated by the pressure of requirements and it could be pressed more generally into service if more satisfactory frequency coordination machinery became established.

D. Permissible Internetwork Interference Level

The determination of constructive levels of permissible internetwork interference can only be done by ITU. Fortunately, this is an area in which the CCIR has found it relatively easy to act; an increase in the recommended level of permissible interference is like a tax which hurts everyone, but nobody need be hurt too much. Up to 1978, the CCIR recommended that interference into the channels of a fixed-satellite network from other satellite networks should be up to 10 percent of all channel noise or bit errors; in that year the level

was raised in general to 20 percent [13]. The introduction of a short-term planning mode of orbit-spectrum management or multilateral coordination in place of bilateral coordination would permit fuller advantage to be taken of the aggregate permissible interference entry. In addition, a further increase in the maximum aggregate level might well be agreed in the future, particularly if the mode of its introduction was such as to permit satellite emission powers to be raised in step.

E. Efficient Transmission Techniques

Finally, transmission techniques. Improved orbit utilization follows in two main ways from optimization of transmission technique, namely the increase in information density that can be made to flow through each network and the reduction of susceptibility to interference and liability to cause it. CCIR has recognized the usefulness of artificial carrier energy dispersal as a means of reducing interference between satellite networks in addition to its basic task of reducing interference to and from analog terrestrial radio systems [14]. However, choice of transmission technique is more fundamentally related to the traffic a network carries and the environment in which it operates than are the other three technical areas discussed here, and CCIR probably does not have enough influence to change it much. Fortunately, other stimuli which are usually present, namely economics and growth of demand, are pressing in directions which are desirable from the orbit utilization standpoint. These stimuli are leading, for example, to dual polar operation, companding in analog telephony systems, voice switching in SCPC FDMA systems, and to TDMA and DSI. These techniques, TDMA/DSI above all, will tend to improve carrier energy dispersal and reduce liability to interference at the same time as they are increasing per-network throughput.

Comments² by P. Sawitz³

It should be emphasized that efficiency of spectrum and orbit utilization is not a goal in itself. The final goal is to provide the services that will satisfy the actual requirements of all Administrations. Efficient spectrum and orbit utilization is only one of the means of achieving this end. When it conflicts with other considerations, the tradeoffs involved might, in some cases, result in a decrease in efficiency in order to provide the desired services.

Regarding Section II, factor e): I am of the opinion that the statement that "Uniformity in spectrum goes with minimum satellite separations" is not invariably true, if "uniformity" is equated with "flat spectrum." Channel interleaving, for example, is an effective method of increasing spectrum use only with peaked (i.e., nonuniform) spectra.

Regarding Section II, factor f): Homogeneity, or uniformity, of adjacent satellites does not always imply minimum separation. Using two homogeneous systems as a baseline, it is possible to make changes in one of the two systems (using higher gain antennas with lower sidelobes and lower power,

both on the satellite and on the ground) so as to make the two systems less homogeneous and to allow closer spacing at the same time.

In general, I think that three negative impacts of WARC-79 decisions on the efficiency of spectrum-orbit utilization should be noted: 1) The WARC, in effect, endorsed detailed, *a priori* planning for the BSS in the 12-GHz band. It is my opinion that such planning may lead to less than optimum spectrum-orbit utilization; 2) The call for the 1984/1985 space planning conferences has a strong bias for *a priori* planning. As mentioned immediately above, such planning may lead to inefficient spectrum-orbit utilization for those services as well; 3) The allocation of additional bands for services may reduce the incentive for efficient use of all allocated bands.

Author's Reply⁴

1) Clearly, maximization of the capacity of orbit and spectrum is meaningless by itself. With operational, technical, and economic circumstances taken into account, systems will be diverse in characteristics, some much less efficient than others. The final goal is surely to manage the use of orbit and spectrum so as to avoid unnecessary further loss of efficiency and to persuade users to improve system characteristics sufficiently for all needs to be met, cost being distributed in some acceptable way.

2) Channel interleaving is sometimes an effective way of reducing the separation required between two satellites. It is questionable whether it is feasible to use this method when more than two bandwidth-limited satellites have to be coordinated and so it is quite limited as a technique. I doubt whether interleaving does much more than mitigate the effects of spectral nonuniformity.

3) Section II of the paper identifies eight factors, most of them interdependent, which affect satellite spacing. The reviewer says, in effect, that homogeneity could be traded off against antenna characteristics. I must agree.

4.1) *A priori* planning may have advantages in broadcasting which are not relevant to other services, such as minimization of receiving installation cost and permanence of arrangements. Political and commercial sensitivity over national coverage areas is another possible reason for preferring planning in broadcasting. These advantages may compensate for loss of the higher efficiency that other orbit/spectrum management techniques may provide.

4.2) WARC-1984/1985 was set up because enough countries placed equitable access to the orbit ahead of other considerations and *a priori* planning is the approach to equitable access which comes first to mind. Perhaps other approaches will emerge by 1984.

4.3) I agree that the additional allocated bandwidth may reduce interest in efficient use of spectrum. Perhaps ways can be found to persuade system designers to design their networks to meet the interference situation likely to arise in the middle life of equipment rather than the conditions current at the time of designing.

² Manuscript received May 12, 1981.

³ P. Sawitz is with Operations Research, Inc., Silver Springs, MD.

⁴ Manuscript received May 15, 1981.

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REFERENCES

Note: At the time of writing this paper the ITU Radio Regulations have not been republished as revised by WARC-79, and the References below use the numbering system contained in the Final Acts of the Conference itself.

- [1] ITU, *Final Acts of WARC-79*. Geneva, Switzerland, 1979, Article N27, paragraphs 6107-6110H.
- [2] ITU, *Final Acts of WARC-79*. Geneva, Switzerland, 1979, Appendix 29A, Annex 8, sec. 3.11.
- [3] ITU, *Final Acts of WARC-79*. Geneva, Switzerland, 1979, Article N27, paragraph 6111.
- [4] ITU, *Final Acts of WARC-79*. Geneva, Switzerland, 1979, Appendix 29A, Annex 8, sec. 3.14.
- [5] ITU, *Final Acts of WARC-79*. Geneva, Switzerland, 1979, Article N7, Section IV.
- [6] ITU, *Final Acts of WARC-79*. Geneva, Switzerland, 1979, Article N7, Section IV and paragraphs 3748A, 3793B, 3796A, 3794H, and 3814B.
- [7] ITU, *Final Acts of WARC-79*. Geneva, Switzerland, 1979, Articles N11, N13 and Appendices 1A, 1B and 29.
- [8] ITU, *Final Acts of WARC-79*. Geneva, Switzerland, 1979, Resolution BP.
- [9] ITU, *Final Acts of WARC-79*. Geneva, Switzerland, 1979, Article N1, paragraph 3102.
- [10] CCIR Report 391-3, draft revision 1980 (Document 4/248).
- [11] CCIR Report 558-1.
- [12] ITU, *Final Acts of WARC-79*. Geneva, Switzerland, 1979, Appendix 29A, Annex 8, sec. 3.13.3.
- [13] CCIR Recommendations 466-2 and 523.
- [14] CCIR Recommendation 446-2.

Mobile Services—The Impact of the 1979 World Administrative Radio Conference

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Abstract—The decisions of the 1979 World Administrative Radio Conference (WARC-79) will have a major impact on the future development of the Mobile services. This paper summarizes the scope and structure of the Conference and details the changes in the allocations, resolutions, and recommendations which are of interest to the Mobile services. Substantial changes were made in the Maritime

and Land-Mobile services and to a lesser degree to the Aeronautical-Mobile service. Mobile Satellite also attained footnote allocation status in two Regions (2 and 3) and in two countries of Region 1. In most part, the changes made at WARC-79 are beneficial to the future development of the Mobile services. However, it remains for future specialized conferences to establish the bases for expanding these services in the newly allocated bands.

INTRODUCTION

AFTER FIVE YEARS of formal preparation and 11 weeks of intense conference work, the 1979 World Administrative Radio Conference (WARC-79) was completed. It was attended by over 2200 delegates from 148 countries and 38

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recognized international organizations. The Final Acts of the Conference reflect the decisions taken on over 15 000 individual proposals, including nearly 12 000 proposals concerning frequency allocations. The revisions of the Radio Regulations agreed upon at this Conference will come into effect on January 1, 1982.

This paper provides a review of the allocation decisions, resolutions, and recommendations that were reached concerning the Mobile services. However, the authors caution that serious workers in the field of international regulations will find no substitute for a thorough study of the WARC-79 Acts and, in particular, the numerous footnotes which are part of the Allocation Table. The Mobile services summarized here include the satellite equivalents.

In general, the Mobile services received substantial additional allocations on either a primary, permitted, or secondary basis. In terms of primary allocations alone, Mobile was added on a regional basis as follows:

- Region 1 98 MHz
- Region 2 110 MHz
- Region 3 161 MHz.

In each region, various countries provided for additional Mobile allocations beyond those given a primary allocation, either by allocation footnote or by formal reservation.

The additional primary Mobile allocations for the most part share primary status with other services, most notably Fixed and Broadcast and a future specialized conference will be needed to establish the basis for each service in such shared bands.

CONFERENCE ORGANIZATION

At the first plenary meeting on September 23, 1979, it was agreed to establish nine committees as follows:

- 1) Steering Committee (to coordinate the work of the Conference, fix the timetable of meetings, etc.)
- 2) Credentials Committee (to verify the credentials of delegations, etc.)
- 3) Budget Control Committee (to determine the organization and facilities available to delegates and examine and approve accounts for expenditure incurred, etc.)
- 4) Technical Regulations Committee (to consider proposals concerning various technical articles of the Radio Regulations, including designation of emissions, interference, tests, etc.)
- 5) Frequency Allocations Committee (to consider proposals concerning frequency allocations and other related matters)
- 6) Regulatory Procedures Committee (to consider proposals concerning coordination, notification, and registration of frequency assignments, etc.)
- 7) General Administrative Committee (to deal with proposals on general administrative matters not covered by other Committees)
- 8) Restructure of the Radio Regulations and Additional Radio Regulations Committee (to consider specific proposals concerning the basic rearrangement of the above)

- 9) Editorial Committee (to perfect the form of the texts of the Final Acts without altering the sense).

The most significant committee for mobile communications was Committee 5, which dealt with frequency allocations. This committee was subdivided into six working groups, each concerned with a specific segment of the frequency band from 9 kHz to 240 MHz.

COMMITTEE PROCEDURES

In Committee 5 there was a general discussion of the issues raised in the various countries' proposals after which they were referred to a Working Group. Within each of the Committee 5 Working Groups, the same general procedure was followed and, to the extent possible, simultaneous meetings of the individual groups were avoided in order to permit participation by those countries having a limited delegation. Approximately 12 000 input proposals made to the Conference by various countries were concerned with frequency allocations. These input documents formed the basis for initial discussion in Committee 5 and its Working Groups.

Each Working Group reviewed, in detail, the various input documents on each specific frequency proposal and attempted to reach agreement on a compromise position which was produced in written form as a Yellow document. After further discussions within the Working Group, final decisions were taken and the results published in a Green document as a draft report which was then forwarded to Committee 5 for its consideration. Committee 5 then examined in some detail, revised, or on some occasions returned the report to a Working Group for further consideration.

The allocation of documents to the Working Groups of Committee 5 was as follows:

Frequency Band	Number of Proposals Treated
9 kHz–4000 kHz	2196
4000 kHz–27.5 MHz	2634
27.5 MHz–960 MHz	2150
960 MHz–40 GHz	4392
40 GHz–400 GHz	631

Agreements within Committee 5 were consolidated periodically and submitted to the Editorial Committee (No. 9) for placing into proper language. The Editorial Committee could not alter the substance of any document given to them for its review. The Editorial Committee issued its review as Blue documents for a first reading at a Plenary Meeting. The Blue documents were accepted as submitted or changed in accordance with discussions and were issued as Pink documents for a second reading at a succeeding Plenary Meeting. Normally, only items of major significance were considered for altering at this second reading. The documents were then issued as "Whites" for adoption at the final Plenary Meeting where the Final Acts were signed. At this time, only editorial amendments were permitted.

It may be appreciated from the foregoing explanation that the volume of papers produced was tremendous and that keeping track of the various papers was a major undertaking. Although the process may appear slow, it did ensure that every

country had the opportunity to have its views considered at various stages in reaching final agreement. The system worked well and, at the end, produced a set of Radio Regulations which the greater majority of the countries accepted. In the course of developing agreements, the various countries obtained "footnotes" to the allocation tables which provided alternative solutions to difficult problems.

Specific and more detailed discussion of the results of the decisions at WARC-79 on the various Mobile frequency allocations is provided in the following paragraphs for each of the Mobile Services.

MARITIME MOBILE

VLF and LF Bands

In the frequency range of 9–300 kHz, there were a few changes which, in general, will have minimum effect on Maritime-Mobile service. In order to provide for increased protection to the navigation services, primarily Loran-C, operating at 100 kHz, the status of both the Maritime-Mobile service and the fixed service were reduced to secondary. The other minor changes in this portion of the band are identified in Table I.

MF Band

In this band from 300 to 3 000 kHz, there was major discussion and disagreement particularly in the allocations between 400 and 530 kHz. Prior to WARC-79, the Maritime-Mobile service had an exclusive allocation in the band 415 to 490 kHz and, generally, enjoyed a similar worldwide status between 490 and 525 kHz. However, at this WARC there was a strong effort to get additional frequencies for aeronautical navigation which would permit the assignment of frequencies to aeronautical radio beacons to facilitate aircraft operations.

There were many meetings of the Working Group and its working subgroups in order to attempt to arrive at a compromise position for all three regions. There was considerable disagreement among various countries and the Chairman of the Working Group had to resort to a showing of hands in order to develop a consensus.

As noted in Table I, the final allocation resulted in different allocations among the three International Telecommunication Union (ITU) Regions. There is a common band between 435 and 510 kHz that the Maritime-Mobile service has either a primary or an exclusive status.

The radio direction-finding frequency of 410 kHz was retained in a footnote allocation. The guard bands around the frequency were reduced to $\pm 3\frac{1}{2}$ kHz. In the final protocol to the Conference, Greece and Yugoslavia made the following reservation:

"The present Conference has adopted for Region 1 different allocations than those for Regions 2 and 3 in the band 415 to 495 kHz. The two services to which this band is allocated, namely, aeronautical radio-navigation and maritime mobile, are both extremely important safety services. These delegations consider therefore that this decision will lead to serious problems hazarding the safeguard of human life."

HF Band

At both Working Group and Committee 5 levels, the Maritime-Mobile service experienced difficulty in obtaining additional frequency spectrum, particularly between 4 and 12 MHz. The only way that additional frequencies could be obtained would be to reduce the allocations to the Fixed service. Since there were a great many countries that still rely on the fixed service for their internal communications, particularly on the continents of Africa and South America, it was extremely difficult to persuade them to provide additional frequencies for the Maritime-Mobile service. Proposals to expand the maritime-mobile band on an exclusive basis were usually defeated, and it was only possible to obtain additional frequencies where the expansion included a sharing proposal. However, between the band 12 and 26 MHz, a larger amount of frequency space was obtained subject to the fixed stations being satisfactorily moved to other frequencies. This will take considerable time to accomplish.

In the final protocol a reservation from the United States was taken which stated: "In view of the fact that the conference failed to provide adequate allocations for the HF maritime mobile service, particularly below 12 MHz, the U. S. A. states its intention to satisfy maritime mobile requirements in the several HF bands below 10 MHz allocated to the mobile service on a primary basis."

VHF/UHF Band

The major effort in these bands was improvement of the Maritime-Mobile service in the vicinity of 150 MHz. There was majority support to place Channel 16 (156.8 MHz) together with guard bands of ± 37.5 kHz into the frequency table on a worldwide basis. The country of Guinea made a proposal to amend Radio Regulation 287 footnote to recognize the superior status of the maritime-mobile channels in this band on a worldwide basis. This was defeated by a number of Administrations including the United States. At a later meeting, Guinea proposed a revised amendment to Radio Regulation 287 to give the maritime-mobile channels protection worldwide. Once again, this was defeated but on a vote of 28 for, 30 opposed, and 36 abstentions—very close results.

In the United States, the railroad industry as well as other land-mobile services make use of these channels which were allocated internationally to the Maritime-Mobile service at the 1959 WARC. It may be anticipated that there will be continued action to ultimately obtain a common worldwide allocation for the Maritime-Mobile service within this band.

In the band allocated to the Maritime-Mobile-Satellite service at 1.6 GHz, more success was achieved than elsewhere. An additional $6\frac{1}{2}$ MHz for the space-to-Earth and $11\frac{1}{2}$ MHz for the Earth-to-space directions were obtained. This ultimately provides for 14 MHz in both directions and an additional 5 MHz inbound from ships for the handling of wide-band services such as high-speed data.

The 1-MHz band, located at the boundaries between the Aeronautical-Mobile-Satellite service and the Maritime-Mobile-Satellite service was allocated to the Mobile-Satellite service for

TABLE I
CHANGES TO FREQUENCY ALLOCATIONS AFFECTING THE MARITIME MOBILE SERVICE

30-300 kHz				
Band	Remarks			
90-110 kHz	MM and Fixed reduced to Secondary services			
110-130	Various minor changes			
130-148.5	In Region 1 Fixed raised to permitted. Radionavigation also Primary in Region 3			
148.5-160	MM still Primary in Regions 2 and 3. Shared with Fixed and Radionavigation Services.			
300-3000 kHz				
405-415	Radionavigation world-wide. Secondary aeronautical mobile in Regions 2 and 3.			
415-526.5 kHz				
415-435	Region 1: Aeronautical Radioavigation (Primary) MM reduced to Permitted			
435-495	MM (Primary) Aeronautical Radionavigation (Secondary)			
*495-505	Mobile Distress and Calling			
505-526.5	MM (Primary) Aeronautical Radionavigation (Permitted)			
415-495	Region 2: MM exclusive			
* 495-505	Mobile Distress and Calling			
505-510	MM exclusive			
510-525	Mobile and Aeronautical Radionavigation			
415-495	Region 3: MM exclusive			
* 495-505	Mobile Distress and Calling			
505-526.5	MM (Primary) Aeronautical Radionavigation (Permitted) Aeronautical Mobile (Secondary) Land Mobile (Secondary)			
1605-3000 kHz				
1606.5-1625, 1635-1800 and 2045-2160	(a) in Region 1 only, the sub-bands: will be allocated to MM (Primary), fixed and Land Mobile (both Permitted)			
2065-2107	(b) a Worldwide MM sub-band			
2182	guard bands to be reduced from ± 12 kHz to $\pm 8\frac{1}{2}$ kHz at a date to be decided by the next competent WARC, which will also replan the entire band.			

8	8100	8195	8815	95	Shared with Fixed Service on an equal Primary basis
12	12230	12330	13200	100	Condition of use to be settled at WAR7-82 and subject to Fixed Stations being satisfactorily moved to other frequencies
16	16360	16460	17360	150	Conditions same as for 12 MHz
18	18780	18900		120	Conditions same as for 12 MHz
19	19680	19800		120	Conditions same as for 12 MHz
22	22000	22720	22855	135	Conditions same as for 12 MHz
23	23350	24000		650	Intership only
25	25070	25110	25210	100	Conditions of exclusive use to be decided by WARC 82 and subject to all Fixed and Land Mobile stations working in this band being satisfactorily moved to other frequencies
26	26100	26175		75	Conditions same as for 25 MHz

LEGEND

New additional allocations from WARC 79

Existing allocations

30-300 MHz	
Band	Remarks
156.8 MHz	Moved from a footnote into the Table of Frequency Allocations. Guard band reduced to $\pm 37\frac{1}{2}$ kHz.
216-220	In Region 2, shared with Fixed service on an equal Primary basis.
121.5 MHz 243	Also allocated for reception on board satellites of emissions from emergency position-indicating radio beacons.
300-3000 MHz	
405.5-406	An additional allocation in Canada to mobile satellite service, except aero.
406-406.1	No change
406.1-410	Same as 405.5-406.1
806-890	Mobile satellite, except aero on a Primary basis in Region 2, 3, Norway and Sweden.
942-960	Mobile satellite, except aero on a Primary basis in Region 3, Norway and Sweden.
1530-1660.5	6 $\frac{1}{2}$ MHz added in space to earth and 11 $\frac{1}{2}$ added in earth to space directions. Totals will be 19 MHz up and 14 MHz down. The increase in down link at 1530-1535 MHz will not be available until 1 Jan. 1990.

High Frequencies 3-30 MHz				
Band	Increase	Remarks		
3 MHz	3155 3200	45	In 22 countries, mainly Europe	
4	4000 4063 4438	63	Shared with Fixed Service on an equal Primary basis	
6	6200 6525	-	Limited to ship station using radiotelephony	

distress and safety operations. This is an expansion over the existing Radio Regulations which will permit the use of these frequencies for distress and safety operations involving ships, planes, and land-mobile units.

SHF and EHF Bands

In the range from 3 to 240 GHz, the number of available bands were doubled by the actions of the WARC. The pre-WARC allocations available to both the Aeronautical- and the Maritime-Mobile-Satellite services were broadened to the Mobile-Satellite service, thus, the Land-Mobile-Satellite service is now included. New allocations were made at 7, 8, 14, 20, 30, 40, 50, 70, and 80 GHz. Existing allocations at 45, 66, 95, 145, 195, and 255 GHz were retained. Although these frequencies are in the realm of the future, at least the maritime community is included so it may plan in the years ahead.

RECOMMENDATIONS AND RESOLUTIONS AFFECTING MARITIME MOBILE

At each of the WARC's there is always a set of Recommendations and Resolutions. At WARC-79 there were 57 Recommendations which were of interest to maritime communications with 30 of them being of particular concern. Recommendations typically request studies, and future actions, by ITU members or other international organizations. A listing of Recommendations is given in Appendix I. There were 43 Resolutions of interest to the maritime community with 19 of them being of specific interest. Resolutions typically "resolve" that specific proposals should be accomplished by an administration or organization. Alternatively, they may urge or invite action by such personalities. A listing of Resolutions is given in Appendix II.

AERONAUTICAL MOBILE

The U. S. objectives for the Aeronautical Mobile and Aeronautical-Mobile-Satellite services were satisfied at WARC-79. All existing allocations which are presently being used were retained. In addition, a very small amount of new aeronautical-mobile allocation was provided to satisfy future needs. While there was a small loss of existing aeronautical-mobile-satellite allocations, which are not now being used, an adequate amount of spectrum was retained to meet the needs of aviation through the turn of the century. The major allocation changes are described below and listed in Table II.

2.85-27.5-MHz Band

The Aeronautical-Mobile (R) service was deleted from the 21 870-21 924-kHz band and the Aeronautical Fixed service was deleted from the band 21 924-22 000 kHz. The purpose of the change was to eliminate the existing band sharing between these two somewhat incompatible services.

27.5-960 MHz

The 118-136-MHz Aeronautical Mobile (R) band was expanded to 137 MHz, effective January 1, 1990. The purpose of this change was to satisfy the expected increase in air-ground communications requirements.

TABLE II
CHANGES TO FREQUENCY ALLOCATIONS AFFECTING THE
AERONAUTICAL-MOBILE (R) AND AERONAUTICAL-
MOBILE-SATELLITE (R) SERVICES

BAND	REMARKS
	<u>9-300 kHz</u>
	No Changes
	<u>300-3000 kHz</u>
510-525	In Region 3, band was expanded to 505-526.5 and the aeronautical radionavigation service was added on a permitted basis.
	<u>3-30 MHz</u>
21870-22000	Aeronautical Mobile (R) deleted from the sub-band 21870-21924; Aeronautical Fixed deleted from the sub-band 21924-22000 (The objective was to eliminate band sharing between these two somewhat incompatible services).
	<u>30-300 MHz</u>
136-137	Aeronautical Mobile (R) added to this band on a primary basis effective 1 January 1990.
	<u>300-3000 MHz</u>
1435-1535	Footnote was added stating that in Region 2, Australia and Papua New Guinea, the use of this band by the aeronautical mobile service for telemetry purposes has priority over other uses by the mobile services.
1542.5-1543.5	The down-link band for aeronautical satellite distress and safety operations was changed to 1544-1545 and the aeronautical mobile satellite (R) allocation (and maritime mobile-satellite allocation) was changed to Mobile Satellite (space-to-Earth).
1543.5-1558.5	The down-link band for aeronautical mobile-satellite (R) operations was reduced by 1 MHz and moved to 1545-1559.
1644-1645	The up-link band for aeronautical satellite distress and safety operations was changed to 1645.5-1646.5 and the aeronautical mobile-satellite (R) allocation (and maritime mobile-satellite allocation) was changed to Mobile Satellite (Earth-to-space).
1645-1660	The up-link band for aeronautical mobile-satellite (R) operations was reduced by 1 MHz and moved to 1646.5-1660.5.
2310-2390	Footnote was added stating that in the United States, Australia and Papua New Guinea, the use of this band by the aeronautical mobile service for telemetry purposes has priority over other uses by the mobile services.

960 MHz-40 GHz

There was an entirely new "pie cutting" of the 1535-1660-MHz band (primarily to accommodate the NAVSTAR Global Positioning Satellite and to satisfy the expanding requirements of the Maritime-Mobile-Satellite service) which resulted in the following changes to the aeronautical mobile satellite (R) allocations:

The 1543.5-1558.5-MHz (downlink) and 1645-1660-MHz (uplink) bands were changed to 1545-1559 MHz and 1646.5-1660.5 MHz, respectively.

The 1542.5-1543.5-MHz and 1644-1645-MHz bands were changed to 1544-1545 MHz and 1645.5-1646.5 MHz, respectively. In addition, the actual allocation was changed from the two individual service designations of Aeronauti-

cal Mobile Satellite (R) and Maritime Mobile Satellite to the generic Mobile Satellite term.

Above 40 GHz

Companion terrestrial-mobile allocations were added to the existing space-mobile allocation bands. In addition, there were some minor adjustments in the actual band limits and all allocations were changed to generic terms, e.g., aeronautical-mobile-satellite and maritime-mobile-satellite allocations were changed to mobile satellite.

LAND MOBILE

The Land-Mobile services have not as yet been considered to be an international service requiring agreement on a three-region basis. As a result, the decision taken at WARC-79 regarding these services were on an individual regional basis.

100-108 MHz

This band was reallocated in Region 1 on an exclusive basis to Broadcasting, thereby removing the prior mobile allocation. This change was made to enlarge the band for FM Broadcast.

220-225 MHz

In Region 2, Mobile was added on a primary basis, and Radiolocation given secondary status in the Table entry. A footnote, however, accords Radiolocation primary status until January 1, 1990.

420-430 and 440-450 MHz

Regions 2 and 3 aligned the Table with the prior allocations in Region 1. As a result, Mobile was added on a primary basis in both Regions. Radiolocation was reduced from primary to secondary status.

The United States, however, entered a footnote retaining Radiolocation on a primary basis in both bands.

470-806 MHz

In Region 2, Mobile was added on a secondary basis in the bands 470-512 and 614-806 MHz. The United States, however, entered footnotes raising Mobile to a primary status in the 470-608- and 614-806-MHz bands and entered a formal reservation removing the condition that operational authorization be subject to agreement under Article N13A. That Article would subject the authorization of expanded domestic mobile operations to formal International Frequency Registration Board (IFRB) notification and coordination.

Region 3 added Mobile on a primary basis in the 470-610-MHz band. In Region 1, numerous European countries added Mobile on a primary basis in the band 790 to 862 MHz.

806-890 MHz

Region 2 added Mobile (except Aeronautical Mobile) for land-mobile usage on a primary basis throughout this band. In Region 1, Mobile was added on a primary basis from 862 to 890 MHz.

890-960 MHz

Region 1 added Mobile (except Aeronautical Mobile) on a primary basis throughout this band, and is now in alignment with Region 3. Region 2 added Mobile on a primary basis in the bands 890-902 and 928-942 MHz, and on a secondary basis in the bands 902-928 and 942-960 MHz. The United States, however, entered a footnote making Mobile primary in the bands 942-947 and 952-960 MHz. The U. S. reservation regarding the procedure of Article N13A is also applicable to these bands. As a result, the total band 890-960 MHz is in alignment with the U. S. domestic mobile allocation table through a combination of Table entries, footnotes, and reservation.

MOBILE-SATELLITE SERVICE BELOW 2 GHz

WARC-79 adopted several new allocations below 2 GHz which will permit the future development of a global operational search and rescue system and national mobile-communications systems employing space techniques.

Search and Rescue

A new footnote, applicable worldwide, was added to the 117.975-136- and 235-267-MHz bands which reads:

"ADD 3572A The bands 121.45-121.55 MHz and 242.95-243.05 MHz are also allocated to the mobile-satellite service for the reception on board satellites of emissions from emergency position-indicating radio-beacons transmitting at 121.5 and 243 MHz."

Changes were also made to the Mobile-Satellite service allocation in the 406-406.1-MHz band. The 1971 WARC-ST had included, by footnote, allocations to the Radiolocation, Fixed, and Mobile, except Aeronautical Mobile, services in a number of countries. These footnotes were deleted so that the band is now exclusively allocated to the Mobile-Satellite service (Earth-to-space) on a worldwide basis. The use of the band is further restricted by footnote:

"3634/317A The band 406-406.1 MHz is reserved solely for the use and development of low-power (not to exceed 5 W) emergency position-indicating radiobeacon (EPIRB) systems using space techniques."

Two additional frequency bands, 1645.5-1646.5 MHz (Earth-to-space) and 1544-1545 MHz (space-to-Earth) were allocated to the Mobile-Satellite service: and by Footnote 3695A were limited to distress and safety operations by WARC-79. These bands are adjacent to the bands allocated to the Maritime- and Aeronautical-Mobile-Satellite services.

These new provisions will be reviewed at a World Administrative Radio Conference for Mobile Telecommunications (WARC-MT) to be convened in March 1982. The Conference agenda emphasizes those aspects of the Mobile and Mobile-Satellite services dealing with distress and safety communications. However, it is unlikely that the Conference will do anything to change the mobile-satellite provisions simply because there are still a number of competing concepts for a global distress system and little experimental data on which to base new or revised International Radio Regulations.

Mobile-Satellite Communications

WARC-79 adopted allocations which, for the first time, could bring satellite communications directly into the hands of the general public. The United States, Canada, and several other countries submitted proposals to allocate by footnote the 806-890-MHz band to the Mobile-Satellite service. This proposal was generally accepted by Region 2 countries (essentially the Americas) with the stipulation that it would be limited to national service and that aeronautical operations would be excluded. The allocation in Region 2 is

"ADD 3670B Additional Allocation: in Region 2 the band 806-890 MHz is also allocated to the mobile-satellite, except aeronautical mobile-satellite, service on a primary basis. The use of this service is intended for operation within national boundaries and subject to agreement obtained under the procedure set forth in Article N13A."

The proposals submitted by the Region 2 countries stimulated interest in Region 1 and 3 countries in obtaining similar allocations. Norway and Sweden attempted to obtain an allocation for the whole of Region 1, but were unable to primarily because of the concern for the broadcasting service which is a primary table allocation. After much debate, the following footnote was added:

"ADD 3662CA Additional Allocation: in Norway and Sweden, the bands 806-890 MHz and 942-960 MHz are also allocated to the mobile-satellite, except aeronautical mobile-satellite, service on a primary basis. The use of this service is limited to operation within national boundaries and subject to agreement obtained under the procedure set forth in Article N13A. This service shall not cause harmful interference to services operating in accordance with the Table."

Similarly, Japan submitted a proposal during the Conference to allocate the band in Region 3 to the Mobile-Satellite

service. After some debate, again over protection to the broadcast service, the following footnote was added:

"ADD 3662C Additional Allocation: in Region 3, the bands 806-890 MHz and 942-960 MHz are also allocated to the mobile-satellite, except aeronautical mobile-satellite, service on a primary basis. The use of this service is limited to operation within national boundaries and subject to agreement obtained under the procedure set forth in Article N13A. This service shall not cause harmful interference to services operating in accordance with the Table."

In all three Regions, the mobile-satellite allocation is shared with Table allocations to the Fixed, Mobile, and Broadcasting services, with the exception that in Region 1, Mobile is not allocated below 862 MHz.

CONCLUSIONS

The WARC, after eleven weeks of hard work, produced the new Radio Regulations of more than 1000 pages. The problems solved were the most difficult yet to be experienced by a Radio Conference. The 2200 delegates from 148 countries worked together with seriousness, cooperation, and understanding. The final result did not meet all the desires of the mobile communities; but neither did it meet the full desires of any other service. This was an impossibility since total requirements for frequencies well exceeded the available bandwidth. However, mobile communications received a fair share. Mr. M. Mili, the Secretary General of the ITU, termed WARC-79 as a BRILLIANT SUCCESS.

FUTURE

The next two Radio Conferences of interest to the Mobile Services will be held in 1982 and 1986. The 1982 Conference will be of a limited nature with a major interest centered on distress and safety. Efforts are under way to prepare for this meeting by Special Committee 76 of the Radio Technical Commission for Marine Services (RTCM).

APPENDIX I

WARC-79 RECOMMENDATIONS OF MOBILE INTEREST

<u>Designation¹</u>	<u>Subject</u>
202 (F)	Relating to the Improvement of Protection of Distress and Safety Frequencies, and those Related to Distress and Safety, against Harmful Interference
73 (J)	Relating to the Use of the Term "Channel" in the Radio Regulations
63 (M)	Relating to the Provision of Formulas and Examples for the Calculation of Necessary Bandwidths
709 (O)	Relating to Sharing Frequency Bands between the Aeronautical Mobile Service and the Inter-Satellite Service
403 (V)	Relating to the Development of Techniques which would help to Reduce Congestion in the High-Frequency Bands Allocated to the Aeronautical Mobile (R) Service
405 (Y)	Relating to a Study of the Utilization of the Aeronautical Mobile-Satellite (R) Service
61 (ZB)	Relating to Technical Standards for the Assessment of Harmful Interference in the Frequency Bands above 28 MHz
9 (ZG)	Relating to the Measures to be taken to prevent the Operation of Broadcasting Stations on Board Ships or Aircraft outside National Territories

¹ Parentheses identify the provisional designations and numbers identify the definitive designations.

603 (ZH)	Relating to Technical Provisions for Maritime Radiobeacons in the African Area
402 (ZJ)	Relating to Cooperation in the Efficient Use of Worldwide Frequencies in the Aeronautical Mobile (R) Service
400 (ZK)	Relating to the Transition from the Present to the New Frequency Allotment Plan in the Bands Allocated Exclusively to the Aeronautical Mobile (R) Service between 2850 and 22 000 kHz
65 (ZM)	Relating to the Technology for New Spectrum Sharing and Band Utilization Schemes
71 (ZN)	Relating to the Standardization of the Technical and Operational Characteristics of Radio Equipment
708 (ZQ)	Relating to Frequency Bands shared between Space Radiocommunication Services and between Space and Terrestrial Radiocommunication Services
72 (ZR)	Relating to Terminology
703 (ZU)	Relating to the Need to Cease Operations of the Fixed and Mobile Services in the Bands 149.9–150.05 MHz and 399.9–400.05 MHz Allocated to the Radionavigation-Satellite Service
704 (ZV)	Relating to the Compatibility between the Broadcasting Service in the Band 100–108 MHz and the Aeronautical Radionavigation Service in the Band 108–117.975 MHz
305 (ZW)	Relating to the Use of Channels 15 and 17 of Appendix 18 by On-Board Communications Stations
404 (ZX)	Relating to the Use of the Band 136–137 MHz by the Aeronautical Mobile (R) Service
310(ZY)	Relating to an Automated UHF Maritime Mobile Radiocommunication System
200 (ZZ)	Relating to the Date of Entry into Force of the 10 kHz Guardband for the Frequency 500 kHz in the Mobile Service (Distress and Calling)
203 (YA)	Relating to the Future Use of the Band 2170–2194 kHz
309 (YB)	Relating to the Designation of a Frequency in the Bands 435–495 or 506–526.5 kHz (525 kHz in Region 2) on a Worldwide Basis for the Transmission by Coast Stations of Navigational and Meteorological Warnings to Ships, using Narrow-Band, Direct-Printing Telegraphy
300 (YD)	Relating to Planning the Use of Frequencies by the Maritime Mobile Service in the Band 435–526.5 kHz in Region 1
301 (YE)	Relating to Planning for the Use of Frequencies in the Bands between 1606.5 and 3400 kHz Allocated to the Maritime Mobile Service in Region 1
406 (YF)	Relating to the Revision of the Frequency Allotment Plan for the Aeronautical Mobile (R) Service
67 (YH)	Relating to the Definitions of “Service Area” and “Coverage Area”
5 (YI)	Relating to the Means of Reducing the Congestion in Band 7 (3–30 MHz)
4 (YJ)	Relating to the More Efficient Consolidation of National and International Radiocommunication Circuits Operating in the Bands between 4000 and 27 500 kHz
601(YK)	Concerning the Matter of Providing a Suitable Frequency Allocation for a Collision Avoidance System in the Aeronautical Radionavigation Service
307 (YL)	On the Choice of a Frequency in the Mobile Maritime Bands between 1605 and 3800 kHz to be Reserved for Safety Requirements
302 (YM)	Relating to the Improved Use of the HF Radiotelephone Channels for Coast Stations in the Band—Allocated Exclusively to the Maritime Mobile Service
401 (YN)	Relating to the Efficient Use of Aeronautical Mobile (R) Worldwide Frequencies
308 (YO)	Relating to the Designation of Common Frequencies in Medium Frequency Bands for Use by Coast Radiotelephone Stations for Communicating with Ships of other Nationalities
304 (YP)	Relating to the Frequencies in Appendix 17 Rev., Section B, of the Radio Regulations, Provided for Worldwide Use by Ships of all Categories and by Coast Stations
306 (YQ)	Relating to the Establishment of a Watch by Coast Stations for Distress Purposes on the Frequency 156.8 MHz
313(YR)	Relating to Temporary Provisions Covering the Technical and Operational Aspects of the Maritime Mobile-Satellite Service
201 (YS)	Relating to Distress, Urgency, and Safety Traffic

- 312 (YT) Relating to Studies of the Interconnection of Maritime Mobile Radiocommunication Systems with the International Telephone and Telegraph Networks
- 706 (YW) Relating to Frequency Sharing by the Earth Exploration-Satellite Service (Passive Sensors) and the Space Research Service (Passive Sensors) with the Fixed, Mobile (except Aeronautical Mobile), and Fixed-Satellite Services in the Band 18.6–18.8 GHz
- 600 (YZ) Relating to the Use of the Frequency Band 9300–9500 MHz
- 605 (XA) Relating to Technical Characteristics and Frequencies for Shipborne Transponders
- 602 (XD) Relating to Maritime Radiobeacons
- 604 (XI) Relating to the Future Use and Characteristics of Emergency Position-Indicating Radiobeacons
- 303 (XJ) Relating to the Use of the Carrier Frequencies 4125 kHz and 6215.5 kHz to supplement the Carrier Frequency 2182 kHz for Distress and Safety and for Call and Reply Purposes in the Zone of Regions 1 and 2 South of Latitude 15° North, but including Mexico, and in the Zone of Region 3 South of Latitude 25° North
- 7 (XK) Relating to the Adoption of Standard Forms for Ship Station Licenses and Aircraft Station Licenses
- 311 (XL) Relating to the Introduction of an Additional Tone After the Radiotelephone Alarm Signal Transmitted by Coast Stations
- 12 (XM) Relating to the Convening of Future Administrative Radio Conference to Deal With Specific Services
- 8 (XN) Relating to Automatic Identification of Stations

APPENDIX II

WARC-79 RESOLUTIONS OF MOBILE INTEREST

<u>Designation¹</u>	<u>Subject</u>
201 (AB)	Relating to Operational Provisions, Charging and Accounting for Public Correspondence in the Mobile Services
315 (AC)	Relating to the Eventual Abolition of Mobile Station Charges for Public Correspondence in the Maritime Mobile Service
66 (AE)	Relating to the Division of the World into Regions for the Purposes of Allocating Frequency Bands
10 (AF)	Relating to the Use of Radiotelegraph and Radiotelephone Links by Red Cross, Red Crescent, and Red Lion and Sun Organizations
63 (AG)	Relating to the Protection of Radiocommunication Services against Interference Caused by Radiation from Industrial, Scientific, and Medical (ISM) Equipment
60 (AJ)	Relating to Information on the Propagation of Radio Waves Used in the Determination of the Coordination Area
601 (AL)	Relating to the Recommendations and Standards for Emergency Position-Indicating Radiobeacons Operating on the Frequencies 121.5 MHz and 243 MHz
200 (AN)	Relating to the Use of Class R3E and J3E Emissions for Distress and Safety Purposes on the Carrier Frequency 2182 kHz
305 (AO)	Relating to the Use of Class R3E and J3E Emissions on the Carrier Frequencies 4125 kHz and 6215.5 kHz Used to Supplement the Carrier Frequency 2182 kHz for Distress and Safety Purposes
307 (AQ)	Relating to the Conversion to Single-Sideband Techniques of Stations of the Radiotelephone Maritime Mobile Service Operating in the Bands between 1605 and 4000 kHz
314 (AR)	Concerning the Establishment of a Coordinated Worldwide System for the Collection of Data Relating to Oceanography
304 (AS)	Relating to the Implementation of the New Channeling Arrangement for AIA Morse Radiotelegraphy in the Bands allocated to the Maritime Mobile Service between 4000 and 27 500 kHz
309 (AT)	Relating to the Unauthorized Use of Frequencies in the Bands allocated to the Maritime Mobile Service
303 (AV)	Relating to Inter-ship Frequencies in the Bands between 1605 and 3600 kHz in Region 1
306 (AW)	Relating to the Use of Single-Sideband Technique in the Radiotelephone Maritime Mobile Service Bands between 1605 and 4000 kHz

- 2 (AY) Relating to the Equitable Use, by all Countries with Equal Rights, of the Geostationary Satellite Orbit and of Frequency Bands for Space Radiocommunications Services
- 300 (AZ) Relating to the Use and Notification of Paired Frequencies Reserved for Narrow-Band Direct-Printing Telegraph and Data Transmission Systems in the HF Bands allocated to the Maritime Mobile Service
- 301 (BA) Relating to the Notification of Non-Paired Ship Station Frequencies used for Narrow-Band Direct-Printing Telegraph and Data Transmission Systems
- 308 (BB) Relating to the Channel Spacing of Frequencies allocated to the Maritime Mobile Service in the Bands 156–174 MHz
- 503 (BC) Relating to the Coordination, Notification, and Recording in the Master International Frequency Register of Frequency Assignments to Stations in the Broadcasting-Satellite Service in Region 2
- 407 (BF) Relating to the Unauthorized Use of Frequencies in the Bands Allocated to the Aeronautical Mobile (R) Service
- 400 (BH) Relating to the Treatment of Notices Concerning Frequency Assignments to Aeronautical Stations in the Bands Allocated Exclusively to the Aeronautical Mobile (R) Service between 2850 and 22 000 kHz
- 401 (BI) Relating to the Implementation of the Frequency Allotment Plan in the Bands Allocated Exclusively to the Aeronautical Mobile (R) Service Between 2850 and 22 000 kHz
- 406 (BL) Relating to the Use of Frequency Bands, Higher than the HF Bands, in the Aeronautical Mobile (R) Service and the Aeronautical Mobile-Satellite (R) Service for Communication and for Meteorological Broadcasts
- 38 (BR) Relating to the Reassignment of Frequencies of Stations in the Fixed and Mobile Services in the Bands Allocated to Radiolocation and Amateur Services in Region 1
- 404 (BT) Relating to the Implementation of the New Arrangement of Bands Allocated Exclusively to the Aeronautical Mobile (R) Service Between 21 924 and 22 000 kHz
- 403 (CB) Relating to the Use of Frequencies 3023 kHz and 5680 kHz Common to the Aeronautical Mobile (R) and (OR) Services
- 405 (CC) Relating to the Use of Frequencies of the Aeronautical Mobile (R) Service
- 316 (CE) Relating to Technical Cooperation with the Developing Countries in Maritime Telecommunications
- 310 (CN) Relating to Frequency Provisions for Development and Future Implementation of Ship Movement Telemetry, Telecommand, and Data Exchange Systems
- 600 (CO) Relating to the Use for the Radionavigation Service of the Frequency Bands 2900–3100 MHz, 5470–5650 MHz, 9200–9300 MHz, 9300–9500 MHz, and 9500–9800 MHz
- 8 (CV) Relating to Implementation of the changes in Frequency Allocations in the Bands between 4000 kHz and 27 500 kHz
- 703 (CW) Relating to the Calculation Methods and Interference Criteria Recommended by the CCIR for Sharing Frequency Bands between Space Radiocommunication and Terrestrial Radiocommunication Services or between Space Radiocommunication Services
- 11 (CY) Relating to the Use of Radiocommunications for Ensuring the Safety of Ships and Aircraft of States not Parties to an Armed Conflict
- 312 (DA) Relating to the Introduction of New Calling Procedures for HF AIA Morse Telegraphy
- 311 (DB) Relating to the Introduction of a Digital Selective Calling System to Meet the Requirements of a Maritime Mobile Service
- 12 (DC) Relating to the New Rules for the Formation of Call Signs
- 313 (DD) Relating to the Introduction of a New System for Identifying Stations in the Maritime Mobile and Maritime Mobile-Satellite Services (Maritime Mobile Service Identities)
- 14 (DG) Relating to the Transfer of Technology
- 202 (DH) Relating to the Convening of a World Administrative Radio Conference for the Mobile Services
- 702 (DK) Relating to the Convening of a Regional Administrative Radio Conference to Establish Criteria for the Shared Use of the VHF and UHF Bands Allocated to Fixed, Broadcasting, and Mobile Services in Region 3

CISPR Plenary Assembly

(Tokyo, July 1980)

Jerzy RUTKOWSKI
CCIR Senior Counsellor

Introduction

CISPR (*Comité international spécial des perturbations radioélectriques* or International Special Committee on Radio Interference) is an organ of the International Electrotechnical Commission (IEC) aimed at promoting international agreement on the following aspects of radio interference:

1. Protection of radio reception from interference sources such as:

- electrical appliances of all types;
- ignition systems;
- electricity supply systems, including electric transport systems;
- industrial, scientific and electro-medical radio frequency equipment (excluding radiation from transmitters intended for conveying information);
- sound and television broadcasting receivers.

2. Equipment and methods for the measurement of interference.

3. Limits for interference caused by the sources listed in item 1 of this clause.

4. Requirements for the immunity of sound and television broadcast receiving installations from interference and (in liaison with IEC Technical Committees) the prescriptions of methods of measurement of such immunity.

5. Impact of safety regulations on interference suppression of electrical equipment.

The CISPR co-operates very closely with the International Radio Consultative Committee and, in particular:

- undertakes special studies of radio interference at the request of the CCIR;
- consults with the CCIR where it appears that an extension of the range of measuring equipment or of the scope of measurements, beyond those related to the primary interest of the CISPR, would be mutually advantageous;
- brings to the attention of the CCIR details of any CISPR studies which appear likely to interest them;
- exchanges observers at meetings;
- accepts a representative of the CCIR as an observer at the meetings of the CISPR Steering Committee.

The CISPR is composed of the following member bodies:

- each National Committee of the IEC (now about 43 countries all over the world);
- European Broadcasting Union (EBU);
- International Radio and Television Organization (OIRT);
- International Conference on Large High Voltage Electric Systems (CIGRE);
- International Union of Producers and Distributors of Electrical Energy (UNIPED);
- International Union of Railways (UIC);

— International Union of Public Transport (UITP).

The International Civil Aviation Organization (ICAO) and the International Union for Electroheat (UIE) also send observers to meetings of CISPR.

Any other international organization having a recognized interest in the international aspects of the abatement of radio interference may become a member of the CISPR, subject to acceptance by the Plenary Assembly of the CISPR.

The CISPR meets regularly, a Plenary Assembly being held almost every year, but most of its work is done within its Sub-Committees and their working groups.

The results of the work of the CISPR are published in the form of "CISPR Publications" edited by the Central Office of the International Electrotechnical Commission (1, rue de Varembe, CH-1211 Genève, Switzerland). Up to the present, the following publications have been issued:

CISPR 7 [1969]
Recommendations of the CISPR, and Amendment No. 1 [1973]

CISPR 7A [1973]
First supplement

CISPR 7B [1975]
Second supplement

CISPR 8 [1969]
Reports and Study Questions of the CISPR, and Amendment No. 1 [1973]

CISPR 8A [1973]
First supplement

CISPR 8B [1975]
Second supplement

CISPR 9 [1978]
Limits of radio interference and leakage currents according to CISPR and national regulations. Section one: CISPR limits of radio interference and report of national limits. Section two: Maximum permissible values of leakage currents and limiting values of capacitance and energy for radio interference suppression capacitors

CISPR 10 [1976]
Organization, rules and procedures of the CISPR

CISPR 11 [1975]
Limits and methods of measurement of radio interference characteristics of industrial, scientific and medical (ISM) radio-frequency equipment (excluding surgical diathermy apparatus), and Amendment No. 1 [1976]

CISPR 11A [1976]
First supplement

CISPR 12 [1978]
Limits and methods of measurement of radio interference characteristics of vehicles, motor boats, and spark-ignited engine-driven devices

CISPR 13 [1975]
§ Limits and methods of measurement of radio interference characteristics of sound and television receivers.

CISPR 14 [1975]
Limits and methods of measurement of radio interference characteristics of household electrical appliances, portable tools and similar electrical apparatus

CISPR 15 [1975]
Limits and methods of measurement of radio interference characteristics of fluorescent lamps and luminaires, and Amendment No. 1 [1978]

CISPR 16 [1977]
CISPR specification for radio interference measuring apparatus and measurement methods

(Publications 1 to 6 are now superseded in Publication 16.)

The complete list of CISPR publications, including prices and detailed description of their content, is included in the catalogue of IEC publications available on request from the IEC central office at the above-mentioned address (Price: 9 Swiss francs).

1980 CISPR Plenary Assembly

The 1980 Plenary Assembly of the International Special Committee on Radio Interference and the meetings of its Sub-Committees:

- A — Radio interference measuring equipment
- B — Interference from industrial, scientific and medical radio-frequency apparatus
- C — Interference from overhead power lines, high voltage equipment and electric traction systems
- D — Interference relating to motor vehicles and internal combustion engines
- E — Interference characteristics of radio receivers
- F — Interference from motors, household appliances, lighting apparatus and the like

was held in Tokyo, 14 to 25 July 1980, in the premises of the Japanese Economic Council (Keidanren Building). One hundred and four delegates from 15 countries and three observers from international organizations (CCIR, ICAO and UIE) participated. The CCIR presented a report to this meeting on its work related to CISPR activities, describing, in particular, the implications of Final Acts of the World Administrative Radio Conference (WARC-79), also taking into account the results of the Interim Meetings of CCIR Study Groups, June-July 1980 (mainly Study Group 1—Spectrum utilization. Monitoring). This report complemented the report by the CISPR observer to the WARC-79, Mr. A. de Jong (Netherlands), giving more details on radio-frequency spectrum utilization in the frequency bands designated for industrial, scientific and medical (ISM) applications. It also included among its annexes a new draft study programme of Study Group 1 concerning the limitation of radiation from ISM equipment.

The matters of mutual interest to CISPR and CCIR and/or concerning co-operation between these two organs were included in the agendas and discussed at the meetings of the CISPR Steering Committee at its Plenary Assembly, and at the meetings of almost all the CISPR Sub-Committees.

The following important decisions and/or conclusions of interest to the CCIR and to the ITU as a whole were adopted:

1. A new CISPR study question on interference to mobile radiocommunications

by the ignition systems of individual vehicles and groups of vehicles (as a response on CCIR Opinion 49-1).

The first results of the work of CISPR in this respect were presented by some administrations.

The feeling was expressed that the value of the usable field strength to be protected for the mobile services *should be determined by the CCIR* and that close co-operation between CCIR Study Group 8 (Mobile services) and the CISPR Sub-Committee D to solve the problems of limits on interference to mobile radio-communications by mobile systems in order to find a compromise between the quality and reliability of the service and the economic factors concerning the interference suppression systems in vehicles would be desirable.

2. Amendments to table II of Amendment No. 1 [1976] to CISPR Publication 11 [1975] on limits and methods of measurements of radio interference characteristics of ISM radio-frequency apparatus for a frequency range from 150 (148.5) to 1000 MHz were introduced taking account of the changes in the Table of Frequency Allocations introduced by the WARC-79.

3. Note was taken of Resolution 63 (AG) of the WARC-79 and of the new draft study programme of the CCIR on the limitation of radiation from ISM equipment.

The feeling was expressed that to assure proper co-operation between CCIR Study Group 1 and CISPR Sub-Committee B it would be highly desirable to convene an Interim Working Party of Study Group 1 to study this problem. The CISPR Sub-Committee B experts could participate as regular members of this Interim Working Party. In connection with the Table of ISM frequencies included in the report by the CISPR observer (Doc. CISPR (Secretariat) 980, March 1980), the CCIR Secretariat is requested to make available the definitive footnote numbers when they are available.

4. In connection with the new CISPR study questions on interference from data processing equipment (DPE) and similar appliances, preliminary contributions have been noted and a draft document on the limits of interference and methods of measurement for electronic data processing equipment was adopted for circulation between the CISPR member countries within the 6-months rule (according to IEC procedure).

5. The following CCIR documents of interest to the CISPR (transmitted to the CISPR in The Hague, 1979) were presented and noted by the meeting: Opinion 2-1, Question 10/1, Question 4-1/1, Study Programme 4A-1/1, Question 46-1/1 and Study Programme 46A/1 (modifications to these documents introduced by the Interim Meeting of CCIR Study Group 1 were brought to the attention of the meeting).

6. Since, in many CISPR publications, data on frequency usage are based on the preceding version of the Table of Frequency Allocations from the Radio Regulations (Geneva, 1959), the CCIR Secretariat was requested to review those CISPR publications concerned and to forward its comments to the CISPR Secretariat. (They do concern such changes as the lower limit of radio-frequency spectrum 9 kHz (instead of 10 kHz) changes in frequency allocation limits for broadcasting service—148.5 kHz instead of 150 kHz, etc.).

It should be noted that in some cases the change from 10 to 9 kHz may have not purely formal consequences as for example for artificial networks used to measure conducted interference and which are calibrated for a frequency range going down to 10 kHz. The competent CISPR Sub-Committee A Working Group will investigate this problem.

7. Some problems concerning the terminology used in CISPR arose during the meeting. Working Group 2 of CISPR Sub-Committee B on data processing and office machines introduced a new term "conducted emanation" having practically the same meaning as the term "conducted interference" widely used up to now in other CISPR documents. The attention of Study Group B was drawn to unforeseeable consequences which may arise from the introduction of such new terms not defined either in the document itself or in the IEC Vocabulary.

8. The French Administration volunteered to undertake a study of the electromagnetic radiation produced by electrical equipment using radio-frequency generators (in the air and on the ground). This proposal was supported by several delegations and also by ICAO (and the CCIR) and it was agreed that a new CISPR study question will be prepared for the next meeting. ICAO already conducts similar studies and is prepared to offer some preliminary results to the Interim Meeting of Study Group 8 of the CCIR.

9. Within CISPR Sub-Committee E (Interference characteristics of radio receivers), a proposal was presented by the Federal Republic of Germany delegation (Doc. CISPR (Germany) 3) aiming at improvement of the antenna input voltage, the characteristics of the receivers described in CISPR Publication 13 by about 6 to 16 dB, depending on the case. The original proposal met fairly strong opposition, mainly from industry, and a compromise proposal was drafted by a special *ad hoc* group. This compromise proposal obtained wide support from many delegations, but some needed to consult their governments before taking a definitive decision. Finally it was decided that further study of this question is necessary.

The CCIR observer pointed out the importance of improving characteristics of television and FM sound broadcasting receivers in the light of the forthcoming International Telecommunication Union (ITU) planning conferences for television and FM sound broadcasting for the European and African broadcasting areas.

The updating of frequency band limits in Publication 13 will also be necessary in the light of the extensions of the frequency allocation for FM sound broadcasting up to 108 MHz by the WARC-79.

10. In connection with Recommendation 704 (ZV) of the WARC-79, CISPR Sub-Committee E took note of this new Recommendation and decided that the matter should be discussed by its Working Group 1, especially with regard to the limits of radiation from the local oscillators of FM receivers in the extended frequency band up to 108 MHz (see CISPR Publication 13).

11. Considerable progress may be noted in the drafting by CISPR Sub-Committee C of a CISPR manual (code of practice) on radio interference from overhead power lines and high-voltage equipment. Work on this manual has almost been completed and the individual chapters of the text will be sent to the CISPR National Committees for final approval under the 6-months rule.

Concise information on this manual will be presented as an official contribution of CISPR to the work of CCIR Study Group 1 for its final meeting in 1981.

12. A new revision of CISPR Study Question 52 was adopted on measurement of interference in the frequency range above 30 MHz (in two ranges from 30 to 300 MHz and 300 to 1000 MHz) from high-voltage lines as amended by

Doc. CISPR/C (Secretariat) 30 April 1980.

13. A number of modifications were introduced by CISPR Sub-Committee F to CISPR Publication 14 "Interference from household appliances incorporating electric motors and control devices", the most important change probably being a slight increase of about 4 dB (μ V) in the value of the limit of discontinuous interference of specific appliances in the frequency band 0.15 to 0.2 MHz. The other changes mainly concern details of measurement methods and/or drafting improvements on the additions of new clauses concerning new types of appliance not up to now included in Publication 14 such as: automatic dispensing machines, juke-boxes, automatic entertainment machines, etc. A new revised version of CISPR Publication 14 including all the above-mentioned amendments will be available during the spring of 1981.

CISPR Publication 15 on interference from luminaires was also slightly amended by Sub-Committee F.

14. In connection with the new CISPR Study Question 52/1, a question was raised within Sub-Committee C as to whether the CISPR should study the problem of passive interference (ghost images and re-radiation caused by high power lines). When this problem was raised in the Steering Committee, it was decided that the problem of ghost images shall not be the subject of study within the CISPR. As regards the problem of re-radiation from high power lines, it was decided that a decision be deferred to the next CISPR meeting (1981) to permit consideration of this question within the CISPR and the CCIR.

15. The next meeting of CISPR Sub-Committees and Steering Committee will take place in Toronto, Canada from 19 September to 4 October 1981. There will be no CISPR Plenary Assembly in 1981.

16. During the meetings of the CISPR Sub-Committees, at the CISPR Plenary Assembly and at the final meeting of the Steering Committee, the feeling was expressed many times that close co-operation between the CISPR and the CCIR is of the utmost importance and that new ways of making this co-operation yet closer should be found. In this connection, the possibilities of direct participation by CISPR representatives in the Interim Working Parties of the CCIR concerned with radio interference problems was highly recommended.

(Original language: English)

United States

national spectrum management

Introduction

SPECTRUM management in the United States is derived from the Communications Act of 1934. This Public Law created the Federal Communications Commission, an independent Government agency directly accountable to the Congress. The FCC is responsible for regulating non-Federal Government telecommunications. The FCC issues licenses to all public users of radio frequencies including local and state governments.

Under the Communications Act of 1934, the President has authority to assign frequencies to all Federal Government agencies. By Executive Order, that authority is delegated to the Secretary of the Department of Commerce. Within the Department of Commerce this responsibility is exercised by the Administrator of the National Telecommunications and Information Administration (NTIA). The Administrator is the President's principal telecommunications advisor and is responsible for use of the radio spectrum by all Federal Government agencies.

Government and non-Government frequency management structures are not identical but they combine to satisfy national objectives. This dual control over a single resource is unique in the United States. It has proven effective and benefits from the checks and balances system which is fundamental to the United States Government.

NTIA's primary source of advice is the Interdepartment Radio Advisory Committee, or IRAC, representing major Federal Government users of the radio spectrum. The FCC maintains a liaison with the IRAC to represent non-Federal Government interests since almost half of the frequency bands are shared by Government and public users. The third branch of the United States Government, the Judiciary, may review and decide on the constitutionality or legality of all Presidential (NTIA) and Congressional (FCC) decisions and policies (see figure 1).

International frequency coordination is carried out through the Department of State. The FCC and NTIA together advise the State Department and help prepare United States policy with respect to treaty obligations, international conferences, and other international spectrum matters.

The management structure within any nation is determined by the culture of its people and by the structure of each nation's Government. Since national frequency management policies are based on and reflect the rules and regulations of the International Telecommunication Union, there is a commonality shared by all ITU Member countries. It is the purpose of this article to provide an understanding of the US frequency management system so as to facilitate a dialogue between ITU Member nations and the United States regarding the use of a vital natural resource, the radio frequency spectrum.

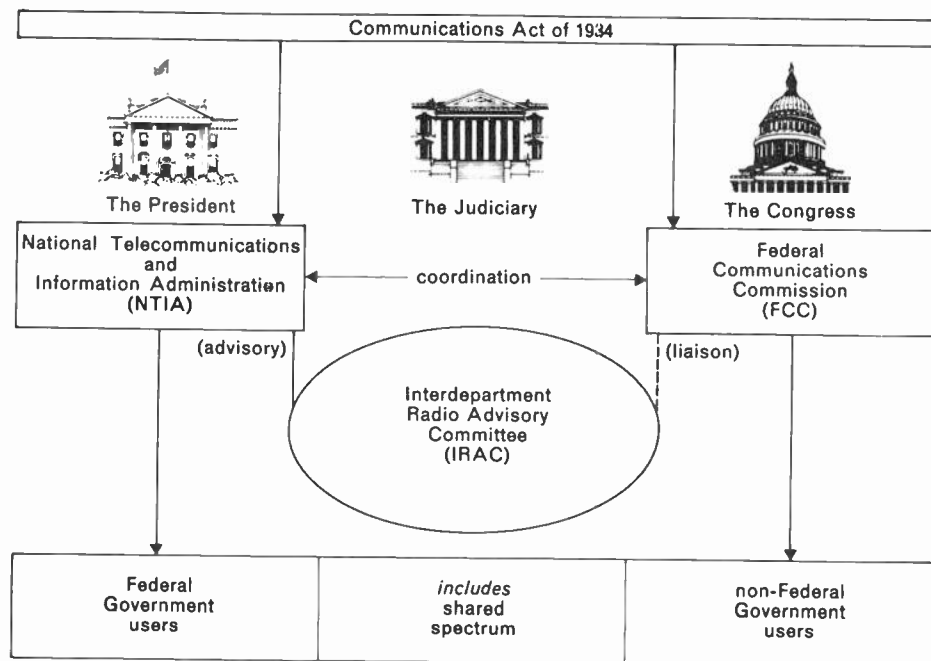


Figure 1—National spectrum management

Part I

The NTIA role in national spectrum management

THE National Telecommunications and Information Administration is the organizational element within the Department of Commerce which exercises the President's responsibility concerning the use and management of the radio spectrum by agencies of the Federal Government. The principal spectrum functions are to provide: frequency assignments to the Federal Government agencies; plans and policies for the effective and efficient use of the spectrum in coordination with the FCC; and assistance to the Department of State in the development of US proposals and positions for conferences of the ITU.

Structure

The NTIA is directed by the Assistant Secretary of Commerce for Communications and Information, who is the principal advisor to the President for telecommunications (see figure 2). The main staff element in NTIA concerned with spectrum matters is the Office of Federal Systems and Spectrum Management which is headed by an Associate Administrator (see figure 3). Within this office there are four organizational elements concerned with spectrum management. The Director of Spectrum Plans and Policies is concerned with both international and national spec-

trum policy. It is the focal point for the Government preparations for ITU Conferences. The IRAC is chaired by the Director and provides assistance to him. The Frequency Assignment and IRAC Administrative Support Division is directly concerned with the day-to-day processing of requests for frequency assignments and the day-to-day management of these assignments. The Spectrum Engineering and

Analysis Division provides engineering and analysis support to the Associate Administrator required in the resolution of electromagnetic compatibility problems and for the preparation of technical studies required both for national and international frequency management. The Computer Services Division supports all the other organizational elements associated with spectrum management by providing

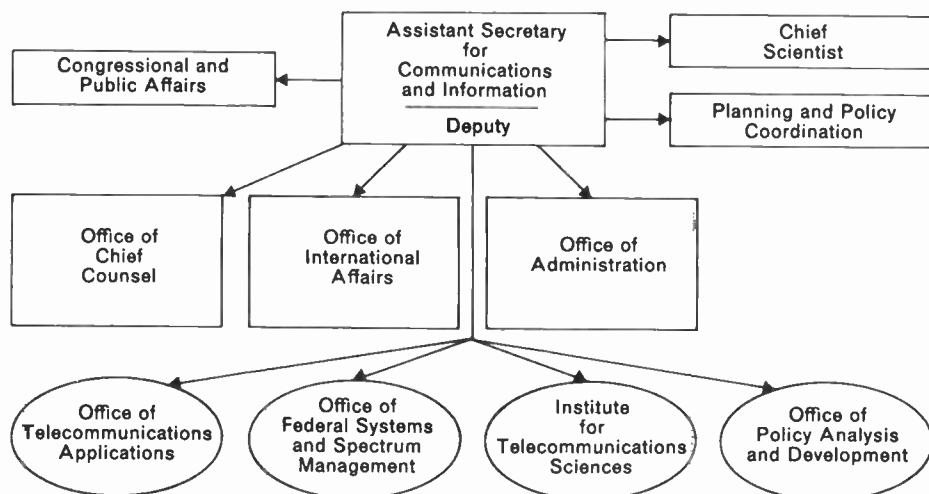


Figure 2—Department of Commerce—National Telecommunications and Information Administration

the computer operations and software. The Institute for Telecommunications Sciences provides research in support of spectrum management in such areas as propagation and the use of new technologies.

Management is divided into four program areas: namely, Spectrum Plans and Policies; Spectrum Management; Spectrum Analysis; Frequency Assignment and Utilization, all of which are under direction of

a Deputy Associate Administrator for Spectrum (see figure 4).

The Spectrum Plans and Policies Program is concerned primarily with:

- long-range plans for national use of the spectrum, including development of the US National Table of Frequency Allocations and revisions thereto;
- preparing and coordinating US proposals and positions for ITU Radio Conferences as recommendations to the Department of State;
- developing, coordinating, and implementing plans and policies for the use of the spectrum by agencies of the Federal Government;
- resolution of conflicting requirements for the use of the spectrum; and
- providing direction and guidance to the IRAC.

The Spectrum Management Program is concerned primarily with:

- providing technical and administrative support for the IRAC; and
- providing training for new personnel entering the spectrum management career field, and in-service training for spectrum management personnel.

The Spectrum Analysis Program is primarily concerned with:

- assessing the various frequency bands to determine whether existing and future uses can be operated in a compatible manner, and determining opportunities for new radio services to share the spectrum;
- reviewing new communications-electronics system developments to determine how they may be accommodated within the spectrum;
- resolving technical problems relating to national and international spectrum issues; and
- developing analysis techniques and computer software to assist in the resolution of spectrum related problems.

The Frequency Assignment and Utilization Program is concerned primarily with:

- reviewing and processing of requests for frequency assignments and the authorization of such assignments;
- developing and maintaining data bases concerned with the use and management of the spectrum, including the development of appropriate computer software; and
- measuring the Federal Government's spectrum use by means of a mobile measurement van.

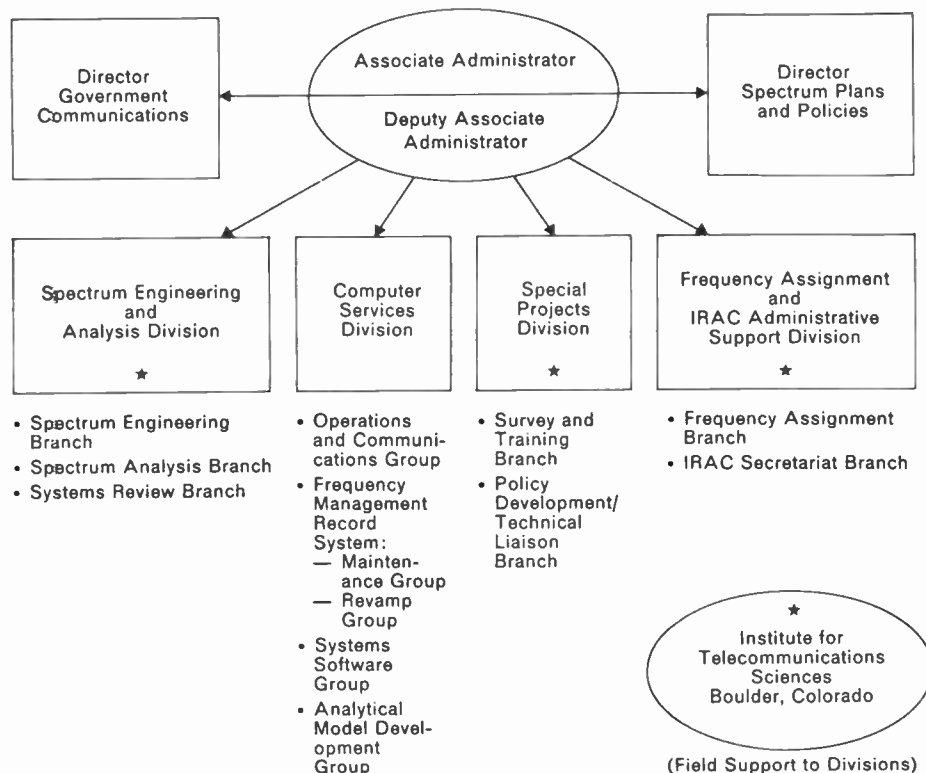


Figure 3—National Telecommunications and Information Administration—Federal Systems and Spectrum Management (January 1979)

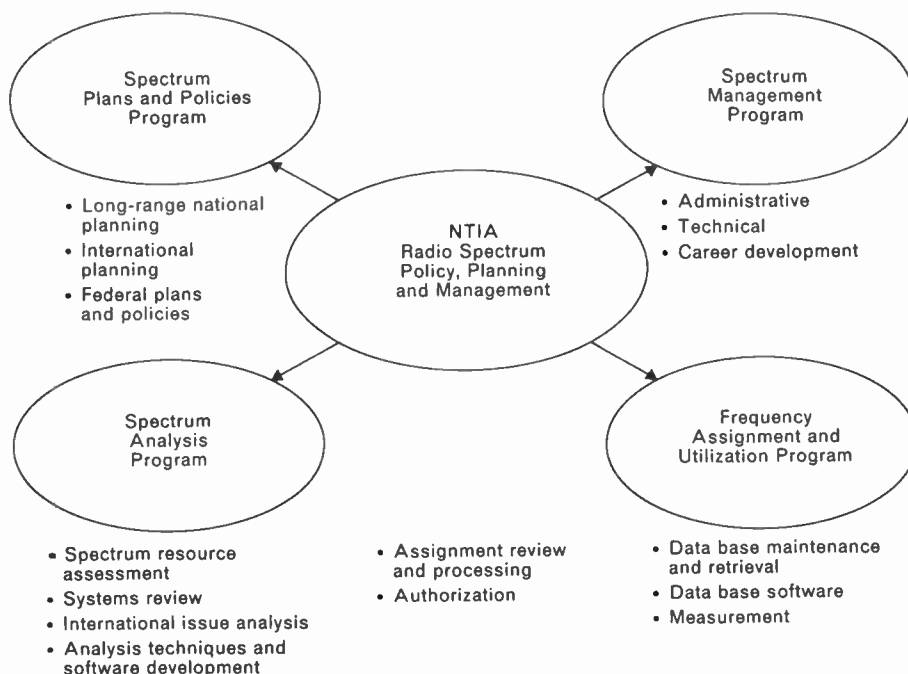


Figure 4—Coordinated Federal Government—spectrum management

In addition to the formal organization, NTIA utilizes the services of three advisory bodies to provide assistance and inter-agency coordination (see figure 5).

The first and most important group is the Interdepartment Radio Advisory Committee. This Committee, which has been in existence since 1922, consists of 18 representatives from the major Federal Government users of the spectrum and a liaison representative from FCC. It is the function of this Committee, which meets twice a month, to provide advice and assistance to the Administrator of NTIA in all areas related to spectrum management. Representatives on this Committee provide a broad range of expertise with respect to use of the spectrum by all of the radio services. The IRAC provides a forum which permits a knowledgeable discussion of the problems associated with the management of the spectrum and means by which recommendations can be developed and coordinated. The IRAC is primarily concerned with the Federal Government's use of the spectrum, the FCC liaison representative provides, however, comments on behalf of the public. This Committee and its subcommittees supply the primary means for coordination between the Government and non-Government users of the spectrum.

There are three subcommittees as part of the IRAC:

- 1) the Frequency Assignment Subcommittee (FAS) which meets monthly to consider, coordinate and recommend frequency assignments for the Government users of the spectrum;
- 2) the Spectrum Planning Subcommittee (SPS) that meets semi monthly to:
 - a) review new Government systems, determining the availability of spectrum support for these systems,
 - b) review International Frequency Registration Board (IFRB) circulars concerning space systems, and
 - c) develop frequency plans in support of Government operations;
- 3) the Technical Subcommittee that provides technical support to the IRAC, FAS and SPS.

In addition, an International Notification Group processes notices to the IFRB and provides recommendations concerning queries and requests received from the Board.

The second advisory group is the Frequency Management Advisory Council (FMAC) that is composed of high-level experts from the non-Government sectors



The President

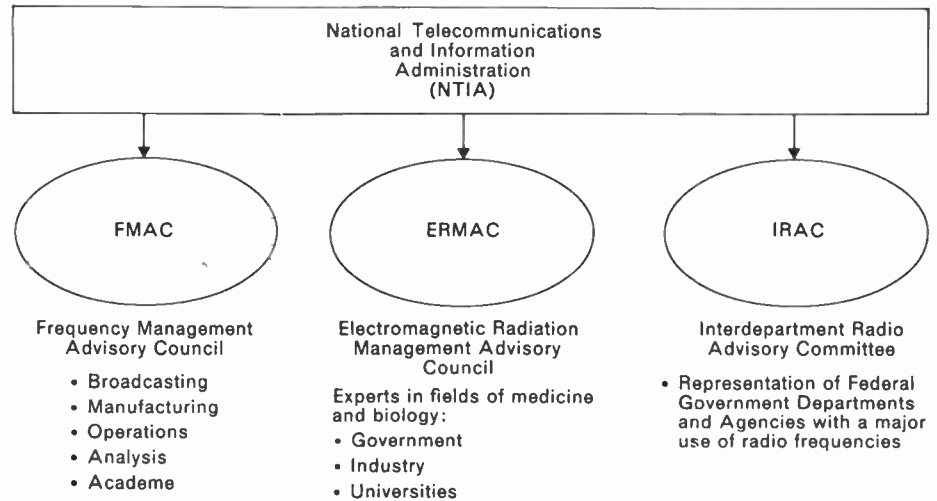


Figure 5—Spectrum management

of industry and academe. This Council provides assistance and advice to the Administrator of NTIA based on its overview of the functioning of the Government's management of the spectrum.

The third advisory body is the Electromagnetic Radiation Management Advisory Council (ERMAC) which is composed of well known non-Government experts in the field of the potential effects of non-ionization radiation on people and things. This Council provides recommendations to the Administrator of NTIA with regard to

search and policies concerning hazards which may be obtained from the radiation of electromagnetic energy, i.e. the use of the radio spectrum.

Spectrum management

NTIA has a five-fold approach to spectrum management.

The first function is directed towards ensuring that spectrum is available before a Federal Government agency is permitted to purchase new systems.

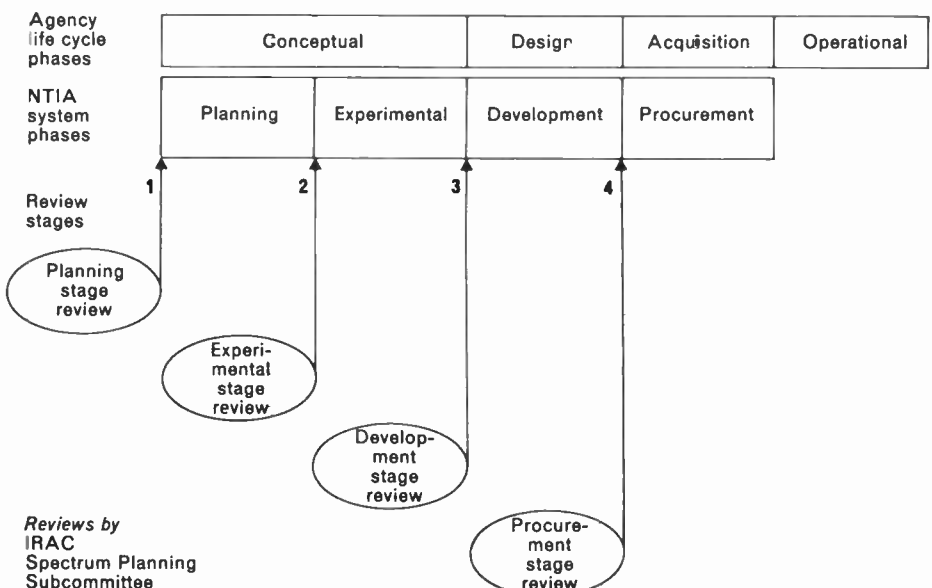


Figure 6—Relationship between NTIA systems review and Federal Agency life cycle phases

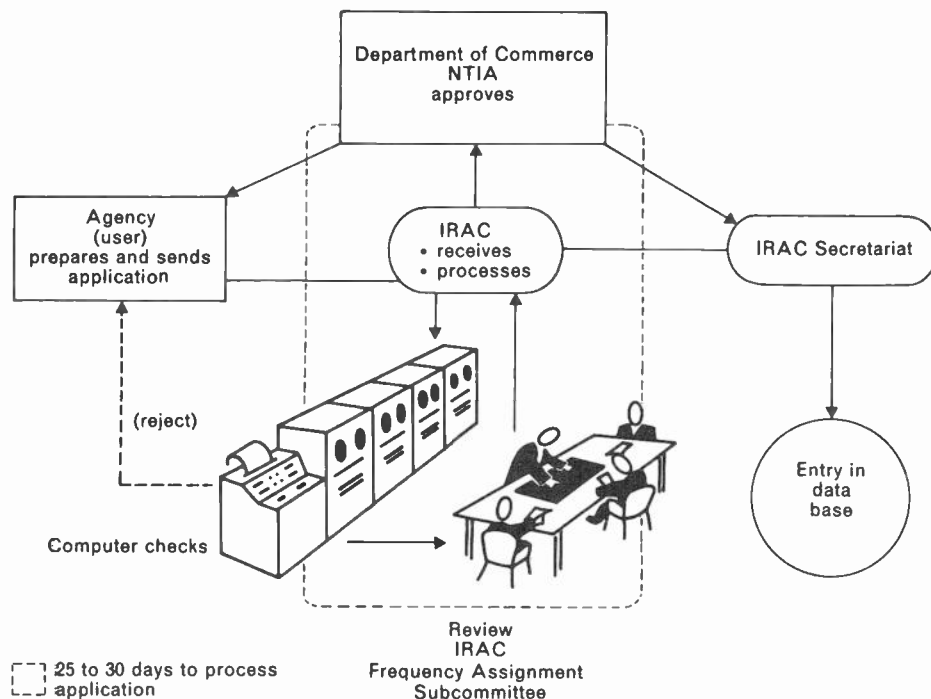


Figure 7—Government frequency applications processing

The second function is to ensure that frequency assignments are engineered so that systems will neither cause interference to, nor receive harmful interference from, existing and planned systems.

The third function is directed toward surveillance of the use of the spectrum after assignments have been made to ensure they are being used as authorized.

The fourth function is to assess the actual, planned and potential use for each frequency band available for Government use to determine probable cases of incompatibility, the potential for intra- and inter-service sharing and for the expansion of new uses of the spectrum.

The fifth function is directed toward a timely and accurate record (data base) of

all uses of the spectrum. This approach directly supports the other four approaches to spectrum management in providing the necessary information on which spectrum decisions can be made.

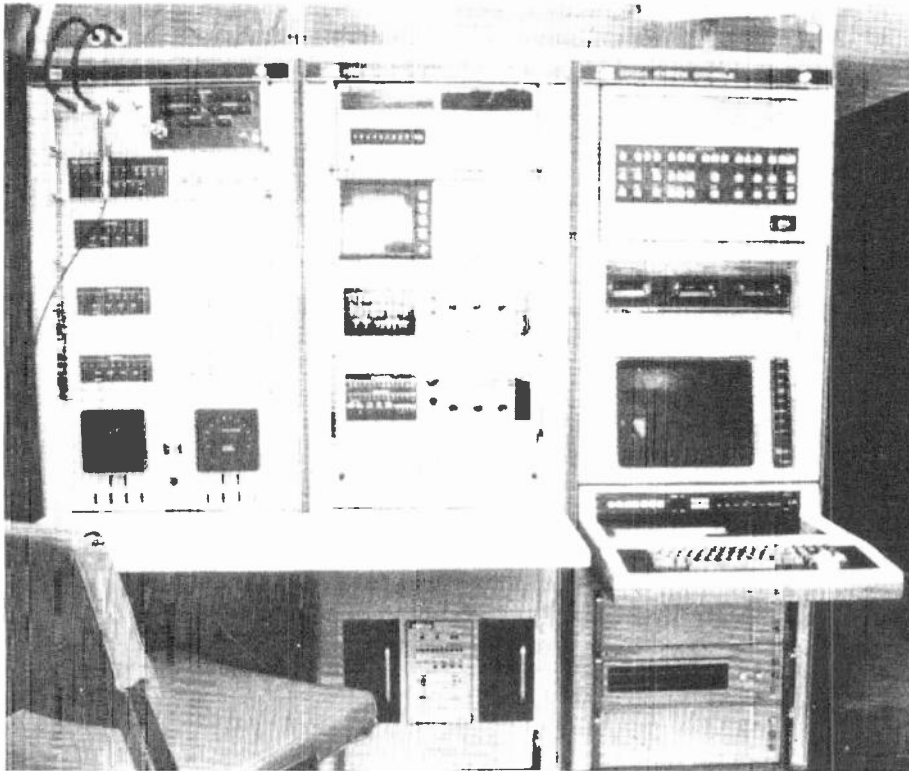
NTIA's first function in spectrum management is to ensure that new proposed uses of the spectrum take into consideration each existing and planned use so as to ensure that interference will not be caused or received by the new uses. NTIA requires that each Government agency that plans to develop or procure a new major telecommunications-electronics system provide detailed technical, employment and deployment information to NTIA for review before the agency commits funds for such systems. This information is reviewed by the Spectrum Planning Subcommittee (SPS) of the IRAC to ensure that the intended use is in conformance with international and national radio regulations and that it can be operated compatibly with other systems in the frequency band proposed. These reviews are conducted through all phases of each system's development (see figure 6). The SPS utilizes the service of the Spectrum Analysis Program to assess these factors in providing its recommendations to the Director of Spectrum Plans and Policies. If the review by the SPS is favorable, then the NTIA will permit the Government agency to proceed to develop or procure the system. If the review is unfavorable, the NTIA will either deny spectrum support or provide suggestions whereby the system may be accommodated in the spectrum. This procedure ensures that funds will not be expended for systems that cannot be supported in the spectrum as proposed. It also provides a means by which each of the Federal agencies and the FCC become aware of the plans of all agencies for systems that will use the spectrum. The guidance and authority given by NTIA is broad and flexible. It provides an early warning to new systems designers of those environmental factors which may inhibit the use of new systems and provides direction for the most fruitful manner in which spectrum may be obtained by the applicant.

NTIA's second function in spectrum management is to ensure that individual frequency assignments are engineered so as not to cause or receive interference to or from other frequency assignments. Specific authority from NTIA must be obtained for all uses of the radio frequency spectrum by the Federal Government agencies. Each agency must select the specific frequencies it needs to meet its requirements, based on frequency assignment data made available by NTIA. Applications for frequency assignments received from the agencies are



Figure 8

800141



800142

Figure 9

reviewed by the Frequency Assignment Subcommittee (FAS) of the IRAC to ensure that the assignments conform to national and international regulations and that they are compatible with existing and planned frequency uses. The Spectrum Analysis Program of NTIA is utilized by the FAS to provide analysis support when complex assignment problems are encountered. After review of the applications for frequency assignment, the FAS provides its recommendations to the NTIA with respect to the approval or disapproval of the applications. Based on this review the NTIA makes the appropriate frequency assignments to the agencies involved in behalf of the President (see figure 7).

As with any system of management, it is essential that surveillance of the end product is conducted to ensure that desired results are obtained. The third function addresses that area. NTIA utilizes a spectrum measurement van which it deploys to measure how the spectrum is used by agencies that have been assigned frequencies (see figures 8 and 9). A typical output from this van is shown in figure 10. Members of the NTIA staff also make inspection visits to the radio stations and spectrum management offices of the Federal agencies to ensure that effective spectrum use is being maintained. In addition, each frequency assignment is limited to a term of not more than five years at which time it must be reexamined and reviewed by the FAS to determine its need.

The fourth function is concerned with future planning and consists of an intensive analysis of each frequency band, e.g. 960-1215 MHz. This technical, administrative and operational analysis is designed to determine potential interference situations, and develop administrative and operational approaches leading towards a more intensive use of the spectrum available. Each band available for Government use is reviewed on a periodic basis to ensure that future spectrum planning is based on sound technical and operational facts.

The fifth function is concerned with the provision of data to support spectrum decisions. Automated data bases are maintained of the assignments made by the FCC and the NTIA as well as the International Frequency List. In addition the technical and operational characteristics of systems reviewed by the SPS are available. These data bases are maintained on a daily basis by computer techniques and extracts of pertinent information are available to agency spectrum managers for their use in selecting proposed frequency assignments and for the selection of frequency bands for new operations.

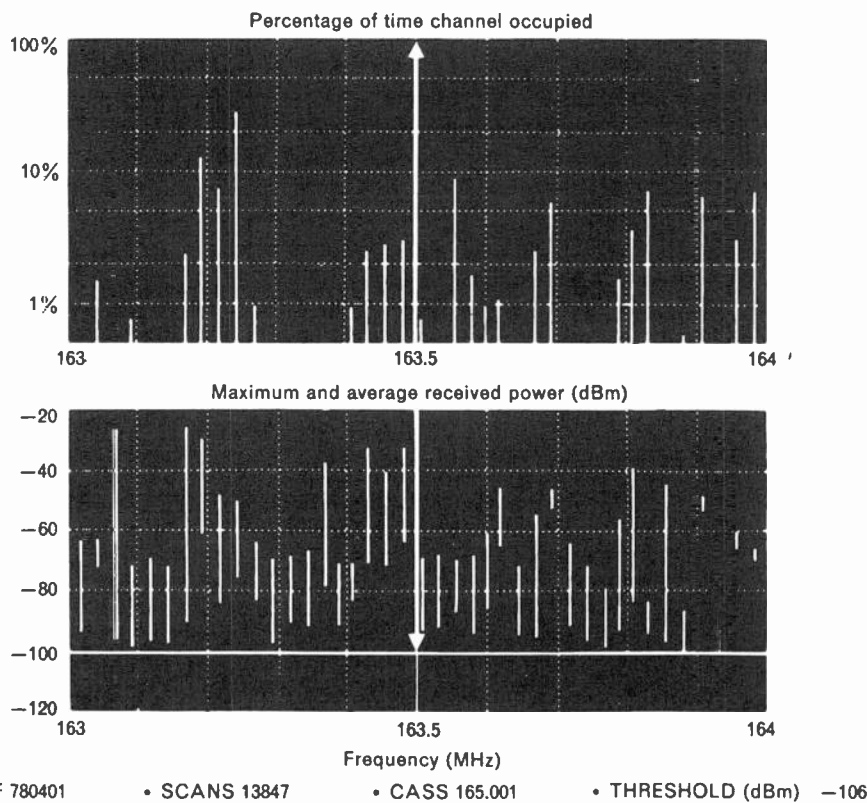


Figure 10—Occupancy statistics for Washington, DC area (June 1978). Usage summary plot for 163-164MHz:

Part II

The FFC role in national spectrum management

THE Federal Communications Commission is an independent regulatory agency, responsible to the Congress, and derives its authority from the Communications Act of 1934, as amended, and the Communications Satellite Act of 1962. The Commission has three functions: rule-making, administration and adjudication. The Communications Act (as did its predecessor statute which established the Federal Radio Commission, the Radio Act of 1927), gave the President the authority to assign frequencies to Federal Government stations,* while giving the Commission responsibility for management of the radio spectrum used by the civil sector, including state and local governmental entities.

Structure

Organizationally, the Commission is comprised of seven Commissioners who are appointed by the President, with the advice and consent of Congress, for overlapping terms of seven years. No more than four may be from the same political party and one is appointed Chairman. Congressional control is exercised through subcommittees of the US Senate and the House of Representatives.

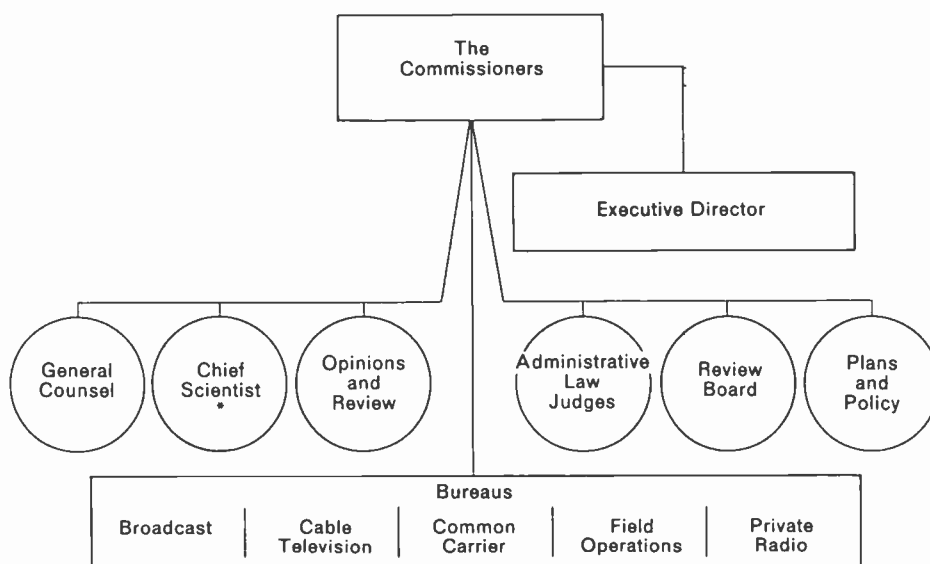
The Commission is supported by 12 principle staff elements and employs approximately 2200 with all but about 475 located in the Washington, DC area (see figure 1). Briefly, the Executive Director's office is responsible for administrative functions and support. The Secretary falls within his responsibilities as does the data processing effort, emergency communications activities, and personnel and financial management.

The General Counsel's office is responsible for providing legal opinions and advice to the Commissioners and staff elements. The Office of Science and Technology (formerly the Office of Chief Engineer) is responsible for the allocation of frequencies and for rendering advice concerning engineering, technical and scientific aspects of telecommunications activities, domestic

and international. Since the Office is also responsible for development and implementation of broad frequency management policies and for coordination with the Executive Branch in that area, more will be said later in this paper about this advisory element.

and render advice to the Commissioners and staff officers on matters under their jurisdiction.

The Field Operations Bureau (FOB) has six Regional Directors and maintains 31 District and Limited Enforcement Offices.



* Interface with NTIA Frequency Management and FCC Liaison with IRAC including subcommittees.

Figure 1

The Office of Plans and Policy provides coordinated policy advice to the Commission in all areas of agency authority and responsibility. Since it manages the agency research budget, the Office is responsible for coordinating research and contractual activities within the Commission.

The elements responsible for developing and implementing specific policies and for licensing individual stations in their particular areas are sometimes referred to as "operating bureaus". These are the Broadcast, Common Carrier, Private Radio (formerly Safety and Special Radio Services), and Cable Television Bureaus. Within their respective spheres of responsibility, they conduct the principal licensing and rulemaking activities of the Commission

Their 13 monitoring stations (see figure 2) provide valuable support for frequency management activities. These facilities, located throughout the United States and Puerto Rico, are broadly responsible for enforcement of our rules, and assist in resolving interference complaints.

The three remaining offices—Opinions and Review, Review Board, and Administrative Law Judges—are the judicial arm of the Commission, holding adjudicatory hearings and disposing of appeals and related matters.

Spectrum management

For administrative reasons, the radio spectrum has been divided into essentially three

* This authority has subsequently been delegated to the National Telecommunications and Information Administration and is discussed elsewhere in this issue.

categories—exclusive Government (administered by the NTIA); exclusive non-Government (administered by the FCC); and shared (administered jointly). Division of the spectrum into such a segmentation scheme took place largely during the period 1935-1940 and, as technology has expanded to make use of the higher regions of the spectrum, the concept has continued. This segmentation is based solely on administrative agreement rather than statutory fiat.

Needless to say, the dual jurisdiction requires extensive coordination between the FCC and the NTIA. Such coordination takes place on many levels, but the primary liaison link is maintained through the Interdepartment Radio Advisory Committee. That organization is discussed elsewhere in this issue. However, as inferred previously, the Office of Science and Technology is responsible for developing and establishing spectrum management policies for the Commission and for coordinating, with the NTIA, the development of national policies regarding use of the radio spectrum. Consequently, liaison with

the NTIA and the Executive Branch agencies is a principal responsibility of the Office of Science and Technology, and that office provides the liaison representative for the Commission.

The FCC's approach to spectrum management covers a broad range of techniques. It extends from carefully engineered and protected assignments (such as broadcasting) to citizens' band where literally hundreds in a given locale must share use of a portion of the spectrum. Overall, the Commission currently provides for 68 different services, with additional services to meet new requirements being considered constantly.

Although rules governing each of the services are promulgated in ten volumes which are generally administered by the operating Bureaus referred to earlier, they have their frequency genesis in Part 2 Volume II which contains the national Table of Frequency Allocations and which is administered by the Office of Science and Technology.

As is the case with all Member nations of the ITU, the international Radio Regulations form the framework of our national regulations, and use of the radio spectrum is constrained by adherence to treaty obligations and other agreements to which the US is a party. Accordingly, spectrum management techniques are based on the internationally defined concepts of allocation, allotment, and assignment.

Because radio, from the very beginning of its use in this country, has been treated as a "public" or "free" good and because, under Section 303(g) of the Communications Act of 1934, as amended, the Congress directed the Commission to "...generally encourage the larger and more effective use of radio in the public interest...", the resource has been applied extensively. Use of the radio spectrum has become essential to our society because of the multiplicity of applications resulting from this climate and the pervasiveness of those applications.

Consideration of need for domestic civil allocation changes to permit expansion of

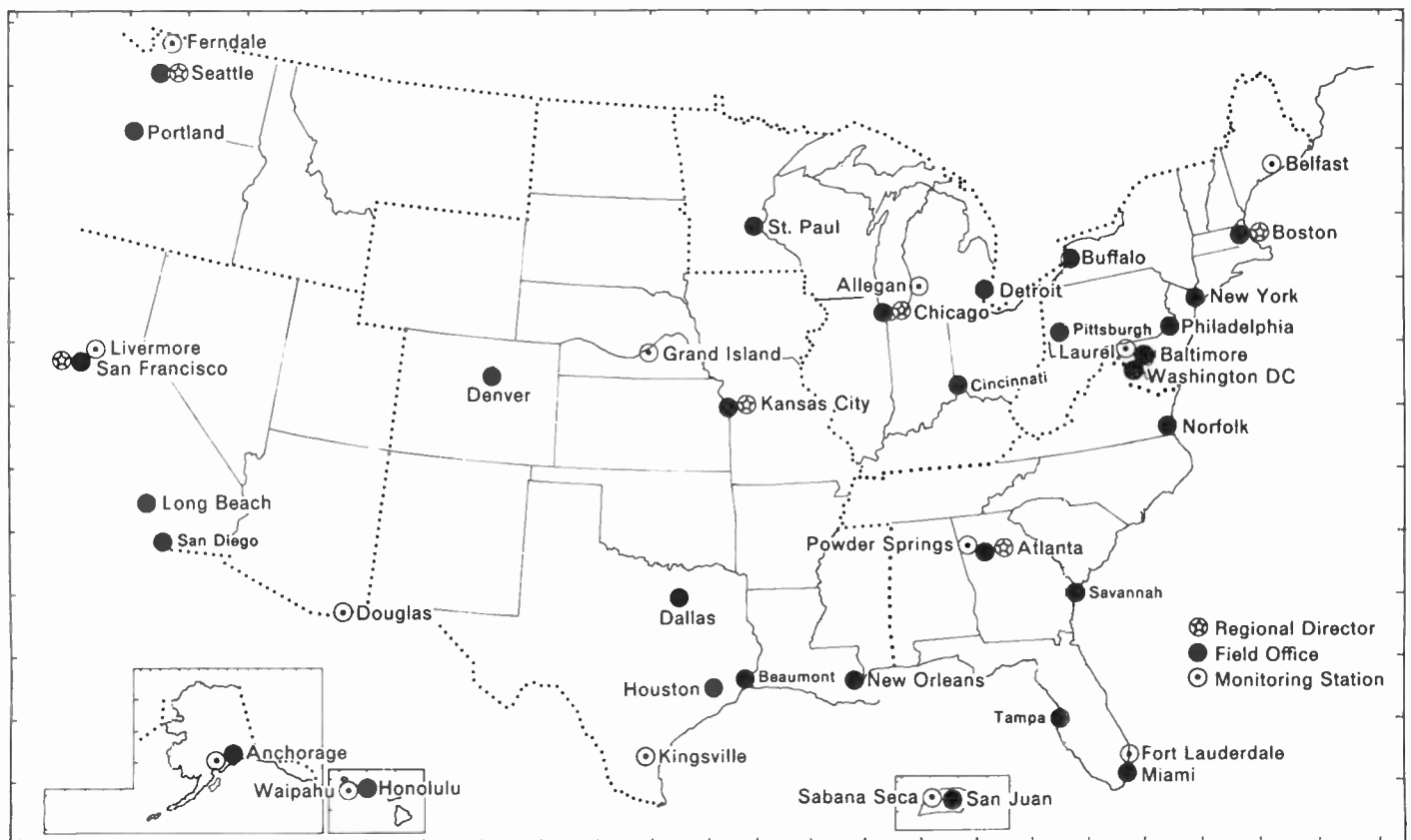


Figure 2—FCC field installations (October 1978)

existing applications or to accommodate new applications is primarily the responsibility of the Spectrum Allocations Division (SAD) of the Office of Science and Technology. In so doing, SAD conducts engineering, economic, social, statistical and legal studies looking toward making more efficient and effective use of the radio spectrum and radio technology. The studies are, of course, conducted primarily in conjunction with appropriate Commission Bureaus and Offices, and, as necessary, with private industry and government agencies as well. On completion of the studies, domestic allocation proposals are developed and recommended to the Commission for consideration.

In conducting these studies, other elements of the Office of Science and Technology are usually involved to varying degrees. The Research and Standards Division is responsible for developing technical standards for radio equipment. In this connection, the Commission, many years ago, adopted a fundamental policy of not inhibiting the design latitude of equipment manufacturers. Consequently, while performance goals or standards are set, the details of achieving these goals are not regulated. Additionally, the Division reviews and analyzes scientific and technical data concerning radio wave propagation for both terrestrial and space communications systems. Basic research is rarely conducted by the Commission but theoretical and experimental data are obtained from various sources by the Division regarding new communication techniques for applicability to those analyses.

The Laboratory Division, located in Laurel, Maryland, also conducts studies of new technology and equipment, but is responsible for the equipment authorization program and for calibration and installation of equipment used by other Commission offices. The equipment authorization program involves tests and/or analyses of radio equipments to ensure the capability of complying with established technical standards. Lists of type approved, type accepted, and certified equipments are then made available to the public. Unless specifically exempted, a given piece of equipment may not be sold, operated or even demonstrated legally unless it appears in these lists. It should be noted, however, that, with few exceptions, the FCC does not have jurisdiction over receivers.

Finally, the International and Operations Division is responsible for two major functions, namely, agency liaison and coordination with the NTIA and other Executive Branch agencies in spec-

trum related matters, and, in spectrum management activities, liaison between the US (as an administration) and the ITU. Included in the latter function are such activities as assisting in the resolution of international interference complaints, submitting notifications and other reports to the International Frequency Registration Board, and, for the International Telecommunications Satellite Organization (INTELSAT), acting in the capacity of notifying administration. Ancillary responsibilities in the area of frequency management include coordination of the Commission's preparation for radio conferences held under the auspices of the ITU, and the regulation of restricted radiation or low power devices, industrial, scientific and medical applications (ISM) equipment and experimental uses of radio.

Turning now from the broad aspects of spectrum management, let us consider the differences in approach taken by the various Operating or Licensing Bureaus, particularly since the Commission has generally followed the "block allocation" method in the sense that spectrum allocated to particular classes of service is largely under the jurisdiction of the Bureau that administers the service.

Broadcasting radio services

The principal broadcasting services addressed in this discussion are AM broadcasting (535-1605 kHz), FM broadcasting (88-108 MHz), and television broadcasting (54-72 MHz, 76-88 MHz, 174-216 MHz, and 470-806 MHz). In addition to these services, the broadcasting activity is concerned with administering auxiliary services such as: remote pickup, television auxiliary, studio-to-transmitter links and intercity relays, FM and television translators, instructional television fixed service and the international broadcasting service. In the interest of developing a discourse having reasonable bounds, the focus here shall be restricted to managing the allocation affecting the AM, FM, and television services.

AM broadcasting

The band of frequencies allocated for AM broadcasting is divided into 107 channels, with carrier frequencies separated by 10 kHz. The channels are categorized as clear channels, regional channels, and local channels, and the number of channels in

each category is 60, 41, and 6, respectively. Stations assigned to the various channels are further classified as shown in the table below.

Table

channels	stations
clear channels	Class I-A, Class I-B, Class II-A, Class II-B, Class II-D
regional channels	Class III-A, Class III-B
local channels	Class IV

A station's class tends to define the extent of service it is designed to render and the degree of protection from other stations it is to be afforded.¹ In general, Class I stations render service over wide areas, including skywave service at night. Class II stations provide groundwave service only and must afford protection to the nighttime service of Class I stations, which in most cases requires that Class II stations limit operation to daytime only. Class III stations are intended to render service to larger urban areas and contiguous suburbs. Class IV stations generally have very limited service areas and are designed to provide local service to smaller communities.

The Federal Communications Commission authorizes AM stations pursuant to a set of rules which address both technical and administrative considerations. An application to build and operate such a station may be filed on a "demand" basis. That is, a potential applicant determines that a station may be operated on a particular frequency in or near the community for which the station is to be licensed, and in conformance with all pertinent rules and regulations. Having made this determination, an application may be tendered for filing.

FM broadcasting

The band of frequencies allocated for FM broadcasting is divided into 100 channels with carrier frequencies separated by 200 kHz. The lower 20 channels (88-92 MHz) are reserved for use by noncommercial educational stations and the remaining 80 channels are for assignment to commercial

¹ See p. 329

operations. As an exception to this general division, some few noncommercial educational stations have been authorized use of frequencies in the commercial portion of the band.

Stations are authorized in the noncommercial portion of the band pursuant to a "demand" system. In the commercial portion of the band, however, a Table of Assignments has been developed and incorporated in the FCC's rules, and applications may be filed only for a channel designated for use in the community of interest, as specified in that Assignment Table. Unlike the "demand" system, a Table of Assignments serves two primary goals. It tends to ensure a more equitable distribution of stations among the various communities of the nation and, generally, preserves opportunities to establish a station in a designated community in instances where potential applicants are slow to materialize.

Recognizing that it is impossible to develop that acute foresight which would enable one to forecast precisely all locations where interest in providing service will develop, procedures are available wherein the Table of Assignments may be modified.

In the noncommercial portion of the FM band, stations and facilities are authorized on the basis of providing protection to the 1 mV/m signal strength contour of existing stations. In the commercial portion of the band, where stations are authorized in conformity with the Table of Assignments, three classes of stations have been established.²

Twenty of the 80 commercial channels have been designated for use by Class A stations only. These channels are interspersed throughout the commercial portion of the band. The service range of Class A stations is very limited and, in general, they are intended to provide local service to small and moderate sized communities.

Class B stations are assigned to larger communities in those areas of the nation where many major communities are located in close proximity to each other. Class C stations are generally assigned to major communities located in those areas of the nation where such communities are widely separated and, as a consequence, the extensive rural areas between such communities must also depend upon these wide coverage stations for service.

A significant feature of the Table of Assignments is that there are built into it considerations of service range and protection from interference. The Table has been developed on the basis of providing at least minimum mileage separations between stations which would operate on the same or adjacent frequencies. The required mileage separations are designed to essentially provide interference free service within a station's 1 mV/m signal strength contour. Another feature of the Table is that it accommodates an opportunity for stations to initially begin operation with less than maximum permitted facilities and preserves an option to increase facilities at a later date. This results from the fact that the Table has been developed on the basis of having assumed maximum per-

² Maximum power and antenna height:

class	maximum power	maximum antenna height (feet above average terrain)
A	1 kW (4.8 dBk)	300 (91.4 m)
B	50 kW (17.0 dBk)	500 (152.4 m)
C	100 kW (20.0 dBk)	2000 (609.6 m)

¹ (Source; Section 73.182(V) of FCC Rules and Regulations)

class of station	class of channel used	permissible power	signal intensity contour of area protected from objectionable interference ¹		permissible interfering signal on same channel ²	
			day ³	night	day ⁴	night ⁴
I-A	clear	50 kW	{ SC 100 μ V/m AC 500 μ V/m	SC 500 μ V/m (50% skywave) ⁵ AC 500 μ V/m ³	{ 5 μ V/m	25 μ V/m ⁷
I-B	clear	10 kW to 50 kW	{ SC 100 μ V/m AC 500 μ V/m	SC 500 μ V/m (50% skywave) AC 500 μ V/m ³	{ 5 μ V/m	25 μ V/m
II-A	clear	{ 0.25 kW to 50 kW (daytime) 10 kW to 50 kW (nighttime)	{ 500 μ V/m	500 μ V/m ³	25 μ V/m	25 μ V/m
II-B and II-D	clear	0.25 kW to 50 kW	500 μ V/m	2500 μ V/m ^{3,5}	25 μ V/m	125 μ V/m
III-A	regional	1 kW to 5 kW	500 μ V/m	2500 μ V/m ³	25 μ V/m	125 μ V/m
III-B	regional	0.5 to 1 kW (night) and 5 kW (day)	500 μ V/m	4000 μ V/m ³	25 μ V/m	200 μ V/m
IV	local	0.25 kW (night) and 0.25 to 1 kW (day)	500 μ V/m	not prescribed ⁶	25 μ V/m	not prescribed ⁶

¹ When a station is already limited by interference from other stations to a contour of higher value than that normally protected for its class this contour shall be the established standard for such station with respect to interference from all other stations.

² For adjacent channel, see paragraph (w) of this section.

³ Groundwave.

⁴ Skywave field intensity for 10% or more of the time.

⁵ These values are with respect to interference from all stations except Class I-B, which stations may cause interference to a field intensity contour of higher value. However, it is recommended that Class II stations be so located that the interference received from Class I-B stations will not exceed these values. If the Class II stations are limited by Class I-B stations to higher values, then such values shall be the established standard with respect to protection from all other stations.

⁶ See paragraph (a) (4) of this section.

⁷ Class I-A stations on channels reserved for the exclusive use of one station during nighttime hours are protected from co-channel interference on that basis.

SC = same channel. AC = adjacent channel.

mitted powers and antenna heights for all assignments.

Television broadcasting

Television broadcasting is accommodated within 12 channels in the VHF portion of the radio spectrum and 56 channels in the UHF portion of the spectrum. Each channel is 6 MHz wide. Stations on the five available channels allocated in the 54-88 MHz portion of the radio spectrum are permitted to operate with a maximum effective radiated visual power of 100 kW; stations on the seven channels between 174-216 MHz may employ up to 316 kW; and stations operating on channels between 470 and 806 MHz may employ up to 5000 kW. These powers have been chosen to permit similar service areas at all frequencies taking into account propagation anomalies. Maximum permitted antenna heights for television stations follow the same pattern as distinguishes Class B and Class C FM station assignments.

Unlike the FM channel assignment scheme, television assignments which are reserved for use by noncommercial educational interests are not relegated to a discrete portion of the spectrum available for television. Rather, such assignments are dispersed throughout the entire range of television frequencies. This difference in treatment reflects recognition of differing characteristics of radio signal propagation over the broad range of television frequencies, and an attendant desire to distribute perceived negative and positive propagational effects fairly between non-commercial educational and commercial operations.

As has been done with FM, television stations are authorized pursuant to a Table of Assignments. This Table lists approximately 900 communities and identifies the specific television channels available for use in each such community. In general, the number of channels assigned to a community corresponds to the population of that community. Also, as with the FM Table of Assignments, procedures are available whereby the television Table may be amended to accommodate unanticipated service needs.

Development of the Table of Assignments is based upon assuring that stations which can be sources of mutual interference are adequately separated geographically. Adequate separation is defined in terms of the minimum mileage required between sta-

tions operating on the same or adjacent channels to ensure against generation of objectionable interference. The mileage separation standards on which the Table is based effect a compromise between providing a large number of assignments for each community and providing for stations with sufficiently large service ranges to ensure service to rural areas.

International considerations

The US is a party to regional and bilateral agreements which govern the use of broadcasting frequencies in those regions of signatory countries where mutual use of frequencies must be coordinated. It follows that a US applicant proposing to operate a station in an area which brings an Agreement into play must satisfy not only domestic requirements, but also any additional requirements imposed by such agreements.

Introducing new assignment standards and new technology

As demands for new and improved service develop and as new technology emerges, sound management of the spectrum requires that an accommodation be made to reflect these changing circumstances. Necessary changes to existing standards are effected through formal rulemaking proceedings. Such proceedings afford an opportunity for all interested parties to provide comments, data, and other relevant information to establish a record upon which a Commission decision can be made. This process allows for timely and orderly introduction of new service and new technology into the system.

Private radio services

The Private Radio Bureau administers the 32 separate services under this category. Those services are grouped under seven major classifications; e.g. aviation, industrial, land transportation, maritime mobile, personal, private microwave, and public safety. Virtually all of the Bureau responsibilities for these services are assignment oriented.

The industrial, land transportation, and public safety (land mobile) radio services are further subdivided into services such as business, power, taxicab, police, fire, and others. In those frequency bands

below 470 MHz which are allocated to land mobile, bands are allotted in blocks to the several services and, within those blocks, frequencies are further allotted to the individual services. Above 470 MHz, frequencies are assigned by pair on a localized basis according to need. Thus, the rules meet the needs of the user but are made somewhat more complex than in the lower bands.

The personal radio services include the amateur, radio control, citizens', disaster, and general mobile radio services. Except for the disaster radio service, they are distinguished by the fact that no requirement of need related to use of the radio spectrum is imposed. Operating standards are imposed on licensees, and some of the amateur bands are restricted to certain classes of licensees; however, licensees are not restricted unduly. A similar situation exists for the radio control, citizens' band and general mobile radio services.

In the latter three services, each has its own discrete band of frequencies and, in the citizens' and radio control services, a licensee is authorized to use any available channel. Essentially the same situation prevails in the amateur radio service, except the class of operator license determines which bands may be used. In short, spectrum management in the personal radio services is based on licensing the operator rather than the use of the frequency.

The private microwave service is somewhat different in that the prospective licensee must select the frequency he wishes to have assigned him. If successful, he is granted exclusive use of the frequency in the specific area he serves. In making the frequency selection, he may do so himself or contract with a consulting firm. He must, however, certify as to meeting the technical criteria set forth in the rules.

Although the particular bands allow differing bandwidths to be assigned, only one pair of channels per transmission path may be assigned. Space diversity is permitted if desired, but frequency diversity is not. As a consequence, the Commission manages the spectrum allocated to the private microwave service by maintaining a degree of design supervision for the system.

The land mobile radio services collectively compose the second largest group of licensees in the United States. (Only citizens' band with 14 million is larger.)

At present, there are approximately 400 000 licensees authorized to operate over 5 million transmitters in the private land mobile radio services and over half are authorized in the industrial radio services.

The frequency bands available for land mobile are, roughly, 25-50 MHz, 150-174 MHz, 450-470 MHz and 806-947 MHz, with limited use permitted in the 72-76 MHz and 470-512 MHz bands. As is evident from the aforementioned statistics, frequencies are assigned on a shared basis with multiple licensees sharing the spectrum, particularly in urbanized areas. Historically, and primarily for administrative convenience, the spectrum is allocated to the various services on a block basis. Because of the fact that not all services are required in all areas and the usage varies largely with population density, the spectrum is not utilized evenly. This phenomenon has resulted in some degree of spectrum inefficiency; consequently, in recently allocated bands, particularly in the 470-512 MHz and 806-947 MHz regions, the assignment pattern has not followed the block approach. Furthermore, recent allocation actions affecting other bands are attempting to break down the block allocation format wherever possible by the increased use of cross service sharing.

In developing the assignment criteria for these services, a number of considerations have been incorporated. Eligibility, equipment standards, emission and power limitations serve to maintain a satisfactory environment. Also, the priority of use is a factor.

Assignment of frequencies to a particular user is achieved in three different ways. In some services, the FCC has approved a frequency coordinator who may deal with all of the frequencies allotted to a given service. In others, a coordinator may be empowered to deal with a limited number of assignable frequencies. Finally, some services have no coordinators appointed.

In selecting frequencies for assignment, the coordinators use different techniques. Some are very methodical, but nearly all rely on empirical approaches rather than rigorous mathematical and technical analytic tools. The primary considerations in selecting frequencies include frequency band desired by the applicant, proximity to others using the same or adjacent frequency, and similarity of commercial interest. For Public Safety services, plans of State and local Government agencies are also considered.

Of course, the applicants may also perform the analyses necessary to determine the interference (and consequent usefulness) of the channel selected. If this course is followed, the applicant must submit, with his application, the analytic method and intermediate calculations; however, the coordinator's advice is usually sought prior to issuance of the license.

A second method arises in those services where no coordinator has been appointed. Here, the applicant selects the appropriate frequency and, assuming the eligibility criteria are fully satisfied and the proposed usage is consistent with the pertinent rules, the application is granted without regard to the number of existing users of the frequency.

The third method of frequency selection is through the efforts of the Commission's staff. This method is used in the 800 MHz region where no block of spectrum is allocated to the particular service. Instead, the best selection for the applicant's geographic area is made by the staff. This methodology arose when the traditional theory of equal loading on all frequencies was supplanted by the theory that loading should be progressive with channels lying fallow until adjacent channels have been loaded to theoretical capacity.

As a consequence, spectrum management is applied to the private land mobile services in several ways depending on user needs. Regardless of whether one means "conservation" or "maximizing the economic efficiency of the user", a high degree of spectrum efficiency is obtained.

The last two services administered by the Private Radio Bureau necessitate extensive international and intergovernmental considerations simply because aircraft and ships travel world wide. As a result, communications are frequent with foreign ground stations and ships; consequently, compatibility is essential—not only technically but administratively as well. And, as is the case with other countries, treaties and resultant national statutes form the basis for the Commission's authority to promulgate rules governing the aviation and marine radio services. These include, for the marine service, the International Telecommunication Convention (Malaga-Torremolinos, 1973) (including Radio Regulations), Safety of Life at Sea Convention, the Great Lakes Agreement, the Communications Act of 1934, as amended, and the Bridge-to-Bridge Radiotelephone Act. In addition to the International Con-

vention and Radio Regulations, the International Civil Aviation Convention is applicable to the aviation service.

Since many of the frequency bands in the aviation radio service are jointly shared bands (between Government and civil), the Commission relies heavily on the Federal Aviation Administration for frequency coordination, particularly in the traffic control and navigational bands. For operational control frequency coordination in the non-Government band is performed by a private organization—Aeronautical Radio Corporation, Inc. Other related aeronautical services are generally coordinated by the Commission.

In order to legally operate a station, there are a number of common requirements which must be met in both the aviation and marine radio services. These include basic eligibility requirements which relate primarily to citizenship, and supplemental eligibility requirements relating to the purpose and intended operational aspects of the station. Also, although not applicable to public coast stations, a plurality of stations in a given geographic area may join in a cooperative organization to render service in the event of interference. Other requirements involve defining the points of communication, restricting the nature of service, and circumstances surrounding use of additional frequencies during periods of high loading. Overall, a rather high degree of spectrum management has been achieved in providing for these services and in complying with our treaty obligations.

Common carrier services

The common carrier services fall into three main categories: domestic public radio, international fixed public radio-communications services, and satellite communications. Included in the first category are those services which are open to public correspondence such as the domestic public land mobile radio service, the rural radio service, the point-to-point microwave service, the local television transmission service, the multipoint distribution service, and the newest of the common carrier services, the offshore radiotelecommunications service.

The second category, as the name implies, involves those services open to public correspondence which provide radiocommunications between the contiguous states and any foreign point. The third category

is characterized by services related to communications using satellites.

Frequencies allocated to the common carrier domestic public services are made available to new and existing services as demands increase. Because of the nature of the service, assignment of frequencies is made only in a manner which will facilitate rendition of service on as close to an interference-free basis as possible in each service area. Consequently, in most cases, each frequency is assigned exclusively to a single applicant in a given service area. However, when necessary to resolve potential conflicts, multiple applicants are encouraged to resolve differences by working out time sharing agreements or other conciliatory means.

The use of frequency diversity is normally not authorized in the common carrier services unless a factual showing is made that required communications cannot practicably be attained by other methods. In those cases where it is allowed, it is limited to one protection channel for each three working channels.

As is the case with all other services described earlier, applicants for certain frequencies are required to coordinate the proposed frequency usage with existing users in the desired service area and also with those applicants whose applications are pending.

Technically, a transmitter must maintain the emissions within certain frequency tolerance limits to avoid or at least minimize the likelihood of adjacent channel interference. Additionally, specific types of emissions must be prescribed as well as the bandwidth necessary to provide the particular service. Power permitted is usually restricted to that required to service the area to be served and the predominant local conditions affecting radio transmission and reception. Additionally, many services, particularly those which normally provide point-to-point communications, are required to use directional antennas. To ensure interference-free operation, stations operating in an omnidirectional mode may be required to make appropriate technical changes. Finally, assignment policies also require consideration of antenna polarity, terrain elevations and transmitter locations.

The frequencies used for the international fixed public radiocommunications service are in the high frequency bands below 30 MHz and, of course, are shared with other nations on a world-wide basis. The details of the service are well known to the world telecommunications community

through publications of the ITU and the coordination necessary with the various countries.

The satellite services are provided by both domestic and international carriers. Under the provisions of the Communications Act of 1962, the United States participation in the global communications network is through the Communications Satellite Corporation (COMSAT) which acts as manager of the space segment, operates US earth stations and leases channels to other common carriers for overseas services.

The Commission approves the technical characteristics of satellite systems used not only by COMSAT, but by domestic common carriers as well. This also includes the construction and operation of each station, and since sites and frequencies for such stations are shared between terrestrial and space services, carefully developed coordination procedures are prescribed.

Enforcement and monitoring

The Field Operations Bureau (FOB), as the Federal Communications Commission's enforcement, information gathering, and direct public contact arm, provides the Commission's operating bureaus with information upon which to base spectrum management decisions. FOB maintains 31 field offices and 13 monitoring stations at strategic locations around the US to carry out its mission. The 13 monitoring stations, besides providing the sites for long-range direction finding and large LF, MF, and HF receiving arrays, also serve as bases of operation for mobile monitoring units covering the VHF, UHF, and microwave portions of the spectrum. The field offices also provide bases of operation for fixed monitoring activities, as well as for performing their primary functions of inspection of radio facilities, investigation of interference problems and illegal activity, and public service through the handling of complaints, examination and licensing of radio operators, and education of the radio user public.

By routinely sampling and measuring signals in all parts of the spectrum, the Bureau's monitoring program has provided a statistical base containing data on transmitter frequency stability, excessive bandwidth or deviation, emission type, and permissible communications. Such "real world" data are extremely useful for supplementing theoretical assumptions and calculations when new regulations or allo-

cations are contemplated. Issuance of infringement notices based on these monitoring observations helps avoid interference and prevents a general breakdown of allocation or assignment schemes, and results in a measure of compliance with international and domestic radio laws and regulations.

Long-range direction finding, using wide-aperture arrays with triangulation baselines thousands of kilometers long, allows the network of monitoring stations to locate interfering or violative transmitters, with varying degrees of accuracy, anywhere in the world. This capability is also invaluable, of course, for assisting search and rescue operations involving aircraft and vessels in distress, or in other cases involving safety of life and property.

Because of the short-range propagation characteristics of higher frequency radio waves, routine monitoring of frequencies above 30 MHz is done from specially-equipped vans, except where location of a monitoring station or field office near a population center allows productive monitoring from the fixed location. In the US, 24 of these vans are equipped for general-purpose monitoring of the spectrum up to 1 GHz. Development is being initiated on a program of automating most of the monitoring functions of these vans, with direct interface of the data collected with a computer data base. Six vans are equipped specifically to perform off-the-air measurements of signals above 1 GHz. Besides the usual measurements of transmitter parameters, these vans are capable of analyzing the degree of baseband loading of multiplexed broadband microwave signals, thus allowing the Commission to determine the extent to which requested bandwidth assignments are being utilized. Four more vans are equipped to conduct specialized measurements on FM and television broadcast transmissions as well as signals sampled from cable or wired television distribution systems. These measurements include baseband frequency and insertion levels for multiplexed FM signals, and video waveform measurements for television.

A new monitoring program under development with a prototype facility at Laurel, Maryland, is satellite monitoring. The prototype facility has a fully-steerable, 5 m diameter Cassegrain antenna with interchangeable broadband feed assemblies allowing continuous frequency coverage from 1 to 12 GHz. Its capabilities include frequency, bandwidth, and power flux density measurements, and it allows observation of the degree of satellite tran-

FCC Rulemaking Procedure (FCC Communicator, September 1975)

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 and 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 and 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.

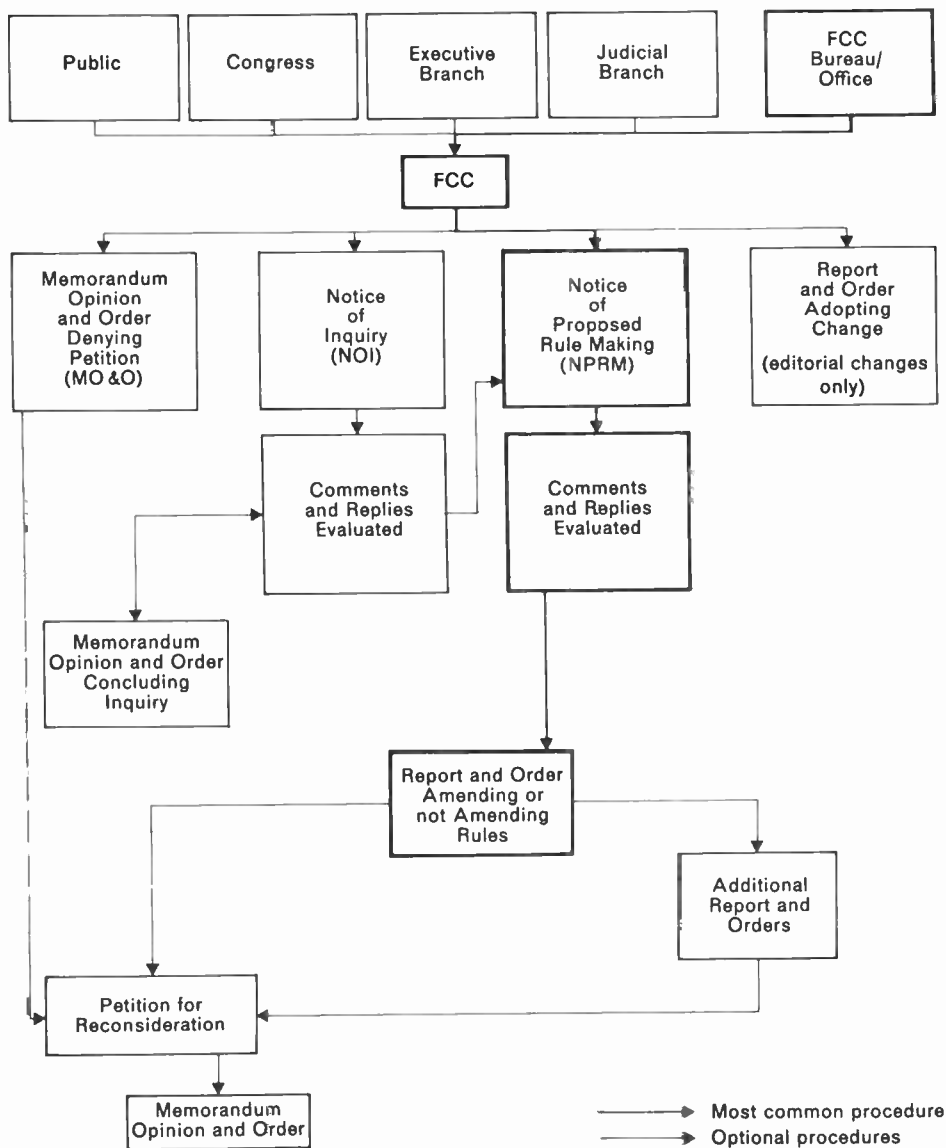


Figure 3

5. Reports and Order Issued. A Report and 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 Report and Orders Issued. The Commission may issue additional Report and 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.

sponder loading, detection of unauthorized transponder use, and direction finding of extraterrestrial interference sources. As spectrum management in the satellite area is presently in a very dynamic state, information provided by this program should prove extremely valuable.

Spectrum occupancy monitoring is a newly assigned function for FOB. Several large vans equipped with computer-controlled receivers and data collection systems will be used on a response basis to collect channel occupancy data, primarily in the very heavily occupied land mobile radio frequency bands. Such information can be used to determine if additional spectrum is necessary for a particular service, if expanded sharing of channels between services is possible, and to audit the performance of private frequency coordinators.

On-the-spot inspection of radio facilities of all types provides enlightenment on their in-service condition and uncovers the presence of ill-maintained, unsuitable, or illegal transmitting equipment which contributes to inefficient spectrum utilization. Such inspections are done both on a routine basis and in response to requests from the licensing offices.

Investigations are undertaken by field engineers when an interference source or radio violator cannot be identified by conventional monitoring techniques. Any means at the Bureau's command, including long-range and close-in direction finding, surveillance monitoring, and cooperation of law enforcement officials, may be used to alleviate a particularly bad interference problem or a case of illegal operation severely disrupting authorized communications.

Most field offices are staffed to serve as a point of contact for the general public in their dealings with the Federal Communications Commission. It has been found that the interests of efficient spectrum management are best served by having a user public that is well informed on regulatory matters and which can receive ready guidance on the proper channelling of problems and complaints. Radio operator examinations, both commercial and amateur, are also administered by these offices. Ensuring competent operators helps guarantee efficient use of the spectrum.

Through specially-trained public contact staff at the field offices, FOB attempts to educate the user public on proper use of their radio facilities. Radio user "workshops", interviews on broadcast "talk" shows, and distribution of printed publications and press releases are some of the means by which this is accomplished.

Spectrum management records

It is apparent from the above discussion that the extensive use and multiplicity of purposes to which the radio spectrum is applied in the United States require increasingly sophisticated management techniques. Obviously, manual processing of applications and card file records are inadequate. Therefore, application of data processing techniques and computers are becoming increasingly important.

At the present time, about 35% of the licenses granted by the Commission and included in the Master Frequency File are generated by use of computers. The Broadcast, Common Carrier and Private Radio Bureaus each have several data base systems which are used in the processing of television and FM broadcasting, microwave, and land mobile applications. Fortunately, one of the earliest candidates for computer processing was the citizens' band radio service. With some 14 million assignments at the present time, the public demand for this service would be otherwise overwhelming.

The non-Government Master Frequency File is an automated data base which contains, with certain exceptions, all of the frequency assignments authorized by the Commission. These exceptions include amateur, aircraft, personal radio (radio control and citizens' band), common carrier domestic land mobile (individual mobile stations) and marine (ship stations). Those services usually are authorized to operate on a multiplicity of frequencies in accordance with an applicable portion of the FCC Rules. For example, the citizens' band may operate on any of 40 channels; consequently, attempts to reflect single frequency assignments would be misleading.

Until recently, input to the Master Frequency File was done on a manual basis. However, with the automated licensing systems, data are now being fed directly to the File.

The Master Frequency File presently contains information on approximately one million assignments. The data contained therein can be accessed on just about every field. The File is available to the public in either microfiche or magnetic tape form. The microfiche is produced in either frequency or service sequence and may be indexed by call sign, location or frequency.

The Master Frequency File is used for many purposes. Not only is it used for notification of frequency assignments to the International Frequency Registration Board in compliance with the international

Radio Regulations and for submission of certain data to Canada and, shortly, Mexico; assignment of call signs; coordination of frequency assignments with Executive Branch agencies; and, increasingly important, for statistical and analytic studies for spectrum allocation. Finally, the File is used for enforcement and interference resolution purposes.

Other data bases available include a Type Accepted Transmitter file and a Tower file which includes information on radio towers requiring marking and lighting. The Commission is also in the process of completing a computerized version of the International Frequency List.

Consistent with the Commission's needs and resources, minicomputers are expected to be applied more frequently in the future for management and planning use of the radio spectrum.

Accommodation of new technology

In the United States, the FCC is required to take actions consistent with the "public interest, convenience, and necessity". In compliance with that mandate, the Commission is constrained by provisions of the Administrative Procedure Act which sets forth certain procedures which must, with few exceptions, be followed when changes in the Commission's Rules are being made or contemplated. These procedures deal with affording public notice of proposed rule changes including changes in the national Table of Frequency Allocations.

The procedure is more fully described in the diagram attached (see figure 3) and, while the procedure appears complex and is often tedious, the public is afforded an opportunity to participate in the making of laws affecting them—an important part of our democratic system.

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FEDERAL SYSTEMS REVIEW PROCESS

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ABSTRACT

Government agencies planning to use telecommunication systems requiring the use of radio frequencies have been directed to take all reasonable measures to ensure that such systems will neither cause nor receive harmful interference to or from other authorized users when placed in their intended operational environments. To assist Government agencies in meeting this responsibility and to support the NTIA (formerly the Office of Telecommunications Policy) and the Interdepartment Radio Advisory Committee (IRAC) in the management of radio spectrum resources, a procedure, known as "System Review," was established. It provides for the review of new Government telecommunications systems by the Spectrum Planning Subcommittee (SPS) of the IRAC at a number of stages during their evolution prior to the assignment of frequencies. Such a review includes an examination of the existing and planned systems in the frequency band being considered.

In general, this procedure is presently applicable to: (a) systems involving the use of satellites or spacecraft; (b) terrestrial systems intended for operation above 420 MHz; or (c) such systems as may be referred to the SPS on a case-by-case basis. In making these assessments, the SPS is supported by the NTIA.

This paper describes the review procedure, and summarizes its current implementation, the environmental data used and the level of analyses made by NTIA.

INTRODUCTION

The radio spectrum is an important natural resource which is in the public domain. It has become a ubiquitous servant of man in his twentieth century society. This phenomenon of nature, though only discovered within the last one hundred years, is the basis of technologies which support industries and applications that are integrated into modern society. Indeed, all sectors of our Nation depend on this public servant for a host of services. Continued access to this resource is vital to U.S. Government departments and agencies for the discharge of their responsibilities and fulfillment of their missions.

The current spectrum requirements of the Federal Government within the U.S. and its Possessions are substantial. Over 150 thousand

individual frequency assignments are involved. An individual assignment may authorize the operation of hundreds or thousands of equipments. The depreciated investment for this communications-electronics equipment amounts to over \$67 billion and the annual new investment for it is estimated to be between \$12 and \$15 billion.

The spectrum stands in constant readiness to continue fulfilling man's increasing utilization within its physical limitations. However, our appetite for this resource is growing faster than our research efforts are developing the technology to "open up" additional spectrum. Our utilization of the resource is increasing and the problems of spectrum congestion and pollution are growing. Access to the spectrum is somewhat competitive, particularly when planning for systems having long lead times or high impact. Not only must proposed systems be assessed along with competing systems in light of national priorities, but continued access to this resource must be assured for future requirements, yet unforeseen. In so doing, new methods for increasing the spectrum's capacity must be fostered and implemented. It is generally conceded that the spectrum management techniques of yesterday will be inadequate to cope with the demands of the future.

Background

Very early in the growth of radiocommunications, it was recognized that orderly procedures for sharing the use of the radio spectrum in its various dimensions were necessary. At the global level, the International Telecommunication Union (ITU) has been a focal point and instrument for achieving such procedures. As such it has received active participation and contribution from the United States. Within the U.S., similar efforts have been focused in both the Interdepartment Radio Advisory Committee (IRAC), which was spontaneously conceived in 1922 as a self regulating body of Federal Government users, and in the Federal Communications Commission (FCC), which was established by the Communications Act of 1934 to regulate non-Federal Government communications. Early in the 1960's, the Department of Defense, which is the largest user of spectrum in the Government, established by DOD Directive 3222.3 a program to ensure that communications-electronics

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equipment will function in the intended operational environment without suffering or causing unacceptable degradation. The Electromagnetic Compatibility Analysis Center (ECAC) was also established to assist in this program.

Starting in 1964, the Director of Telecommunications Management (DTM) in the Executive Office of the President, upon the recommendation of the IRAC, issued several letters and notices to the Government agencies about the need to ascertain that adequate spectrum support is available before obligating funds for research, development and operational projects requiring radio frequencies. Through this policy, it was hoped to curtail spending large sums of money for radio equipment only to find out it could not be accommodated in the spectrum space for which it was designed. Particular emphasis was placed on obtaining such assurance for space systems, for important military systems and for terrestrial stations proposed in bands shared by the space services.

A further step was taken in November 1972, when the Director of the Office of Telecommunications Policy issued OTP Circular No. 11, "Frequency Spectrum Policy Concerning the Development and/or Procurement of Communications-Electronics Systems" to the Heads of Executive Departments and Establishments. This OTP initiative was a major milestone for spectrum management in the Federal Government. It enunciated a lucid statement of policy that Executive agencies will not obligate funds for either the development or procurement of communications-electronics systems requiring the use of the spectrum until the availability of appropriate spectrum support is assured. It also required agencies to obtain the spectrum support for such systems prior to the submission of annual budget estimates to the Office of Management and Budget (OMB) and indicated that OMB and OTP will coordinate the implementation of this policy. As an initial step toward implementing this policy, procedures for the review of spectrum requirements and EMC characteristics of new Government systems were attached to that circular and further promulgated as Part 8.3 of OTP's Manual of Regulations and Procedures for Radio Frequency Management. These procedures established the basic mechanism for assuring the spectrum availability and inter-system compatibility are considered early enough in the life cycle to be effective.

SYSTEM REVIEW PROCEDURES

When first implemented, the procedure provided for the review of new Government (1) systems or subsystems involving the use of satellites, (2) terrestrial systems or subsystems intended for operation in any of the bands allocated for both space and terrestrial services, and (3) such other systems or facilities as may be identified by the OTP, the IRAC, or a Federal agency as involving unusual costs or as having a large potential impact on the spectrum. Since its inception several changes in the procedure have been made. In April 1975, after implementing the procedure for over two years, OTP enlarged the scope to include all new major terrestrial systems or subsystems stated for operation in the bands above 420 MHz and indicated that when the results of EMC analyses

so indicate, prototype EMC tests may be required as an input to the determination of spectrum availability and electromagnetic compatibility. Nearly a year later, in March 1976, the circular was reissued to incorporate specific instructions and forms for the submission of equipment data. It is noted that system review for spectrum use in support of basic research or experimentation is required only if it is directed toward the development of an operational system or for those experimental systems where protection from interference or recognition is necessary.

Presently, systems are reviewed prior to the assignment of frequencies at four stages of their evolution, namely: (1) planning (conceptual), (2) experimental, (3) developmental and (4) operational procurement. As a basis for the review, the agency must provide data on the proposed equipment characteristics, the intended area of deployment, as well as operational requirements. The objective is to assess (1) system compliance with prevailing policy, allocations, regulations and technical standards, (2) the electromagnetic compatibility between the proposed systems and the intended environment, and (3) the possible need for an evaluation of prototype EMC testing.

The review process presently is implemented under the cognizance of the NTIA's Director for Spectrum Plans and Policies and within the IRAC structure. The FCC participates in these procedures for the review of Government systems intended for operation in bands of mutual Government/non-Government interest through the normal FCC liaison representation on the IRAC and its subcommittees. Normally, the proposed systems are reviewed in the Spectrum Planning Subcommittee of IRAC with the assessment and recommendations going directly to NTIA for either (1) unqualified approval of spectrum support for the system at its proposed stage of development, (2) approval of spectrum support at that stage subject to limitations on or modifications of the proposed or competing systems, (3) submission of advance publication information, coordination and notification, as appropriate, under the provisions of Articles 9 and 9A of the ITU Radio Regulations, or (4) disapproval of spectrum support. The determinations of the NTIA and their basis are provided directly to the proposing agency as well as to the Chairman of the IRAC, SPS, and the Frequency Assignment Subcommittee (FAS). This guidance provides a framework for any modifications to system plans, adjustments to existing spectrum use, and appropriate limitations on any frequency assignments for the system.

In reviewing and assessing the proposed system, the Spectrum Planning Subcommittee depends upon the system and equipment characteristics data submitted by the proposing agency and upon available environmental information maintained by the NTIA's Office of Federal Systems and Spectrum Management. Various types of analysis are required in the different preassignment phases and they will vary from a determination of gross impact on the spectrum to detailed EMC analysis. The level and complexity of analysis must depend on the quality of the data available at the various stages of system development.

The results of related technical studies and pertinent EMC analyses are also used in the review. The Systems Review Branch (SRB) of the Spectrum Engineering and Analysis Division (SEAD), located within the NTIA, is dedicated to provide technical support to the SPS in the systems review area. Existing EMC analysis capabilities and additional expertise may be obtained when needed from elsewhere within the SEAD. The system review process as implemented for Government systems is shown in Figure 1.

The Frequency Assignment Subcommittee of TRAC also has a vital link in the process. It has been directed to withhold national frequency assignments from stations of systems that are subject to these procedures until notice is received that support has been approved. Also the FAS is to ensure that the particulars of assignments conform to the terms of the system approval. If assignment applications for systems are received prior to the completion of the review, they are tabled and referred to SPS for review.

Review Results

Since the initiation of the review process, over 300 systems have been examined. Currently about five systems a month are being submitted by the agencies or referred by the FAS. Some of these reviews have involved the conventional use of commercially available equipment at a particular site and have thus focused on the compliance with standards and the EMC with the current environment. Other systems at earlier stages in their life cycle have been less well defined technically and operationally, and thus the review emphasized the allocation aspects and general sharing criteria, that is, a determination of gross impact on the spectrum. Those reviews involving space systems have additionally considered the international registration aspects and requirements for United States coordination with other administrations. A brief summary of several of the systems that have been considered in the SPS is given below.

Pave Paws

The Air Force requested spectrum support for the Pave Paws radar system at two sites. The system was designed to provide an early warning capability against Sea Launched Ballistic Missile (SLBM) attacks on the continental United States and, as a secondary mission, to provide surveillance and tracking of earth orbiting satellites. System operation was proposed in the 420-450 MHz band with stage 3 (developmental) tests to be performed at the contractor facility and at the two proposed operational sites. Based on a preliminary EMC assessment which identified the potential for radiation hazards to personnel and interference interactions with adjacent-band services, the SPS recommended and the NTIA approved spectrum support for stage 3 tests at the contractor facility. However, spectrum support for tests at the other two sites was withheld until the Air Force (1) conducted compatibility tests with potentially-affected users, (2) developed procedures and technical fixes, as necessary, for application at the intended site locations to ensure no harmful

interference would be caused to services operating in accordance with national allocations, and (3) took adequate measures to ensure that people were not exposed to radiation hazards. NTIA staff assisted in developing EMC test plans and also analyzing the test data results for summary presentation to the SPS. Successful demonstration of satisfactory completion of the above requirements by the Air Force enabled spectrum approval to be granted for testing and operational use at the proposed site locations.

Bullet Hit Indicator

In a stage 2 (experimental) review, the Air Force requested spectrum support for two competing systems being proposed to satisfy Air Force requirements for an airborne target scoring system for use at military test ranges worldwide. The system was to be designed for mounting on a towed aerial gunnery target to provide a count of bullets passing through a particular scoring volume about the target and to transmit this data for display within the cockpit of the towing aircraft. The system design utilized both radiolocation and telemetry techniques. Although the method of implementation was somewhat different for the two competing systems, they shared the following characteristics: (1) the radiodetermination function was proposed in a band (1710-1850 MHz) not allocated either nationally or internationally to the radiolocation service; (2) the wide emission bandwidths needed to satisfy operational requirements extended into adjacent bands allocated to other telecommunication services including the meteorological satellite (space-to-Earth), mobile, space research (space-to-Earth) and fixed services, the latter being exclusively allocated to support non-Government operations within the United States and Possessions; and (3) EMC studies showed the potential for interference to Government and non-Government systems. Although one of the competing proposals was approved for limited experimentation at certain U.S. test ranges due to its significantly less impact on existing system operations at these sites, the Spectrum Planning Subcommittee recommended that spectrum support for the radiolocation function be denied for an operational system in the 1710-1850 MHz band and that the Air Force reassess plans for further development of such radiolocation systems in this band. NTIA concurrence in this recommendation motivated the Air Force to redirect the proposed system development into a more appropriate band. Later submission of a stage 3 (developmental) request for this system reflected implementation of the system review guidance and resulted in a system proposal with greater likelihood for compatible integration into a worldwide operational environment.

Tar Sands

The Department of Energy recently submitted a request to the Spectrum Planning Subcommittee for spectrum support consideration of a stage 2 (experimental) system designed to determine the economic feasibility of extracting bitumen (substance from which oil and other petroleum products may be derived) from tar sands deposits via RF heating. The

use of RF heating as a method for liquifying the bitumen and simplifying its recovery had previously been conceived and patented by industry. The proposed system, being a type of industrial, scientific and medical (ISM) application, was not designed for telecommunication purposes and, therefore, was not subject to the systems review procedure. However, as a new radio frequency technique potentially having a significant impact on other users of the spectrum, the system came under the purview of the SPS and, therefore, was considered. Stage 2 system testing was proposed at two U.S. sites on the designated ISM frequency 13.56 MHz and on discrete frequencies in three non-ISM bands: 70-90 kHz, 350-450 kHz and 2.0-2.5 MHz. Although the RF power on these frequencies was transmitted into the ground via an electrode array inserted into the tar sands deposit, the high output power projected for operational use (30 Megawatts) indicated a potential for environmental interactions due to RF leakage. Although miscellaneous ISM equipment may be operated on a non-interference basis on frequencies other than those specifically designated for ISM use, RF leakage must be controlled to ensure certain radiated field strength criteria are not exceeded. Nationally, the maximum allowable field strength is 10 uV/m at a distance of one mile. Estimates of RF leakage provided by the system contractor indicated that the experimental Tar Sands design could radiate signal strength significantly higher than the nationally authorized levels. EMC consideration of such radiation levels indicated the possibility for interference to existing radiocommunication operations. Based on these considerations, the SPS recommended stage 2 support subject to several conditions: (1) operations in non-ISM bands be conducted on a non-interference basis; (2) stage 2 experimentation include ground and airborne measurements of the radiated field strength to better define the EMC potential of an operational system; (3) stage 2 design and experimentation develop techniques for minimizing RF leakage radiation; and (4) EMC studies or tests be performed to demonstrate system compatibility with existing and planned radiocommunication services allocated for operation in the proposed system bands. Stage 2 tests are anticipated to commence in late 1980.

DSCS

Although much of the Phase II portion of the Defense Satellite Communications System (DSCS) was in existence prior to the system review procedure, the system has been the subject of numerous reviews. NTIA has considered that the addition of a new earth station is a major modification to the system and, therefore, subject to review. Also the systems review process has served as a focal point for the review of international registration documentation relating to the advance publication, coordination and notification of the DSCS through the International Telecommunication Union (ITU) forum. When action is required in any of these areas, additional portions of the system come under review.

As part of a systems review of a fixed earth station, coordination contours, determined in

accordance with the procedures of Appendix 28 of the ITU Radio Regulations, are prepared for both the DSCS uplink (7900-8400 MHz) and downlink (7250-7750 MHz) bands. For each nationally authorized station having nominal bandwidth overlap and located within these contours, an assessment is made of the potential electromagnetic interaction with the earth station. By considering the proposed earth station characteristics, calculated propagation loss, antenna pointing relationships and some terrestrial station characteristics, interference-to-noise ratios are calculated for each path. Based on these computations most of the potential interactions are eliminated from further consideration. Where significant interactions are predicted, the agencies are alerted to allow a more detailed analysis and consideration of operational factors. The earth station contours are also used to identify other administrations for which international coordination must be effected in accordance with 639AN of the ITU Radio Regulations.

In addition to fixed earth stations, the DSCS deploys aeronautical mobile and land mobile earth terminals. Within the United States, airborne terminals are presently evaluated throughout their proposed area of operation to determine areas of potential interference with existing band users. This determination is accomplished with the aid of an automated procedure, developed by NTIA, that produces ATTIC (Airborne Terminal-to-Terrestrial Interference Calculations) charts which indicate geographic areas where restrictions on airborne terminal power are necessary to preclude interference. Mobile earth stations are presently accommodated via an interim coordination procedure pending national implementation of procedures established by the 1979 World Administrative Radio Conference (WARC-79). National authorizations for land mobile earth stations are currently restricted to small areas of operation (about 45 km radius) and are on a temporary one-year renewable basis.

The Phase III portion of the DSCS is presently undergoing stage 3 (developmental) review. A major issue being addressed is the international registration requirements of this system. Under 639AJ and Appendix 29 of the ITU Radio Regulations, coordination with the USSR is required for their GALS satellite network and with Belgium for their SATCOM III network. The first meeting with the USSR to effect this coordination was held in Geneva in September, 1980. Coordination with Belgium has not yet been initiated. Coordination with Canada and Mexico is also required under 639AN and Appendix 28. These efforts should be initiated in the near future. It is anticipated that most of these international coordination issues can be resolved prior to the stage 4 (operational) review of the DSCS.

As evident from the previous examples, various types of analyses are required to support the reviews depending on the system complexity and the amount of information available in the different stages of review. Recent years have witnessed a growth in the number of Federal Government space system operations. This trend, coupled with the increased competition in the international arena for geostationary satellite orbital slots and

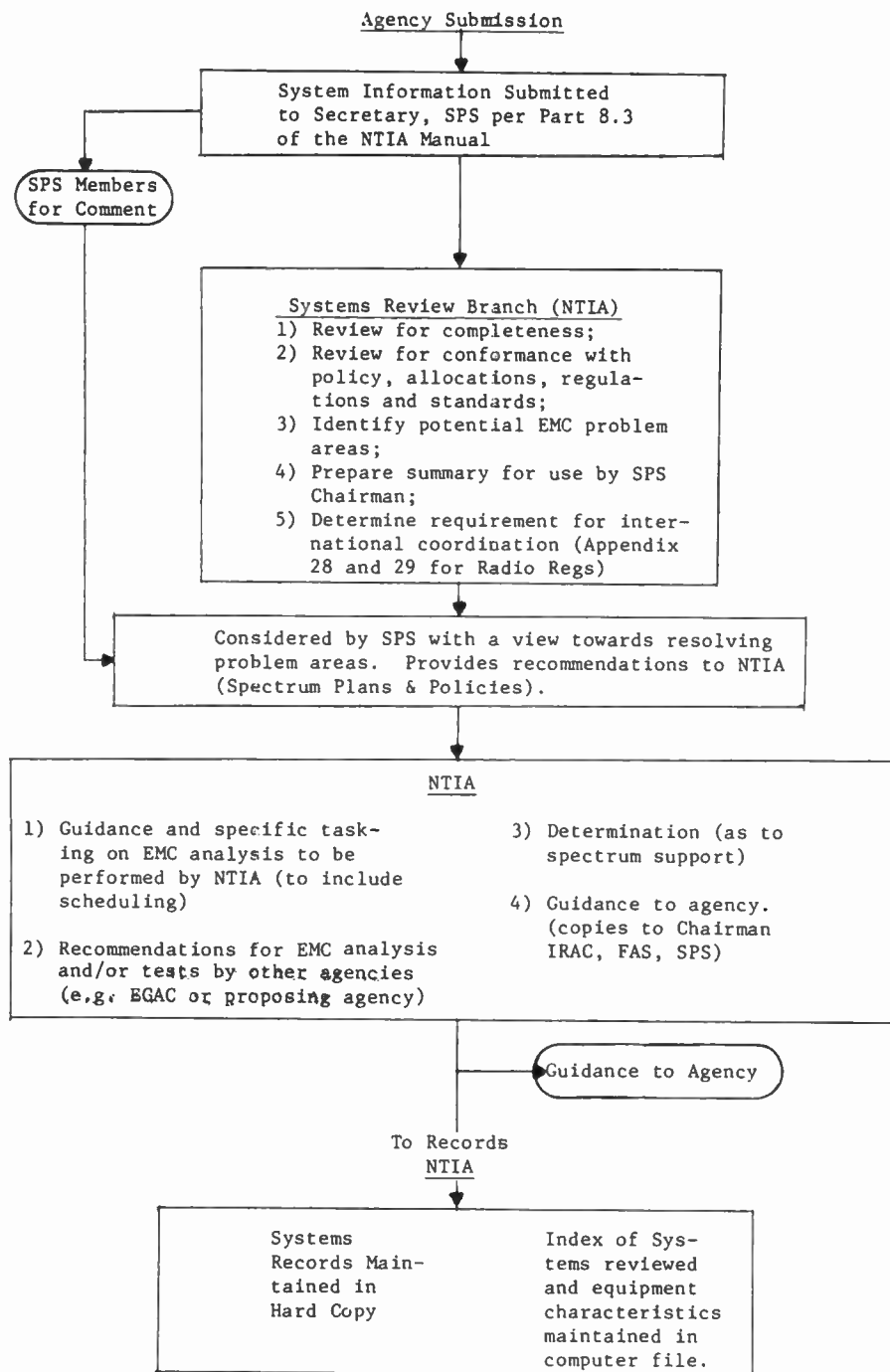


Figure 1. Systems review procedure (Federal Government Systems).

the national policy for internationally registering United States space systems, has resulted in the need for additional NTIA assistance in the advance publication, coordination and notification of Federal Government space systems. The systems review procedure serves as an excellent vehicle for providing such assistance. Also the need for

identifying and assessing the spectrum requirements of major systems early in the system life cycle is generally recognized. The systems review procedure provides the mechanism and catalyst for Federal Government systems planning within the spectrum management community.

NABER Frequency Coordination: The Hows and Whys Of This Process

Meg Gianessi
NABER
Washington, D.C.

The nature of frequency coordination is often misunderstood. NABER explains the process and answers some frequently asked questions.

Since 1970, the FCC has recognized the National Association of Business and Educational Radio (NABER) as a "frequency advisor" or "frequency coordinating committee" in the business radio service. Starting with a computer printout borrowed from the FCC and one staff coordinator, NABER's frequency coordination system today encompasses 400,000 computer records, 11 full-time staff people doing everything from the actual coordination to file maintenance and data processing, and an IBM Systems 3 computer.

What has caused this growth over the past ten years is the increased popularity of business radio. A licensee is required to produce evidence of frequency coordination in order to secure his license from the FCC. While there is an alternative to using NABER's service to satisfy this requirement, it is often faster and less expensive for the prospective licensee to use NABER.

The FCC rules are very specific in *not* delegating to NABER (or any other frequency coordinating committee) the authority to select the frequencies that licensees must use. Rather, "the functions of such committees are purely advisory in character, and their recommendations cannot be considered as

Center: NABER frequency coordinators Rex Jones (left) and Dick Young confer on a difficult application.

NABER's coordinators have a combined total of 77 years experience in radio communications, 31 of them specifically in NABER coordination.

Left: Don Vasek verifies application data by telephone with the dealer.

Most coordinators spend up to half their time in direct consultation with dealers. **Far Right:** FCC frequency occupancy data is periodically provided to NABER in the form of microfiche. Here, coordinator Kathy Curran verifies the loading of a particular frequency for an applicant.



binding upon either the applicant or the Commission, and must not contain statements which would imply that frequency advisory committees have any authority to grant or deny applications." (FCC Rules and Regulations, Vol. V, Part 90, Section 90.175.)

How About Local Coordination?

NABER coordinates recommendations between 450-470 MHz, and

470-512 MHz in the eleven largest U.S. urbanized areas. Neither the frequencies below 450 MHz nor those designated for "itinerant" use require coordination.

In 1980, NABER coordinated and issued 25,639 frequency recommendations. Despite widespread use of the service, some dealers and many radio users seem to misunderstand the nature of frequency coordination. For example, some ask, "Why is a central, nationwide data base necessary? Couldn't local or state frequency coordinators accomplish the job more efficiently and accurately?"

One problem with local coordination is that radio waves don't respect city or state or regional boundaries. A user in Kansas City would have to coordinate his application twice — once with Kansas and again with Missouri. And just think about the poor guy in Harper's Ferry, West Virginia,

who's right at the point where four states meet!

Another advantage of a central coordinating function is its timeliness. While a dealer can himself monitor several frequencies and select what seems to be a relatively clear channel for his customer, another user may have already applied for a license on that frequency, though he may not yet be on the air. NABER's data includes all applicants for frequencies as soon as they apply.

How NABER Locates The Best Frequency

When an application for frequency recommendation is received at NABER, a coordinator considers several factors in trying to arrive at the best choice of frequency for the particular user:

1. *Geographic separation* is a high priority. Typically, the coordinator will secure a computer printout of all known users on certain frequencies within a specific radius of the applicant's location. By visually scanning the printout, the coordinator can compare frequencies and select a suitable one.

2. *Channel loading* is equally important. Of course, the larger the metropolitan area, the more congested the frequencies. When a Chicago user complains about a recommended frequency having four other users on it besides himself, we can only compare his channel to the six or eight or twenty users that were on all the other



frequencies. In other words, until more frequencies are made available to business radio use, users will have to live with a certain amount of frequency congestion.

Frequency congestion is also created by the business radio service's broad eligibility standards. Persons primarily engaged in the operation of a commercial activity, educational institutions, churches, hospitals and clinics are all eligible to operate on business radio frequencies. Some are eligible in other radio services, too. However, if those services become congested or otherwise unsuitable, an applicant can instead apply for a business frequency. If he's eligible, NABER cannot refuse him a frequency recommendation.

3. Many other technical considerations are factored into the recommendation, such as the number of existing repeaters in a new applicant's vicinity, output power, antenna height, nearness to airports, and Canadian and Mexican communications regulations, where applicable. Also, an applicant is not put on the same frequency with a business similar to his, unless this is unavoidable because of limited frequency availability. NABER also crosschecks its computer data with that of the FCC, through visual inspection of microfiche records.

The final frequency recommendation is decided through a combination of human judgment and computer speed. A coordinator may spend one or two hours on a single appli-

cation, although most routine applications take less time. With bookkeeping, computer time, telephone calls to the dealer to verify data, and other processing work, 80 percent of the applications NABER receives are processed, and a recommendation letter issued, in under six days. Over 50 percent are turned around in one day. At this writing, NABER is processing about 300 applications per week, with virtually no backlog.

An Additional Service

Since January, an additional frequency coordination service has been underway. It's known as "instant coordination," and it complements a new FCC procedure which enables applicants for add-on licenses to existing business radio community repeaters below 470 MHz to go on the air before the FCC issues them a permanent license. Thus, a dealer can now place a phone call to NABER, have his coordination data verified "instantly" on the NABER computer, charge the fee for the coordination to his VISA or MasterCard, and receive a frequency recommendation number over the telephone. As of late January, calls were coming in at the rate of 30 to 40 each day.

There Is An Alternative

The alternative to NABER frequency coordination, as specified in the FCC regulations, is a "field sur-

vey" to determine "degree of probable interference to all existing co-channel stations within 75 miles of the (applicant's) proposed stations." A report of the survey, along with a statement that all such existing co-users have been notified of the intended application, must accompany the FCC license application. Later, the FCC notifies NABER of such an application so that the information can be integrated into NABER's own occupancy data.

A field survey generally costs \$200-\$300; a NABER coordination costs from \$20 to \$60.

Admittedly, the NABER system is not perfect. Data can and does remain on the computer in some cases long after an applicant goes off the air (for whatever reason). This happens because there is no formal procedure whereby NABER is notified when a licensee ceases operation, and it's obviously difficult to control this problem. Also, an application will sometimes take longer than usual to process because of unusual circumstances, or incorrect or incomplete information on the application form.

But one NABER coordinator summarizes NABER's solution to these minor dilemmas thus:

"I take all the time I need to find the best frequency for the customer. I know if I hurry up or get careless, it will just cause a problem later on for some other user or dealer. Somehow, you just have to find the middle position between breakneck speed and thorough, accurate frequency coordination. I think most of the time we find it."

International and US Preparations for the 1979 World Administrative Radio Conference

SAMUEL E. PROBST, SENIOR MEMBER, IEEE

Abstract—The International Telecommunication Union (ITU) will convene a World Administrative Radio Conference (WARC) in 1979 to review and modify, as appropriate, the existing International Radio Regulations. The conference will be attended by delegates from about 150 nations and will have the authority to modify significantly the existing international Table of Radio Frequency Allocations. The last conference with such a broad charter was convened in 1959, and it is anticipated that the results of the 1979 conference will have a significant operational impact on the interests of all countries through the turn of the century and beyond. This paper reviews some of the major WARC 1979 issues and summarizes the international and US preparatory efforts.

INTRODUCTION

IN LATE 1979, the International Telecommunication Union (ITU) will convene a World Administrative Radio Conference. This conference will be attended by about 150 nations and will have the authority to modify, significantly, the existing International Radio Regulations [1]. Particular emphasis will be placed on the content of the Table of Radio Frequency Allocations.

The last conference with such a broad charter was convened in 1959. That conference, however, revised only the small body of radio regulations prepared by the 1947 World Radio Conference in Atlantic City, NJ, and the results of the 1951 Extraordinary Radio Conference. Since then, some eight specialized conferences have dealt with individual radio service rules, regulations, and allocations (see Fig. 1). Those conference results and 20 years of technological progress will measurably increase the scope of review and revision necessary at the 1979 conference.

This conference thus has the potential for a significant operational impact on the interests of all countries. In the United States, and several other countries, the electronics industry represents a significant segment of our economy (see Fig. 2). Therefore, it is essential to the United States and other countries that those Radio Regulations developed by the 1979 Conference contain provisions that accommodate the telecommunications requirements of the world until the year 2000 or beyond.

The growth of telecommunications and the use of spectrum-dependent electronic devices throughout the world necessitate the development of an awareness of the radio-frequency spectrum as a vital natural resource.

In order to minimize interference as much as possible, common procedures, agreed technical criteria, and a willingness to negotiate rationally have been essential. Historically, this common ground has been the development of allocation

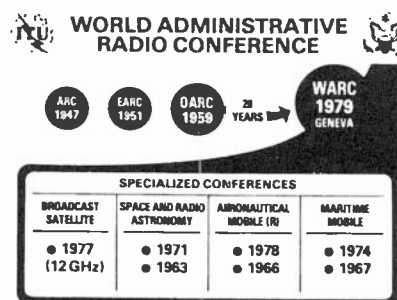


Fig. 1.

MARKET TRENDS in ELECTRONICS

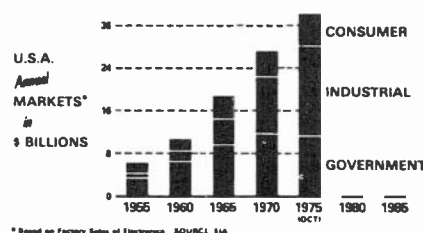


Fig. 2.

proposals that are based on sound technical rationale. The organizational structure of the ITU incorporates this technical concept as a basis for doing business. Technically oriented activities, such as the International Frequency Registration Board, the International Consultative Committees, along with various ITU Conferences, are the heart of the ITU process.

WARC 1979 ISSUES

Recent international experiences show that a sound technical approach alone probably will not meet the needs of a developing country whose political goals outpace its technical and economic capability. Recent international radio conferences have seen the beginning of political action as a short cut to technical preparation. Many such actions are little more than histrionics, but they do reduce progress to the lowest common denominator.

The ITU has defined three regions of the world for frequency-allocation purposes (see Fig. 3). Within this structure, nations must consider the need for the allocation of radio frequencies on a national, a multinational, a regional, and a worldwide basis. Of the 153 member nations of the ITU, 85 can be identified as being nonaligned or developing nations. Dominating this voting picture are the nations of Africa; but of significant importance to the United States are the Latin American nations which constitute a majority within Region 2.

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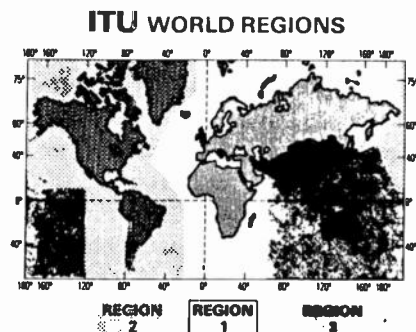


Fig. 3.

Political issues will undoubtedly cloud the 1979 Conference and the United States, among others, must be fully prepared to consider the valid needs of developing nations.

Technical issues will, of course, also arise and will have to be treated. Some of the significant trends in telecommunications development that will give rise to technical issues are:

- 1) reduction in use of HF by international fixed point-to-point operations as satellite and cable use expands, coupled with the increasing demand for HF spectrum to meet maritime and international broadcasting needs;
- 2) rapid growth in VHF and UHF land-mobile operations in the face of continuing vital military requirements and the large use of these bands for TV broadcasting;
- 3) rapid growth of both domestic and international fixed-satellite requirements in the SHF spectrum coupled with growth in microwave radio relay, space research, and earth-exploration satellite services, and the continuing need for protection of important radio-astronomy operations.

INTERNATIONAL PREPARATION

Formal preparation for the 1979 WARC began with the adoption of Resolution 28 by the Plenipotentiary Conference of the ITU, Malaga-Torremolinos, Spain, 1973 [2]. That resolution stated in part "that a World Administrative Radio Conference to revise, as necessary, the Radio Regulations and the Additional Radio Regulations shall be convened in 1979" and it further instructed the Administrative Council to make preparations for convening that conference. In the Additional Protocol, the Plenipotentiary Conference further provided for fiscal support sufficient for a conference of approximately 10-weeks duration. The 1976 session of the Administrative Council adopted a proposed Agenda for the 1979 WARC, and that Agenda will be further reviewed by the 1977, and possibly the 1978, sessions of the Administrative Council. An ITU International Radio Consultative Committee (CCIR) Special Preparatory (SPM) Meeting is scheduled for October 23-November 17, 1978 (see Appendix).

Several nations of the world, members of the ITU, have begun their preparatory efforts in accordance with their own internal governmental structure (see also the Appendix).

US PREPARATORY ORGANIZATION AND STATUS

The Director of the Office of Telecommunications Policy is charged with the responsibility for coordinating those inter-

departmental and national activities of the federal government which are conducted in preparation for US participation in international telecommunication conferences and negotiations. He also provides advice and assistance to the Secretary of State with respect to telecommunications in support of the conduct of foreign affairs. Likewise, the Federal Communications Commission is responsible for assuring that the needs of nonfederal government US users of the radio spectrum are developed and considered concurrently with the needs of the federal government. The Commission also provides advice to the Secretary of State.

Supporting both the Office of Telecommunications Policy and the Federal Communications Commission is the US International Radio Consultative Committee (CCIR). The US CCIR parallels the structure of the International CCIR (see Fig. 4). The Executive Committee of the US CCIR is chaired by a representative of the Department of State's Office of International Telecommunications Policy. Historically, the technical recommendations of the CCIR to the conferences of the ITU have not been questioned. Rather, they have provided the technical basis on which the conference develops the Table of Frequency Allocations, the coordination criteria, and many of the operating regulations.

The Director, Office of Telecommunications Policy, is assisted in his function of preparing for international telecommunication conferences by the Interdepartment Radio Advisory Committee (IRAC) which is chaired by OTP's Assistant Director for Frequency Management. The IRAC now consists of representatives of the 18 federal agencies with major telecommunications involvement.

A liaison representative of the FCC participates in all proceedings of the IRAC, and though having no vote, the FCC views are given full consideration in the treatment of federal government problems.

To address the specific task of preparation for the 1979 WARC, the IRAC, in January 1974, constituted a subordinate group designated Ad Hoc 144 whose terms of reference are

"To develop recommended US Federal Government proposals for the 1979 World Administrative Radio Conference, comment on the proposals of other administrations, develop position papers for the US delegation to the conference and plan for the eventual national implementation of the Final Acts of the Conference."

Ad Hoc 144, in the light of the broad scope of its terms of reference, established four subgroups to assist in the preparatory work. These groups and their responsibilities are as follows.

Ad Hoc 144-I: This subgroup is to prepare, for consideration by Ad Hoc 144, the draft US position regarding the definition, allocation, notification, coordination, and registration provisions of the Radio Regulations. (This subgroup has further divided its efforts, particularly with regard to the International Table of Frequency Allocations, into additional subgroups dealing with separate areas of the spectrum.)

Ad Hoc 144-II: This subgroup is to prepare, for consideration by the Ad Hoc 144, the draft US position regarding the operational and procedural provisions of the Radio Regulations.

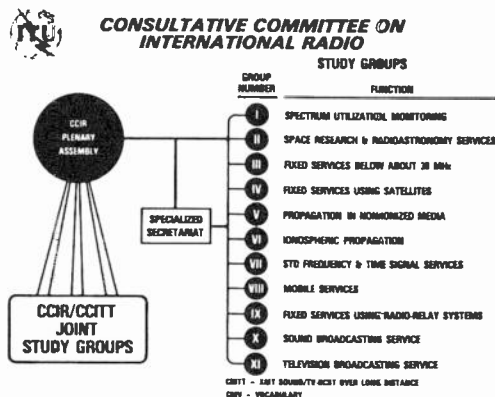


Fig. 4.

Ad Hoc 144-III: This subgroup is to prepare, for consideration by Ad Hoc 144, the draft US position regarding the technical provisions of the Radio Regulations. (This subgroup, recognizing the need for consistency of effort, has invited participation by the US CCIR. Accordingly, each study group of the US CCIR has designated representatives to Ad Hoc 144-III in order to identify those technical questions which need to be addressed within the CCIR, and to provide consistency in the technical planning being undertaken by both the CCIR and the government participants in Ad Hoc 144.)

Ad Hoc 144-IV: In early 1976, a fourth subgroup was added to the structure, initially to assist in eliminating redundant efforts among government agencies, particularly in the application of automatic data processing. The terms of reference have now been expanded to include the identification of support facilities which may be required by the delegation, both at the conference site and here in the United States.

The Federal Communications Commission (FCC), in parallel with the activities of OTP/IRAC, in January 1976, initiated formal public proceedings on behalf of the national preparatory efforts for the WARC 1979 in Docket 20271. The FCC has established a Steering Committee to coordinate these proceedings. This committee consists of representatives of all offices, divisions, and bureaus of the FCC staff. It is chaired by the Office of the Chief Engineer. The Steering Committee receives inputs from national standing organizations such as the US CCIR and from well-known radio-service working groups. For example, the aeronautical and maritime industries are represented by the Radio Technical Commission for Aeronautics (RTCA) and the Radio Technical Commission for Maritime Services (RTCM). The broadcasting industry has organized itself into service groups which include AM broadcasting, FM broadcasting, television, international broadcasting, satellite broadcasting, and auxiliary broadcasting. The American Radio Relay League (ARRL) has participated in the planning for the conferences. Likewise, the land-mobile interests are focused by the Land-Mobile Coordinating Council.

The FCC's Steering Committee is advised and assisted by internal organizational committees dealing with functional areas associated with the Radio Regulations which, to a great extent, parallel the structure of the IRAC Ad Hoc 144 sub-

groups. The Steering Committee, through its liaison representatives to the IRAC and to the Ad Hoc 144 and its subgroups, participates fully in the IRAC/AH-144 preparatory work. The Steering Committee determines when preparatory work has reached the formative stage, and makes recommendations to the commissioners of the FCC for further formal public Notice of Inquiry proceedings in Docket 20271. Finally, upon resolution of the filings in response to these public proceedings, the FCC and the OTP will make their joint recommendations to the Department of State regarding essential changes to the Radio Regulations which they feel the United States should present at the 1979 WARC.

To guide national preparatory work for the 1979 WARC, virtually identical broad guidelines have been adopted by both the IRAC and the FCC. These guidelines are as follows.

1) *Flexibility:* The primary goal will be to maintain flexibility to meet the future needs of users in telecommunications matters within the framework of the International Radio Regulations.

2) *Minimal Change:* The preparatory efforts should result in proposals for only those changes to the Radio Regulations that are absolutely required in order to meet the needs of users.

3) *Defendable Positions:* The proponents of new requirements should be in a position to defend the required revisions of the Radio Regulations, including allocations, using sound and fully developed technical arguments including accurate and current listings in the Master International Frequency List.

4) *Accommodate World Needs:* The preparatory work must take into full account the proposals for changes to the Radio Regulations advanced by other nations and should resist only those that might impede our national flexibility to an unacceptable degree.

5) *Point of No Retreat:* Where it is apparent that changes to the Radio Regulations, including modified allocations, are likely to be opposed, the preparatory work must develop, in advance of the Conference, final fall-back positions.

The national preparatory work is progressing in accord with a timetable which has been prepared to focus both federal government and public efforts on the myriad of details inherent in the unique American spectrum-management process (see Figs. 5-8).

As public comments are received in response to the several Notices of Inquiry in Docket 20271, the initial draft proposals will be modified and refined. The United States will seek every available opportunity to meet with, and discuss the issues and potential proposals with, as many of the other member nations of the ITU as possible. The results of these discussions will also help to shape and revise the draft proposals. This process will continue until very late 1978 or early 1979 when the FCC and OTP will simultaneously forward, to the Department of State, the recommended formal US proposals for the 1979 WARC. These proposals will be forwarded, by the Department of State, to the Secretary General of the ITU, eight months prior to the convening of the conference.

The ITU General Secretariat will translate the proposals received from all the member nations into the working languages of the ITU and distribute them for study. Position papers will then be developed for the US Delegation, defining

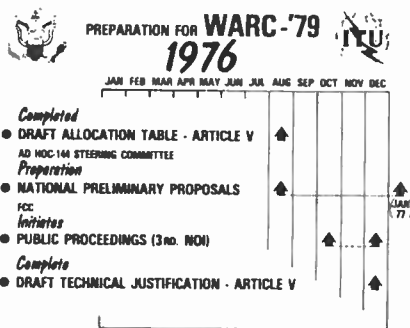


Fig. 5.

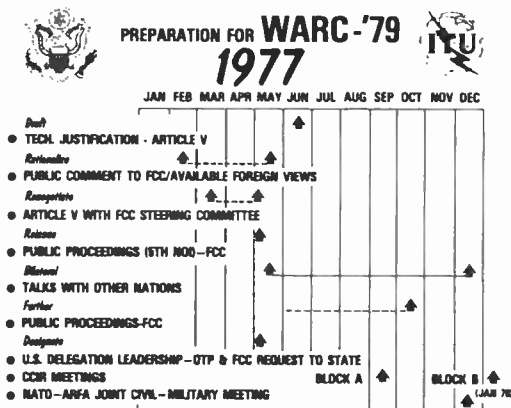


Fig. 6.

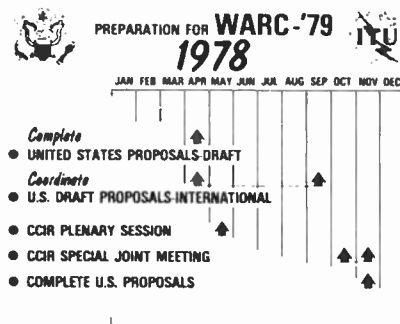


Fig. 7.

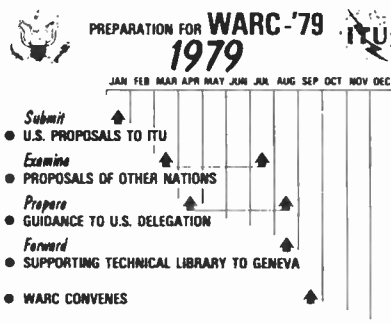


Fig. 8.

its negotiating latitude with regard to each US proposal and each significant proposal of all the other ITU members.

Finally, in September 1979, the Delegation will depart for Geneva, Switzerland, where, on September 24th, the 1979 WARC will convene and begin its deliberations. When the ten weeks of negotiating, bargaining, counterproposing, accommodating, and final reaching of accord are over, the job will not, even then, be completed. Then will begin what will probably be several years of national implementation of the Final Acts of the 1979 World Administrative Radio Conference.

APPENDIX

SPECIAL PREPARATORY MEETING OF THE CCIR FOR THE WORLD ADMINISTRATIVE RADIO CONFERENCE 1979*

Members of the CCIR and other participants in its work will be aware that a World Administrative Radio Conference (WARC-79) is scheduled to be held in Geneva beginning on September 24, 1979. The agenda for this first general radio conference to be held since 1959 is contained in Resolution 801 of the ITU Administrative Council. By Resolution 804, the Administrative Council has further charged the CCIR to carry out the necessary technical studies, and to organize a Special Preparatory Meeting (SPM) of the CCIR, to prepare a report providing technical bases for the WARC-79, and for the use of Administrations in preparing their proposals. Normally, it would be the task of a CCIR Plenary Assembly to make the necessary arrangements for such a meeting. However, as the XIVth Plenary Assembly of the CCIR is expected to take place during June 1978, the Director of the CCIR has met with Chairmen and Vice Chairmen of the Study Groups during the period June 13-17, 1977 with a view to making preliminary arrangements for the SPM. This Appendix summarizes the main aspects of the preparation for the SPM to date.

1) Date and Place

The SPM will open in Geneva on Monday, October 23, 1978, and close on Friday, November 17, 1978.

2) Terms of Reference

To prepare a report providing technical bases for the WARC-1979 and for the use of administrations in preparing their proposals to that conference. This report is to be based on the texts approved by the XIVth Plenary Assembly of the CCIR as well as on new contributions submitted by administrations and other participants in the work of the CCIR; the report should be presented in a form consistent with the various items of the agenda of the WARC-79.

3) Structure of the Preparatory Work for the SPM

It was not considered desirable by the CCIR Study Group Chairmen to organize the work of the SPM along usual study group lines, though participants from all study groups, except

*This material is summarized from CCIR Administrative Circular A.C./191, July 19, 1977, by Mr. R. C. Kirby, Director.

perhaps the CMTT, are clearly involved. Preference was given to a structure following, in general, the agenda for the WARC-79. The Chairmen also proposed Dr. J. A. Saxton (United Kingdom, Chairman of CCIR Study Group 5) as overall Coordinator of the SPM preparatory work, and Mr. M. Thue (France, Chairman of the CCIR Editorial Committee) as Coordinator for the editorial work.

4) Program of Studies

A program of CCIR studies for the WARC-79 (available from the ITU, Geneva) considered to be nonexhaustive, contains the following CCIR Questions and Study Programs:

- a) CCIR texts identified by the IFRB as relevant to the work of the WARC-79;
- b) texts adopted in conformity with No. 308 of the Convention, in the interval following the 1976 Interim Study Group meetings;
- c) texts identified by the Study Groups during their interim meetings or subsequently by the Study Group Chairman as important to the agenda of the WARC-79.

In view of the evolution of radiocommunications, and the need to assure the availability of as much effective preparatory time as possible, it is considered essential for the SPM to have available, in addition to the conclusions of the XIVth Plenary Assembly, further contributions which would allow the most recent developments to be taken into account when formulating the report to the WARC-79.

5) Report of the SPM to the WARC-1979

The proposed outline of this report is given below. It is proposed that the report take the form of the agenda of the WARC-1979 in order to facilitate its use, both by the conference and by administrations, in formulating their proposals to the conference. Toward this goal, it is therefore scheduled to be dispatched not later than February 1, 1979.

The provisional outline is as follows:

- 1) Introduction—containing information on procedures for preparing the report, organization, number of texts, annexes, figures, etc.
- 2) Terms and definitions.
- 3) Designation and classification of emissions.
- 4) Technical bases for allocations and regulations concerning spectrum utilization, except for space systems and space/terrestrial sharing.
- 5) Technical bases for allocations and regulations concerning spectrum utilization by space systems and for space/terrestrial sharing.
- 6) Technical bases for allocations and regulations concerning frequency bands at present unallocated or unused and new services for which allocations are not yet provided.
- 7) Technical aspects of optimum use of the frequency spectrum.

- 8) Technical characteristics of equipment and emissions (former Article 12 RR).
- 9) International monitoring, interference and testing, and identification of stations (former RR Articles 13, 14, and 19, respectively).
- 10) Radio wave propagation data relevant to frequency allocation, associated regulation, and frequency sharing.
- 11) Technical aspects of marking, identifying, locating, and communicating with medical transports protected under the 1949 Geneva convention.
- 12) Resolutions and recommendations of administrative conferences since 1959 relating to the CCIR.

6) Submission of Documentation

Document contributions are invited from all administrations (whether or not they normally participate in the work of the CCIR) related to the agenda of the WARC-79. In order that contributions to the work of the SPM may be processed in time for them to reach participants sufficiently in advance of the meeting, the documents should reach the Director not later than May 31, 1978, and, *if at all possible earlier*.

Documents should follow the usual CCIR presentation as set forth in CCIR Resolution 24-3 and should bear the following identification:

CCIR Special Preparatory Meeting Geneva 1978	Doc.*
 Date received:*	 Original language:*
 Concerns Topic: . . . (see Annex IV)	
(Name of Administration) (Title of contribution)	

* To be completed by CCIR Secretariat.

7) Announcement of Participation

In order that the necessary material arrangements may be made for the SPM, administrations and other participants in the work of the CCIR are requested to announce their participation not later than *September 1, 1978* stating, if possible with names, the number of persons by which they will be represented.

REFERENCES

- [1] Ed. of 1976 Radio Regulations and Additional Radio Regulations, Appendices, Resolutions and Recommendations ITU, Geneva, Switzerland, ISBN 92-61-00185-5.
- [2] International Telecommunication Convention, Final Protocol, Additional Protocols, Resolutions, Recommendations, and Opinions, Malaga-Torremolinos, Spain, 1973.

Part II

Management Tools and Methods

INTRODUCTION

THE spectrum manager has many tools and methods at his disposal to ensure that the spectrum is used efficiently and to prevent harmful interference from occurring. Seventeen papers are presented that can be divided into seven categories:

- 1) Spectrum Utilization
- 2) Spectrum Metrics
- 3) Measurements
- 4) Assignment Algorithms
- 5) Computer Techniques
- 6) Economics
- 7) Spectrum Standards

Spectrum engineering and EMC analysis techniques are very important tools that could be included, but such techniques are many and are presented separately in Part III. Spectrum Utilization, Spectrum Metrics, and Measurements are all concerned with obtaining a better understanding of how efficiently the spectrum is being used, thereby giving better control to the spectrum manager.

SPECTRUM UTILIZATION

The radio frequency spectrum is a limited resource that requires judicious use. This requirement is the driving force that is placing increasing demands on systems designers to develop systems that are more spectrum efficient and not susceptible to interference. Sviridenko presents a discussion of spectrum utilization problems from the standpoint of communications theory [1]. He emphasizes the development of mathematical models to optimize parameters to obtain improved use of the spectrum. Tou and Roy extend the work further by presenting the efficiencies of various digital modulation systems [2].

SPECTRUM METRICS

A common definition for spectrum efficiency for all users of the spectrum is not easily developed because of the many different types of systems that use the spectrum. A measure of the efficiency of land mobile communications, for example, may not be applicable to a radar employed in aeronautical radionavigation. Nevertheless, a metric based on communications output and spectrum-space input has been developed by Berry in his 1977 paper reprinted herein [3]. A similar article

by Berry was published in 1978 [4]. The CCIR has also developed a report on the definition of spectrum use and efficiency. Report 662-1 presents general considerations for the definition of a measure of spectrum use; criteria for the integrated evaluation of spectrum occupancy and utilization efficiency; and spectrum use efficiency in the terrestrial point-to-point radio relay system [5]. The CCIR report references the works by Berry, Colavito, the JTAC, and Vinogradov (Soviet Union).

Hatfield has developed a measure for land mobile radio spectrum based on erlangs, frequency, and area [6]. The land mobile spectrum problem has also been studied in Italy by Colavito [7] and others referenced in the paper by Berry and the CCIR report.

MEASUREMENTS

Measurements of systems using the spectrum can provide the spectrum manager with knowledge of how the spectrum is being used, and together with other data, can show the spectrum manager whether or not the spectrum is used efficiently.

Measurements of systems using the spectrum have been made for many years although such measurements have been made largely for enforcement purposes and for solving interference problems. With the advent of automated measurement equipment, it became possible to measure large amounts of spectrum in a short time and to conduct sophisticated processing of the measurement data, thereby providing valuable information to the spectrum manager.

Hagn, Jansky, and Dayharsh provide a comprehensive view of the requirements of a measurement system and the purposes of measurements: occupancy, compliance, and compatibility [8]. Spaulding and Hagn have performed an extensive study of measurement times and their significance in the determination of the spectrum use of channels and bands of similar channels [9]. Matheson discusses the hardware and software used in an automated spectrum management system and presents examples of measurement data [10], [11]. Murray and Matheson [12], and Petak [13] have also done work on automated measuring techniques.

Measurements of land mobile radio channels used to determine spectrum occupancy have been studied and discussed extensively [14]–[19]. The measurement of signals in general and of specific devices has also been

adopted into various standards [20]–[23]. Many papers on various types of measurements have been published in the IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY. The papers published through mid-1983 were indexed in the special "EMC Society Silver Anniversary Issue" [24].

Study Group 1 of the CCIR is chartered to address spectrum utilization and monitoring. Volume 1 of the CCIR Green Book Series contains 25 reports and recommendations on the techniques for spectrum monitoring and characterization [25]. The CCIR reports and recommendations address such topics as frequency, field-strength, bandwidth, and direction-finding measurements at monitoring stations; automatic monitoring; and acquisition of spectrum occupancy data for spectrum management purposes. The CCIR has also developed a handbook for monitoring stations that is a valuable source of information on monitoring [26].

Field strength measurements of broadcast band signals are addressed in an EBU Technical Monograph [27] and in the NAB Engineering Handbook [28]. The EBU Technical Monograph covers the measurement of both field strength and frequency, and the NAB Engineering Handbook devotes several chapters to the measurement of field strengths of AM, FM, and TV broadcast signals.

ASSIGNMENT ALGORITHMS

Frequency assignment algorithms are useful when it is necessary to assign frequencies to a large number of stations. The algorithms often take into consideration transmitter, receiver, and antenna parameters; propagation; and protection ratios. The algorithms can provide optimum or near-optimum spectrum efficiency. Computer models are often used to implement the algorithms.

The paper by Hale that is reproduced herein is a comprehensive treatment of assignment algorithms and includes a substantial number of references. Zoellner has examined assignment strategies and concludes that the most heavily committed channel should be assigned before resorting to those less heavily committed [30]. Struzak has addressed the problem of optimum frequency and power assignment and presents a solution [31]. Cram and Hensler have developed an assignment algorithm for aeronautical communications frequencies in the VHF band that integrates data bases, equipment parameters, propagation and protection ratios [32]. Arnaud has employed the lattice theory in broadcast frequency planning [33].

Other recent work on assignment algorithms has been conducted by Carmassi and Tomati [34]; Cox and Reudink [35]; Gressman and Kipitz [36]; Rubinstein, Kaganer and Bessonov [37]; and Struzak [38].

COMPUTER TECHNIQUES

The spectrum manager is very often confronted with the problem of finding spectrum space to satisfy a

telecommunications requirement. This problem is becoming increasingly difficult as the frequency bands become more and more congested. One way to alleviate the situation is by the use of computers. Computers can be used to maintain data bases of frequency assignment records in addition to performing various model analyses to ascertain that the newly considered assignments can operate within the existing electromagnetic environment and with themselves in a compatible manner.

Garber presents a comprehensive treatment of spectrum management data bases emphasizing the various items that are included in the Government Master File (GMF) used by U.S. Government agencies and maintained by the National Telecommunications and Information Administration [39]. Garber also presents a summary of analysis aids that are used in conjunction with the GMF and other data files. Cohen and Mayher provide further information on analytical models and their use on programmable calculators, minicomputers, and large computers [40]. De Mercado and others have applied microcomputers to spectrum management, particularly land mobile communications [41].

The CCIR has recognized the utility of computer-aided techniques in spectrum management. CCIR Report 841 covers spectrum engineering models and computer techniques and presents a catalog of 27 spectrum management models [42]. The CCIR has formed Interim Working Party (IWP) 1/2 that has developed a handbook on spectrum management and computer-aided techniques [43]. The handbook describes the various aspects involved in applying computer-aided techniques to radio frequency management and provides guidelines for various levels of practical application. The handbook describes engineering analysis techniques including frequency files, computer applications, and examples of automated aids, and provides a catalog of data files and computer programs.

Computer techniques are frequently used to implement propagation models. There has been considerable research and development of propagation models using digitized terrain data. A listing of recent works in this area is presented in the Bibliography, Part II.

Additional work in computer techniques in spectrum management has been conducted by Carmassi and Tomati [44]; Dowling [45]; Gressman and Kopitz [46]; Krusch [47]; Mayher and Moran [48]; Mazutis [49]; and Waszkis [50]. Modeling techniques often employ computers because of the complexity of the model. These are discussed in Part III. There is also a close relationship with assignment algorithms where computers are frequently used.

The frequency assignment records, whether kept manually or in computerized data bases, have emission designators associated with them. The paper by Luther reproduced herein presents the procedure of classification and designation of emissions that resulted in WARC-79 [51]. The storage space of such emission

records in computers is one of the factors that should be taken into consideration when developing data bases.

ECONOMICS

Various studies have been conducted on spectrum economics where a value is placed on the spectrum. The paper by Webbink reproduced herein presents examples of various approaches to the economic concept [52].

An extensive study of economic techniques in spectrum management was undertaken in 1979 by Agnew, Gould, Dunn, and Stibolt [53]. The study surveyed various proposed economic techniques in spectrum management and provided examples of the application of such techniques in satellite frequency coordination, multipoint distribution service, land mobile, and satellite orbital slots.

The works of Webbink, Agnew, and others contain many references on spectrum economics. Other studies on spectrum economics were conducted by Alleman [54], Ewing [55], Jackson [56], Melody [57], and Minasian [58].

SPECTRUM STANDARDS

In general, standards establish parameters for the characteristics of a product or service. Spectrum standards are tools of the spectrum manager that permit a degree of control over the technical characteristics of the electronics equipment using the spectrum, resulting in more efficient use of the spectrum and minimizing the possibility of interference.

The CCIR develops reports and recommendations on the technical characteristics of electronic equipment using the spectrum. In some cases, these are adopted by the ITU and placed in the Radio Regulations thereby having the status of international law. Examples of technical standards in the ITU Radio Regulations (Edition of 1982) are [59]:

Article 5—Technical Characteristics of Stations

Appendix 7—Table of Transmitter Frequency Tolerances

Appendix 8—Table of Maximum Permitted Spurious Emission Power Levels

Volume I of the CCIR Green Books contains the following reports and recommendations relating to technical standards [60]:

Recommendation 326-4	Power of Radio Transmitters
Recommendation 445-1	Definitions Concerning Radiated Power
Recommendation 328-5	Spectra and Bandwidths of Emission
Report 836	Necessary Bandwidth Calculations

Report 181-4

Frequency Tolerance of Transmitters

Recommendation 329-4 Spurious Emissions

Recommendation 324-4 Selectivity of Receivers

These reports and recommendations can be revised every four years during a new CCIR cycle of meetings.

The CCIR reports and recommendations can also be adopted on a voluntary basis by administrations (countries) as their national standards. Administrations also frequently develop their own technical standards. The FCC Rules and Regulations contain various technical standards, although they are not contained in just a single part of the Rules and Regulations, but appear in the many appropriate parts where they are applicable. The NTIA "Manual of Regulations and Procedures for Federal Radio Frequency Management" contains a chapter on technical standards [61].

The American National Standards Institute (ANSI) is the coordinator of the U.S. voluntary standards system. Among the major functions of ANSI are the coordination of the voluntary development of U.S. national consensus standards and approving standards. Although ANSI has thousands of standards, only about ten are related to spectrum management. These are concerned with electromagnetic radiation safety levels with respect to human exposure; measurements of hazardous electromagnetic fields; measurements of noise; definitions of terms for radio wave propagation; test procedures for antennas; and measurement of spurious emission from land mobile transmitters [62].

The IEEE develops technical standards, some of which have been adopted by ANSI. The IEEE has about 11 standards that are related to spectrum management. Most of these are also ANSI standards [63].

Organizations such as the Electronics Industries Association (EIA) and Radio Technical Commission for Aeronautics develop standards for use within the U.S. [64], [65]. However, very few are directly related to spectrum management. For example, the EIA has standards on the methods of measurement of land mobile communications systems. The RTCA develops and publishes minimum performance standards for avionics equipment.

The standards developed by the ANSI, EIA, and IEEE are often developed by cooperation between regulatory agencies such as the FCC and the standards groups.

The U.S. military has developed technical standards for its own internal use. Some of these concern EMC, radar systems, communications systems, etc., and are frequently imposed upon equipment developers [66], [67], [68], [69].

International organizations such as the ICAO (International Civil Aviation Organization) and IMO (International Maritime Organization) often develop equipment performance and operating standards that are related to spectrum management [70], [71]. The C.I.S.P.R. of the IEC also develops standards, but they concern limits of spurious radiations and their measurements. The

C.I.S.P.R. is discussed in Part I in the Rutkowski paper and in Part III under "Noise."

White has authored and published a handbook on electromagnetic interference (EMI) specifications, standards, and regulations [72]. Yazar has studied civilian EMC standard and regulations including the EIA, U.K., FCC and the relationship of some of these to U.S. military standards [73]. A workshop on international telecommunications standards was sponsored by the NTIA in 1982 that reviewed various standards [74].

The paper by Wall and Bromery reproduced herein presents the evolution of a technical standard on the radiations from digital equipment such as computers [75]. The paper presents the background of the FCC rulemaking proceeding, test methods, manufacturer's responsibilities, and possible harmonization to C.I.S.P.R. standards. The paper also serves as a good example of the FCC rule-making procedures.

REFERENCES

- [1] S. S. Sviridenko, "Spectrum utilization problems," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part 2, Aug. 1977.
- [2] C. P. Tou and D. A. Roy, "On efficient spectrum utilization from the standpoint of communication theory," *Proc. IEEE*, vol. 68, no. 12, Dec. 1980.
- [3] L. A. Berry, "Spectrum metrics and spectrum efficiency: Proposed definitions," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part 2, Aug. 1977.
- [4] —, "Measuring spectrum use," *Wireless World*, Dec. 1978.
- [5] "Definition of spectrum use and efficiency," Report 662-1, CCIR Green Book, Vol. 1; "Spectrum utilization and monitoring," XVth Plenary Assembly, Geneva, 1982.
- [6] D. N. Hatfield, "Measures of spectral efficiency in land-mobile radio," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part 2, Aug. 1977.
- [7] C. Colavito, "On the efficiency of the radio frequency spectrum utilization in fixed and mobile communications systems," *Alta Frequenza*, vol. XLIII, no. 9, Sept. 1974.
- [8] G. H. Hagn, D. M. Jansky, and T. I. Dayhash, "Definition of a measurement capability for spectrum managers," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part 2, Aug. 1977.
- [9] A. D. Spaulding and G. H. Hagn, "On the definition and estimation of spectrum occupancy," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part 2, Aug. 1977.
- [10] R. J. Matheson, "Automated spectrum analysis," *Proc. IEEE*, vol. 66, no. 4, Apr. 1978.
- [11] R. J. Matheson, "A radio spectrum measurement system for frequency management data," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part 2, Aug. 1977.
- [12] J. P. Murray and R. J. Matheson, "Computer aided spectrum monitoring," presented at the 5th Symp. Electromagn. Compat., Wroclaw, Poland, Sept. 1980.
- [13] L. P. Petak, "An application of automatic spectrum monitoring equipment" presented at the 5th Symp. Electromagn. Compat., Wroclaw, Poland, Sept. 1980.
- [14] G. H. Hagn and T. I. Dayhash, "Land-mobile radio communication channel occupancy, waiting time, and spectrum saturation," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part 2, Aug. 1977.
- [15] O. Efremov, "Measured VHF and UHF signal strength and spectrum occupancy versus antenna height," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part 2, Aug. 1977.
- [16] J. H. McMahon, "Analysis of land-mobile channel-occupancy sampling errors," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part 2, Aug. 1977.
- [17] L. D. Reed, "Land mobile spectrum utilization—Los Angeles and San Diego, CA," Report PRB/RDL 79-02, Federal Communications Commission, Washington, DC, Nov. 1979.
- [18] J. R. Hudak and W. T. Towanen, "Limited spectrum occupancy study" (note: measurement of frequencies assigned to Los Angeles County Sheriff's Department), Report FCC/FOB-84-01, Federal Communications Commission, Washington, DC, Feb. 1984.
- [19] P. Murray, "Fighting for spectrum," *RCR-Radio Communications Report*, Aug. 27, 1984 (note: discussion and comments pertaining to measurements of note 18).
- [20] "Mobile units for the measurement of field-strength and frequency," EBU Technical Monograph No. 3113, European Broadcasting Union, Brussels, Belgium.
- [21] "Specifications for electromagnetic noise and field-strength instrumentation, 10 kHz to 1 GHz," ANSI C63-2-1980, American National Standards Institute, New York, NY, 1980.
- [22] "Measurement of spurious radiation from FM and TV broadcast receivers in the frequency range of 100 to 1000 MHz using the EIA Laurel broadcast band antenna," Standard RS-378, Electronic Industries Assoc., Washington, DC.
- [23] "C.I.S.P.R. specification for radio interference measuring apparatus and measurement methods," C.I.S.P.R. No. 16, International Electrotechnical Commission, Geneva, Switzerland, 1977 (see also C.I.S.P.R. documents 9, 11, 11A, 12, 13, 14, 15, and 17 for limits and measurements of various devices and C.I.S.P.R. specifications 1–5 for measurement equipment).
- [24] *IEEE Trans. Electromagn. Compat.*, EMC Society Silver Anniversary Issue, vol. EMC-25, no. 3, Part 1, Aug. 1983.
- [25] "Spectrum utilization and monitoring," CCIR Green Book, Vol. 1, XVth Plenary Assembly, Geneva, 1982.
- [26] "Handbook for monitoring stations," CCIR, Geneva, 1968. Revised Chapter 4, First Edition, 1976. Revised Chapter 19, 2nd Edition, 1980.
- [27] Mobile units for the measurement of field-strength and frequency," EBU Technical Monograph 3113, European Broadcasting Union, Brussels, Belgium, 1973.
- [28] *National Association of Broadcasters Engineering Handbook*, G. W. Bartlett, Ed. Washington: National Assoc. of Broadcasters, 1975.
- [29] W. K. Hale, "Frequency assignment: Theory and applications," *Proc. IEEE*, vol. 68, no. 12, Dec. 1980.
- [30] J. A. Zoellner, "Frequency Assignment Games and Strategies," *IEEE Trans. Electromagn. Compat.*, vol. EMC-15, no. 4, Nov. 1973.
- [31] R. G. Struzak, "Optimum frequency planning: A new concept," *Telecommunication J.*, vol. 49, no. 1, Jan. 1982.
- [32] C. Cram and T. Hensler, "FAA remote terminal system frequency assignment model," presented at the IEEE Symp. Electromagn. Compat., Atlanta, GA, 1978.
- [33] J. F. Arnaud, "Frequency planning for broadcast services in Europe," *Proc. IEEE*, vol. 68, no. 12, Dec. 1980.
- [34] F. Carmassi and L. Tomati, "A theory of frequency assignment in broadcast network planning," *EBU Review—Technical Part*, no. 198, Apr. 1983.
- [35] D. C. Cox and D. O. Reudink, "Dynamic Channel Assignment in High-Capacity Mobile Communications Systems," *Bell Syst. Tech. J.*, vol. 50, no. 6, July–Aug. 1971.
- [36] R. Gressman and D. Koptiz, "Networks of medium frequency transmitters with different powers," *EBU Review—Technical Part*, no. 147, Oct. 1974.
- [37] G. R. Rubinstein, M. B. Kaganer, and A. P. Bessonov, "Optimum methods of operative frequency assignment to radio communication facilities operating in the metric waveband," presented at the 7th Int. Symp. Electromagn. Compat., Wroclaw, Poland, June 1984.
- [38] R. G. Struzak, "On optimum frequency and power assignment

- in transmitter networks," presented at the 4th Int. Symp. Electromagn. Compat., Zurich, Switzerland, Mar. 1981.
- [39] G. W. Garber, "Spectrum management data bases," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part 2, Aug. 1977.
- [40] D. Cohen and R. Mayher, "The use of computerized analytical techniques in spectrum management," presented at the 3rd Symp. and Technical Exhibition Electromagn. Compat., Rotterdam, Netherlands, May 1979.
- [41] J. deMarrado *et al.*, "Microcomputers for spectrum management," *Telecommunication J.*, vol. 49, no. 4, Apr. 1982.
- [42] "Spectrum management and computer-aided techniques," Report 841, CCIR Green Book, Vol. 1; "Spectrum utilization and monitoring," XVth Plenary Assembly, Geneva, 1982.
- [43] *Handbook—Spectrum Management and Computer-Aided Techniques*. Geneva: CCIR, 1983.
- [44] F. Carmassi and L. Tomati, "A frequency assignment in broadcasting network planning assisted by computer," presented at the 7th Int. Symp. Electromagn. Compat., Wroclaw, Poland, June 1984.
- [45] D. Dowling, "The development and use of an a-priori environmental data base for EMC analysis," International Electromagnetic Compatibility Symposium Record, IEEE, Arlington Heights, IL, July 1972.
- [46] R. Gressman and D. Kopitz, "Some possibilities for computer-assisted planning of the LF/MF bands," *EBU Review—Technical Part*, no. 151, June 1975.
- [47] W. Krusch, "Use of computerized methods to facilitate the tasks of the Deutsch Bundespost radio frequency management," Electromagnetic Compatibility Symposium Record, Montreaux, Switzerland, 1977.
- [48] R. J. Mayher and W. M. Moran, "Minicomputer software development for spectrum management," presented at the 5th Symp. Electromagn. Compat., Wroclaw, Poland, Sept. 1980.
- [49] J. Mazutis, "Computer aided spectrum management," presented at the 4th Symp. Electromagn. Compat., Wroclaw, Poland, September 1978.
- [50] W. Waszkis, "Computer aided design of low-power TV network for efficient use of spectrum space," presented at the 7th Int. Symp. Electromagn. Compat., Wroclaw, Poland, June 1984.
- [51] W. A. Luther, "Classification and designation of emissions," *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, no. 3, Aug. 1981; or *IEEE Trans. Communications*, vol. COM-29, no. 8, Aug. 1981.
- [52] D. W. Webbink, "The value of frequency spectrum allocated to specific uses," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Aug. 1977.
- [53] C. E. Agnew, R. G. Gould, D. A. Dunn, and R. D. Stibolt, "Economic techniques for spectrum management: Final report," prepared for National Telecommunications and Information Administration, Boulder, CO, by Mathtech, Inc., Princeton, NJ, and Telecommunications Systems, Washington, DC, December 20, 1979.
- [54] J. H. Alleman, "The shadow price of electromagnetic spectrum: A theoretical analysis," Report OTR-74-42, Office of Technology Assessment, Washington, DC, July 1974.
- [55] D. R. Ewing, "Economic efficiency: The objective of spectrum management," *IEEE Trans. Electromagn. Compat.*, vol. EMC-20, no. 4, Nov. 1978.
- [56] C. L. Jackson, "The orbit-spectrum resource: Market allocation of international policy," *Telecommunications Policy*, vol. 2, no. 3, Sept. 1978.
- [57] W. Melody, "Radio spectrum allocation: Role of the market," *Amer. Econom. Rev. (Papers and Proceedings)*, vol. 70, 1980.
- [58] J. R. Minasian, "Property rights in radiation: An alternative approach to radio frequency allocation," *J. Law and Econom.*, vol. 18, 1975.
- [59] "Radio regulations—Edition of 1982," International Telecommunication Union, Geneva, Switzerland, 1982.
- [60] "Spectrum utilization and monitoring," CCIR Green Book, Vol. 1, XVth Plenary Assembly, Geneva, 1982.
- [61] "Technical Standards, Requirements and Objectives" in *Manual of Regulations and Procedures for Federal Radio Frequency Management*. Washington, DC: National Telecommunications and Information Administration, updated to 1984, ch. 5.
- [62] *1984 Catalog of American National Standards*. New York, NY: American National Standards Institute, 1984.
- [63] *Summer 1984 IEEE Standards Listing*. Piscataway, NJ: IEEE, 1984.
- [64] *Catalog of EIA and JEDEC Standards and Related Engineering Documents*. Washington, DC: Electronic Industries Assoc., 1984.
- [65] *Listing of Available Documents*. Washington, DC: Radio Technical Commission for Aeronautics, 1984.
- [66] H. K. Mertel, "Experiences with military EMC specifications," EMC Montreux Symposium Digest, June 1977.
- [67] S. J. Caprio, "Applicability of MIL-STD-449D and MIL-STD-469 to modern radar systems," *IEEE Trans. Electromagn. Compat.*, vol. EMC-21, no. 2, May 1979.
- [68] S. Sucknick, "Validity of MIL-STD-461 interference measurements as an estimate of the spectral density of a signal," presented at the 7th Int. Symp. Electromagn. Compat., Wroclaw, Poland, June 1984.
- [69] D. Jaeger, "Application of MIL-STD-461, 462, 463 as a general EMC specification for equipment," Electromagnetic Compatibility Symposium Record, Montreaux, Switzerland, 1975.
- [70] "International standards and recommended practices, Aeronautical Telecommunications, annex 10 to the convention on civil aviation," International Civil Aviation Organization (ICAO), Montreal, Quebec, 1972.
- [71] "International conference on safety of life at sea," Inter-Governmental Maritime Consultative Organization, London, 1974.
- [72] D. R. J. White, *EMI Specifications, Standards and Regulations*. Gainesville, VA: Don White Consultants, Inc., 1981.
- [73] M. N. Yazar, "Civilian EMC standards and regulations," *IEEE Trans. Electromagn. Compat.*, vol. EMC-21, no. 1, Feb. 1979.
- [74] D. M. Cerni and E. M. Gray, "International telecommunications standards: Issues and implications for the 80's—A summary record of a July 1982 workshop," NTIA-SP-83-15, National Telecommunications and Information Administration, Boulder, CO, May 1983.
- [75] A. Wall and R. Bromery, "FCC controls digital equipment," presented at the IEEE International Symposium on Electromagnetic Compatibility, Baltimore, MD, 1980.

Spectrum Utilization Problems

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Abstract—This paper discusses various spectrum utilization problems, including the efficiency of spectrum use considered from the standpoint of communication theory. Mathematical modeling for spectrum efficiency is discussed for linear and nonlinear receiver models. Sharing problems between satellite and terrestrial relay systems are mentioned, and various solutions are discussed.

INTRODUCTION

THE radio-frequency spectrum is a range of frequencies used for wireless transmission of information from one place to another.

Although the problem of radio-frequency spectrum utilization has existed ever since electromagnetic waves were discovered, the spectrum remains one of the least evaluated natural resources despite the amount of study which it has been given [1]–[38]. (These references are general in their scope.)

At the present time, radio communications of all kinds are expanding on a colossal scale and radio spectrum requirements are increasing, accordingly. Spectrum congestion has made it necessary to study the possibilities of sharing among the various radio technical systems [11], [27], [31]–[33].

At the national level, the spectrum is used for the management of industry and national resources, defense and security forces, broadcasting, radio communications, meteorology, astronomy, space research, and other purposes. The role of the spectrum in the international exchange of information needs no further elucidation here. It is clear that the significance of the spectrum is not only technical but also economic and social [14], [19], [25], [34].

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Despite protracted efforts made at an international level, frequency allocation is not yet based on stringent technical criteria, due mainly to the difficulties involved in selecting such criteria.

Guidelines for the use of the spectrum are laid down in the Radio Regulations [8], which define the organizational and technical conditions governing the sharing of frequency bands by individual radio services, specify standards for radio emission parameters, etc. The Radio Regulations cover the following services: fixed, mobile, broadcasting, radionavigation, radioastronomy, standard frequency and time signals, radio amateur, and various types of space service [9].

EFFICIENCY OF SPECTRUM USE

The efficiency of spectrum utilization depends, as is well known [1], [3], [5], [6], [34], on such parameters as radiated power, bandwidth, service area, length of transmission, signal waveform, antenna pattern, class of interference and type of noise, the threshold level of the receiver decision element, the cost of the equipment used, and the methods of frequency planning.

In order to evaluate the efficiency of spectrum utilization it is necessary to have technical criteria for its quantization and measurement. These should be practicable and objective and should take account of the statistical nature of system parameters and the dual nature of the use of the spectrum, for both transmission and reception.

Besides having criteria for the quantitative measurement of spectrum utilization, it will be useful to have criteria for the economic analysis of the spectrum as a resource [11], [14]–[19].

For a long time, bandwidth has been the preeminent factor considered to represent spectrum occupancy, even though

time sharing and geographical sharing have been provided for. More attention has been given recently to a spectrum volume which has as dimensions not only bandwidth, but also explicitly geographical space and time.

Three types of criteria have recently been suggested in evaluating the spectrum utilization [30]

- criterion based on the specific position of radio stations in space;
- criterion geared to the use of standard systems;
- independent criterion depending exclusively on comparison with characteristics of an equivalent system.

For point-to-point voice services, a fourth "optimum use" criterion for spectrum utilization efficiency [22], has been suggested

$$\gamma = \frac{NF}{B}$$

where N is the number of channels used, F is the signal bandwidth (e.g., 4 kHz for speech), B is the necessary bandwidth.

This criterion is based on the consideration that the most effective utilization of the spectrum corresponds to the maximum communication per unit bandwidth between two points. If we introduce a bandwidth expansion coefficient $n = B/F$, then γ is equal to the ratio of the number of channels to the bandwidth expansion coefficient.

Unfortunately, the frequency spectrum cannot be optimized without taking into account the type of antenna used. However, all existing antennas can be subdivided by antenna pattern into a number of types [22]. By expressing analytically the antenna pattern of each type of antenna and the emission bandwidth B for a particular type of modulation, it is possible to calculate γ as a function of the bandwidth expansion coefficient.

Another criterion for fixed and mobile services has been proposed [28]. On the basis of the spectrum value concept which is the product of the geographical space, bandwidth, and time, the spectrum utilization efficiency of a transmitter can be regarded as the product of the frequency efficiency γ_f , spatial efficiency γ_s , and time efficiency γ_t

$$\gamma_{tr} = \gamma_f \cdot \gamma_s \cdot \gamma_t$$

where

$$\gamma_f = \frac{N_r}{N_i} \quad \gamma_s = \frac{d_r}{d_i} \quad \gamma_t = \frac{Q_r}{Q_i}$$

where the indices "r" and "i" stand for a "real" and an "ideal" system, respectively. The symbol N stands for the number of radio channels with the same communication capacity in a given bandwidth, d is the number of times the radio channel is used in the given space, and Q is the amount of information which can be transmitted on one radio channel in a given period of time. A standard system can be taken as a reference instead of an ideal system.

The efficiency concept γ_{tr} has been used to consider the problem of spectrum utilization in the mobile services which

are extremely widespread [23], [28]. One of the main problems for the mobile services is that of better coordination of frequencies used in time and space.

The problem of spectrum utilization can also be approached by using the so-called "amount of service denied to others by the system in question" [3, pp. S8-85].

The efficiency of spectrum use is determined by the ratio of the minimum possible service value of an ideal system to the service value of the system under consideration.

One possible standard unit of spectrum space utilization might be power density over an area and frequency band (PODAF) [86], [7], based upon a specified level of radiated energy density over a specified bandwidth over a specified geographical area.

During the last years, attempts were continued to define spectrum use and efficiency [35], [90], [91]. The article [91] gives formulas for estimating spectrum use based on the product of the occupied bandwidth and the volume of the space occupied by the emission. The boundaries of the volume are defined by the maximum permissible interference power level.

Efficiency is defined in many diverse fields as the ratio of output to input. It is possible to use these ideas to define spectrum efficiency. The desired output of a telecommunications system is "information transferred," and the input of interest to spectrum efficiency is "spectrum-space used." Thus, the general form of a measure of spectrum efficiency is [90]

$$\frac{\text{information transferred}}{\text{spectrum-space used}}.$$

Considerable work is needed to transform this general concept into a calculable number for any particular service.

COMMUNICATION THEORY APPLIED TO SPECTRUM EFFICIENCY

The problem of using coded signals to save spectrum space or transmission time for a given quantity of information has been under study for a long time and is still topical [34]. Various problems relating to the improvement of spectrum utilization are being studied on the basis of communication theory methods by the CCIR [36]-[39], in some cases in collaboration with Union Radio-Scientifique Internationale (URSI).

An important problem is the influence of the system bandwidth limitation on the noise immunity and communication capacity of the communication system [45]-[53], [88], [89]. Bandwidth limitation gives rise to intersymbol errors so that theoretical studies are extremely complex and generally finish up with numerical integration.

The effect of bandwidth limitation on noise immunity in the reception of amplitude-shift-keying (ASK) signals is considered in [50] and [51], [52] in the cases of noncoherent and coherent reception, respectively.

Considerable interest is attached to the question of information transmission by digital pseudorandom signals. The code sequences which are binary bit streams, may vary from a

few tenths, thousands, or millions of bits, and may be linear or nonlinear in their construction.

One of the main advantages of this method of information transmission, known as the spread spectrum technique [92], consists of the possibility of "overcoming" noise and man-made interference by means of special "coded" signals and by reception techniques which are optimum for the given conditions. In essence, this consists of accumulating signal energy at the receiver-decision circuit input. These functions are carried out by the encoder and the decoder of the digital system. The recent development of computer techniques has made it possible to find groups of digital quasiorthogonal pseudorandom signals of length $L = 2^n - 1$, which are generated by an n -stage maximum period shift register. The groups include signals with fixed auto- and cross-correlated properties. They are separated by an M -channel cross-correlated receiver. The upper limit of the mean error probability P_e on reception is defined by the expression [93]

$$P_e = (M - 1) \exp \left[-\frac{E}{2N_0} (1 - \lambda) \right]$$

where

E signal energy;

N_0 white noise spectral density;

and

$$\lambda = \max_{\substack{i,j \\ i \neq j}} \int_0^T S_i(t) S_j(t) dt$$

(the value characterizing the cross-correlated properties of the signals received).

The pseudorandom signals have a narrow self-correlation function peak and a wide band; they can be used to transmit information in a single frequency band in radio or television broadcasting.

System efficiency may be improved by switching over from binary (0, 1 or -1, 1) to M -ary coding, which makes it possible, with limited signal power and high noise immunity, to attain a higher signaling rate.

In the M -ary form, the pulses are represented by different values of amplitude, phase, or frequency, or combinations of these, depending on the coding method used.

A number of fairly effective codes are in use at the present time with a view to efficient utilization of the spectrum (ternary block codes, Bose-Chaudhuri codes, convolutional codes, adaptive-convolutional codes, fast correcting codes, etc.) and also effective methods of decoding [35], [40]–[44].

The question of the minimum bandwidth of an emission is extremely important. On the other hand, limitation of the spectral width of coded signals causes distortion of the received signal, thus leading to a reduction in the signal-to-noise ratio at the receiver output and hence to deterioration in the quality of the information transmitted.

It is therefore extremely interesting, at the present time, to assess the effect of the communication channel characteristics on the form and size of the receiver output signal with a view to finding the minimum required bandwidth.

The assessment of the distortion of complex coded signals in linear circuits constitutes an exceptionally intractable mathematical problem.

In connection with the development of new coding techniques, it is important to define bandwidths for the new signals and the extent to which changes in bandwidths can affect the characteristics of the communications system [46]. For example, in the studies reported in [42], spectral density functions have been obtained for pseudoternary coded signals (three-position code in random sequence) of fixed length used in radio relay systems. The study reported in [53], [54] analyzes cases of bandwidth limitation in the case of input and reference signals with mutually correlative reception.

The idea of using multiparameter modulation to improve the characteristics of communication systems is not a new one [55] (the Russian edition appeared in 1956), but only recently has work on this problem been intensified in connection with the possibility of making a more rational use of the radio spectrum [56]–[66]. Most of the studies carried out are concerned with practical aspects and deal with combined digital amplitude-phase-shift keying (APSK) in communication systems [58], [62]–[64].

Combined modulation increases the channel efficiency and permits more economical use of the frequency spectrum and economies in transmitter power. Basically, combined modulation consists in choosing two or more carrier parameters to be modulated, as a result of which the carrier wave becomes a carrier of multichannel information. Of course there must be no appreciable deterioration in the quality of the information transmitted in each channel. The best type of carrier is a radio-frequency pulse train having a number of parameters which can be used to carry information.

The article [59] gives the results of research on improving the capacity of a digital channel by additionally modulating the time position of the pulses. The main result of the research is that certain combined modulation parameters yield an improvement in the traffic capacity of a digital communication system.

Theoretical investigations are being carried out to work out a set of M -ary signals (coded signals with base more than two) with maximum packing density [60]. A set of hexagonal signals has been found to be close to the optimum but it has not yet been rigorously demonstrated that the hexagonal set is the optimum one.

M -ary amplitude/phase-shift digital modulation requires lower peak and mean powers than other types of digital keying in the same bandwidth transmitted at the same speed and with the same probability of error [61]–[66]. One of the main questions is—what is the optimum ratio between the phase and amplitude modulation depth in a set of signals that results in the minimum mean probability of error for a given signal-to-noise ratio?

MATHEMATICAL MODELING FOR SPECTRUM EFFICIENCY

The mathematical modeling of a communication system and its components with a view to the optimization of its parameters from the standpoint of the rational utilization of the spectrum is a new and highly topical problem. This work is mainly being carried out within the framework of the CCIR [67] - [74].

The corresponding mathematical model of a noncoherent [69] and a coherent [68] receiver of signals with digital amplitude and M -ary phase shift keying is designed to investigate spectrum utilization from the standpoint of interchannel and intrachannel interference. The model includes the modulated signal source, the channel components producing signal distortion, sources of additive and multiplicative noise, the receiver synchronization unit, and signal filtration. The latter is carried out either in digital form or by a convolution of the input signal with impulse filter reaction on the basis of a fast Fourier transform.

The nonlinear receiver model [70] studies such effects as cross modulation, modulation distortion, intermodulation desensitization, and decreases in sensitivity and spurious responses. To represent signals taking into account nonlinear effects, use is made of the Volterra functional and the Fourier transform of Volterra functionals [74]. The investigations aim at finding a logical combination of such parameters as the emitted bandwidth, receiver selectivity, antenna gain, attenuation during propagation, etc., with a view to solving the problem of spectrum utilization.

SATELLITE AND TERRESTRIAL RELAY SHARING PROBLEMS

The use of the spectrum by satellite and terrestrial radio relay systems is a highly complex problem [75] - [85]. One of the main problems is that of the efficient utilization of the geostationary orbit, i.e., the placing of the maximum number of satellites on a given arc of the orbit within tolerable mutual interference limits [84].

A number of engineering solutions have been proposed for a more rational use of the spectrum by satellite systems. One idea [80] is to organize space communication links between satellites, thus considerably reducing the radiation density at the earth's surface and consequently the level of mutual interference. This idea is similar to a system where some satellites serve the same earth territory and every earth station has access to every satellite. Organization of communications links between satellites may reduce the number of down and up links. Another solution is provided by tracking data relay satellite systems (TDRSS) using low orbit satellites [87].

CONCLUSION

The radio spectrum is a limited resource which needs to be used in a rational manner. The difficulties of meeting the spec-

trum requirements of the various radio services increase from year to year. For this reason the evaluation of spectrum utilization efficiency is a highly important and topical task.

Considerable advances have been made in recent years in working out criteria for efficient spectrum utilization and in applying communication theory to the assessment and measurement of existing communication systems.

We now have an almost complete theory of the influence of the limitation of signal bandwidth on noise immunity in the case of reception by nonoptimum receivers and of the distortion of radio signals in channels and filters. Yet the problems of optimum spectrum utilization by geostationary satellites and of spectrum sharing by mobile services are still unsolved, and no criteria have yet been established for the electromagnetic compatibility of communication systems with other types of radioelectronic equipment.

With wide-ranging possibilities now available for using computer methods for studying radio equipment processes, considerable importance attaches to mathematical modeling of communication systems and their individual equipments from the point of view of optimizing their parameters with a view to the rational utilization of the spectrum.

The radio spectrum is still a field of research for many engineers and scientific organizations. The study of efficient spectrum utilization will continue, as it has in the past, to give rise to new ideas, e.g., for new types of signal and modulation, radio equipment components with new characteristics, the optimum combination of all channel-division methods (frequency, time, space, and orthogonal), rational design of communication networks, and utilization of new frequency bands up to the visible spectrum.

At the present time, a considerable volume of scientific research is connected in one way or another with the problem of the rational utilization of the radio-frequency spectrum.

REFERENCES

- [1] "Radio spectrum utilization—A program for the administration of the radio spectrum," IEEE, New York, 1964.
- [2] M. S. Gurevich, *Spectra of radio signals*. Moscow: Sviazizdat, 1963.
- [3] "Spectrum engineering—the key to progress," A report by the Joint Technical Advisory Council (JTAC) of the IEEE and EIA, New York, Mar. 1968.
- [4] CCIR XIIIth Plenary Assembly (Geneva, 1974), vol. 1, question 47/1—"Definition of efficiency and utility of spectrum use," ITU, Geneva, 1975.
- [5] —, vol. 1, Report 420, "Comparative measurements of the occupied band width using different methods," ITU, Geneva (1975).
- [6] CCIR XIth Plenary Assembly (Oslo, 1966), Report 414, "Efficient use of the radio frequency spectrum," ITU, Geneva, 1967.
- [7] R. P. Gifford, "EMC revisited 1966," IEEE Trans. Electromagn. Compat., vol. EMC-8, no. 3, 1966.
- [8] Radio Regulations, ITU, Geneva, 1976.
- [9] Final Acts of the World Administrative Radio Conference for Space Telecommunications, ITU, Geneva, 1971.
- [10] A. L. Badalov, "Some principles relating to the allocation of the radio frequency spectrum and the preparation of plans for different radio services," *Elektros viaz*, no. 3, pp. 1-12, 1965.

- [11] —, "Rational use of the radio frequency spectrum and aspects of electromagnetic compatibility," *Radiotekhnika*, vol. 29, no. 11, pp. 12-15, 1974.
- [12] "The radio frequency spectrum—United States use and management," U.S. Office of Telecommunications Policy, Washington, DC, 1973.
- [13] "Manual of regulations and procedures for frequency management," U.S. Office of Telecommunications Policy, Washington, DC, 1973.
- [14] "Information on management and use of the radio frequency spectrum—a little understood resource," U.S. General Accounting Office, Washington, DC, Sept. 1974.
- [15] de Vany *et al.*, "A property system for market allocation of the electromagnetic spectrum: a legal-economic-engineering study," *Stanford Law Review*, vol. XXI, pp. 1499-1561, June 1969.
- [16] N. Johnson, "Towers of Babel: the chaos in radio spectrum utilization and allocation,"—Law and Contemporary Problems, pp. 505-534, Summer 1969.
- [17] W. H. Meckling, "Management of the frequency spectrum,"—Washington University Law Quarterly, pp. 26-34, Winter 1968.
- [18] H. J. Levin, "The radio spectrum resource," *Journal of Law and Economics*, vol. 2, pp. 435-501, Oct. 1968.
- [19] —, "Spectrum allocation without market," *American Economics Review Papers and Proceedings*, vol. 60, pp. 209-218, May 1970.
- [20] D. W. Webbink, "Setting FCC license fees according to frequency spectrum utilization: a suggestion," *IEEE Trans. Broadcasting*, vol. BC-17, no. 3, pp. 64-69, Sept. 1971.
- [21] M. Toia *et al.*, "New trends in managing the radio spectrum," *EMC Symposium Record*, IEEE, pp. 1-4, 1972.
- [22] L. C. Tillotson *et al.*, "Efficient use of the radio spectrum and bandwidth expansion,"—*Proc. IEEE*, vol. 61, no. 4, pp. 445-452, 1973.
- [23] S. R. McConoughey, "New concepts in spectrum usage," *IEEE Trans.* vol. COM-21, no. 11, pp. 1172-1176, 1973.
- [24] M. N. Lustgarten, "Philosophy of spectrum management," *IEEE Trans. Electromagn. Compat.*, vol. EMC-15, pp. 87-88, May 1973.
- [25] A. P. Walker, "The evolution of radio frequency spectrum management," *Telecommunication Journal of Australia*, vol. 23, no. 3, pp. 210-215, 1973.
- [26] H. Garlan, "FCC improves spectrum utilization thru use of part 15," *EMC Symposium Record*, IEEE, pp. 42-45, 1973.
- [27] *IEEE Transactions* (Special issue), vol. EMC-17, no. 1, Feb. 1975.
- [28] C. Colavito, "On the efficiency of the radio frequency spectrum utilization in fixed and mobile communication systems," *Alta Frequenza*, vol. XLIII no. 9, pp. 640-651, 1974.
- [29] J. H. Alleman, "The shadow price of electromagnetic spectrum: a theoretical analysis, U.S. Department of Commerce, Office of Telecommunications, OTR 74-42, July 1974.
- [30] D. R. Ewing and L. A. Berry, "Metrics for spectrum-space usage," U.S. Office of Telecommunications, Report 73-24, Nov. 1973.
- [31] R. L. Cutts, "Changing spectrum management techniques in a changing society," *Proceedings of EMC Symposium*, Montreux, Switzerland, pp. 72-74, May 1975.
- [32] H. Eden, "Frequency planning for sound broadcasting at long and medium waves," *Proc. EMC Symp., Montreux, Switzerland*, May 1975, pp. 114-118.
- [33] W. S. Wilkinson, "A survey of past, present and possible future systems for the transmission of signals from the EMC viewpoint" *Proc. EMC Symp., Montreux, Switzerland*, May 1975, pp. 323-328.
- [34] CCIR XIIIth Plenary Assembly (Geneva, 1974), Vol. I: Question 18-1/1, "System design for maximizing the efficiency and utility of spectrum use," Study Programme 18A/1, Communication theory, ITU, Geneva, 1975.
- [35] CCIR, Rep. AF/1, Conclusion of the Interim Meeting of S.G. 1, Geneva, May 19-June 1976, pp. 77-89.
- [36] *ibid.*, Question 45/1 "Technical criteria for frequency sharing."
- [37] *ibid.*, Question 11-1/1, "Diversity systems for maximizing the efficiency and utility of spectrum use."
- [38] *ibid.*, Rep. 525, "Provisional signal-to-interference protection ratios required for spectrum utilization investigations."
- [39] *ibid.*, Rep. 178-2, "Possibilities of reducing interference and of measuring actual traffic spectra."
- [40] J. L. Massey, "Coding and modulation in digital communications," in *Proceedings of International Seminar on Digital Communications*, Zurich, Switzerland, pp. E2(1)-E2(4), 1974.
- [41] J. Salz, "Communications efficiency of certain digital modulation systems," *IEEE Trans.*, vol. COM-18, no. 2, pp. 97-102, 1970.
- [42] F. Beghelli, *et al.*, "Power spectrum comparison of some 4B-3T pseudoternary codes," *International Conference on Communications*, Seattle, WA, pp. 7.30-7.36, June 1973.
- [43] G. Tartara, "Continuous information theory and modulation methods," *Alta Frequenza*, vol. XLII, no. 6, pp. 276-279, 1973.
- [44] P. D. Shaft, "Bandwidth compaction codes for communications," *IEEE Transactions*, vol. COM-21, no. 6, pp. 687-695, 1973.
- [45] V. K. Prabhu, "Optimum bandwidth occupancy in PSK systems," in *National Telecommunication Conference*, Atlanta, GA, pp. 24D-1-24D-3, 1973.
- [46] Y. N. Bakaev and V. I. Doronin, "Effect of limitation of the communications spectrum on the noise resistance of communication systems with amplitude, phase and frequency modulation," *Radiotekhnika*, vol. 30, no. 1, pp. 1-5, 1975.
- [47] E. Scheel, "Amplitude and phase distortion and intersymbol interference caused by band limiting," in *International Conference on Communications*, Seattle, WA, pp. 14.21-14.26, 1973.
- [48] I. Korn, "Error probability for systems with casual band-limiting filters and split-phase transmitted signal," *IEEE Transactions*, Vol. COM-21, pp. 891-898, Aug. 1973.
- [49] "Binary communication through a channel with single pole filters," in *Proceedings of 8th Convention of Electrical and Electronics Engineers in Israel*, pp. 2/1-2/10, 1973.
- [50] S. Y. Kwon and N. M. Shehadeh, "Effect of bandlimiting on the noncoherent detection of amplitude-shift-keying signals," in *International Conference on Communications*, Seattle, WA, pp. 7.1-7.6, 1973.
- [51] O. Shimbo, and M. Celebiler, "The probability of error due to intersymbol interference and Gaussian noise in digital communication systems," *IEEE Transactions*, vol. COM-18, no. 2, pp. 113-119, Apr. 1971.
- [52] N. M. Shehadeh and Tu. Kweij, "Effect of bandlimiting on the coherent detection of PSK, ASK and FSK signals," *Archiv für Elektronik und Übertragungstechnik (AEU)*, vol. 26, pp. 369-376, 1972.
- [53] P. Traffon and L. Palmer, "The loss in processing gain in a pseudonoise receiver that utilizes baseband filtering prior to correlation," in *National Telemetering Conference*, Atlanta, GA, pp. 6F.1-6F.6, Nov. 1973.
- [54] S. S. Sviridenko, "Coded signal distortion in communication channels," *Telecommunications Journal*, Vol. 42, no. III, pp. 164-167, 1975.
- [55] V. A. Kotelnikov, *The Theory of Optimum Noise Immunity*, New York: McGraw-Hill, 1959.
- [56] C. R. Cahn, "Combined digital phase and amplitude modulation communication systems," *IRE Transactions*, vol. CS-8, pp. 150-155, Sept. 1960.
- [57] C. M. Thomas, "Amplitude-phase-keying with M-ary alphabets—a technique for bandwidth reduction, presented at the International Telemetering Conference, United States, Oct. 1972.
- [58] C. M. Thomas, "Amplitude-phase-keying: an evaluation for realistic transponder channels," in *Colloque international sur les telecommunications numeriques par satellite*, Paris, pp. 199-207, Nov. 1972.
- [59] S. S. Sviridenko and M. Joachim, "Information transmission with a combination of different types of modulation in radio-communication systems," *Telecommunication Journal*, vol. 41, no. X, pp. 613-617, 1974.
- [60] M. Simon and J. Smith, "Hexagonal multiple phase-and-amplitude shift-keyed signal sets," *IEEE Transactions*, vol. COM-21, no. 10, pp. 1108-1115, 1973.
- [61] G. J. Foschini *et al.*, "On the selection of a two-dimensional signal constellation in the presence of phase jitter and Gaussian noise," *Bell System Technical Journal*, vol. 52, no. 6, pp. 927-965, 1973.
- [62] G. R. Welfi, "Pulse amplitude-and-phase modulation," in *Colloque international sur les telecommunications numeriques par*

- satellite, Paris, 208-217, Nov. 1972.
- [63] S. Benedetto and E. Biglieri, "Digital PM-AM transmission over real channels," *ibid.*, pp. 193-198.
 - [64] G. R. Welter, "Application of hybrid modulation to FDMA telephony via satellite," *Comsat Technical Review*, vol. 3, no. 2, pp. 419-429, Fall 1973.
 - [65] J. Salz *et al.*, "Data transmission by combined AM and PM," *Bell System Technical Journal*, vol. 50, no. 7, pp. 2399-2419, Sept. 1971.
 - [66] G. B. Lockhart, "Hybrid modulation," *IEEE Transactions*, vol. COM-21, pp. 958-966, Aug. 1973.
 - [67] CCIR XIIIth Plenary Assembly, Geneva, 1974, Vol. I: Question 44/1, "System models for the evaluation of compatibility in spectrum use," ITU, Geneva, 1975.
 - [68] *ibid.*, Rep. 519, "Coherent receiver performance model."
 - [69] *ibid.*, Rep. 520, "Non-coherent receiver performance model."
 - [70] *ibid.*, Rep. 521, "Receiver RF nonlinear modelling."
 - [71] *ibid.*, Rep. 522, "A procedure for modelling receiver inter-modulation characteristics."
 - [72] *ibid.*, Rep. 523, "System models for the evaluation of interference. A mathematical model for determining the adjacent-channel interference in radio transmission systems with amplitude modulation."
 - [73] *ibid.*, Rep. 524, "System models for the evaluation of interference. Co-site analysis model."
 - [74] J. O'Donnel, "Communication receivers interference modelling," presented at the International Conference on Communications, United States, June 1972.
 - [75] CCIR XIIIth Plenary Assembly (Geneva, 1974), Vol. IX: Rep. 209-3, "Frequency sharing between communication-satellite systems and terrestrial radio services, ITU, Geneva, 1975.
 - [76] *ibid.*, Vol. II, Recommendation 364-2, "Telecommunication links for near-earth research satellites. Frequencies, bandwidths and interference criteria."
 - [77] *ibid.*, Vol. II, Recommendation 365-2, "Telecommunication links for deepspace research. Frequencies, bandwidths and interference criteria."
 - [78] *ibid.*, Vol. IX, Rep. 387-2, "Protection of terrestrial line-of-sight radio-relay systems against interference due to emissions from space stations in the fixed satellite service in shared frequency bands between 1 and 23 GHz."
 - [79] M. Matsushita *et al.*, "A study of frequency sharing between satellite and terrestrial broadcasting systems," Proceedings of 9th International Symposium on Space Technology and Science, Tokyo, pages 775-786 (1971).
 - [80] "Radio spectrum utilization in space," Report of the JTAC of IEEE and EIA, vol. 33, Sept. 1970.
 - [81] A. L. Badalov, "Allocation of frequency bands for the development of space communications systems," *Elektrosviaz*, no. 1, pp. 15-18, 1972.
 - [82] G. E. LaVean and L. C. Palmer: "Efficient utilization of satellite ERP and bandwidth employing TDMA and FDMA," in *Colloque international sur les télécommunications numériques par satellite*, sponsored by SEE, INTELSAT, VAIL, and FNIE, Paris, pp. 144-153, Nov. 1972.
 - [83] G. W. Haydon and R. K. Rosich, "Technical consideration in the efficient use of the spectrum—Terrestrial surface power flux density limits for services using satellites," United States Office of Telecommunications, Institute for Telecommunication Sciences, Boulder, CO, Apr. 1973.
 - [84] R. B. Chadwick and D. S. Irwin, Technical and economic trade-offs for the geostationary orbit communications resource, *ibid.*
 - [85] D. Pope, "Parametric representatives of ground antennas for communication system studies," *Bell System Technical Journal*, vol. 49, pp. 2145-2168, Dec. 1969.
 - [86] JTAC Proceedings, vol. XXVI, pp. C.78-C.92, 1965-1966.
 - [87] "GSFC Mark I tracking and data relay satellite (TDRS) system concept," NASA/GSFC, vol. I, Nov. 1969.
 - [88] V. K. Prabhu, "Performance of coherent phase-shift-keyed systems with intersymbol interference," *IEEE Transactions*, vol. IT-17, pp. 418-431, 1971.
 - [89] —, "Error rate considerations for coherent phase-shift-keyed systems with co-channel interference," *Bell System Technical Journal*, vol. 49, pp. 743-767, 1969.
 - [90] L. A. Berry, "Output oriented measure of spectrum efficiency, in *International Symposium on Electromagnetic Compatibility*, Washington DC, July 1976, pp. 59-61.
 - [91] N. V. Vinogradov, "Criteria for estimating the efficiency of radio frequency spectrum utilization," *Telecommunications and Radio Engineering*, vols. 28/29, no. 12, pp. 37-42, Dec. 1974.
 - [92] *Spread Spectrum Techniques*, R. C. Dixon, Ed. IEEE Press, 1976.
 - [93] J. M. Wozencraft and I. M. Jacobs, *Principles of communication engineering* New York: Wiley, 1965.

On Efficient Spectrum Utilization from the Standpoint of Communication Theory

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Abstract—This paper reviews the concepts of spectrum efficiency, the parameters for assessing system performance, and the techniques for improving spectrum utilization.

The rationale of possible bandwidth reduction and power savings by combined modulation techniques is discussed and special attention is given to combined amplitude and phase modulation (APSK) systems.

It is believed, based on the available results of several analyses over additive Gaussian noise channels, that certain combined modulation systems can have significant power savings over single-parameter modulation systems when the number of bits per symbol of the signal is large and can achieve more efficient use of the spectrum for signal-to-noise ratios greater than certain levels.

I. INTRODUCTION

THE RADIO spectrum is an invaluable but limited natural resource. Proper management is essential for efficient spectrum utilization as ever increasing demands for frequency spectrum are made. One of the most important measures which has been adopted is radio frequency allocation. Frequency allocation in spectrum management is based on the propagation characteristics of the radio wave, the electromagnetic environment, the type of signal and service, technological advances, and social and economic considerations. The efficiency of spectrum utilization may be evaluated in terms of several parameters such as frequency bandwidth, radiated power, service area, transmission path, antenna pattern, polarization, signal waveform, immunity to noise and interference, quality of performance, and cost of the system used. Traditional techniques of spectrum management constrained signal and system parameters and geographical locations in the different radio services involved to permit frequency sharing within and among services.

In order to increase the efficiency of spectrum utilization, it is necessary to continue exploring new concepts, techniques, and strategies of spectrum management. Various modulation, coding, and multiplexing techniques have been applied for effective spectrum utilization and continuing developments of new coding and modulation techniques on the basis of communication theory deserve more attention. Recently, the idea of using combined modulation techniques has been considered promising for more rational use of the spectrum [1]–[7].

Combined modulation is actually a multiparameter modulation, such as combined digital amplitude-phase-shift keying (APSK), which means two or more parameters are varied instead of only one carrier parameter and the carrier wave becomes a carrier of multichannel information. As a result, the combined modulation process may offer various possibilities of improving the characteristics of communication systems by increasing the channel efficiency and providing more efficient use of the radio spectrum and the transmitted power.

This paper discusses a definition of spectrum efficiency, the parameters for assessing spectrum efficiency, the techniques of improving spectrum efficiency and the rationale of possible bandwidth reduction by combined modulation techniques. The present state of the art will be reviewed and the future prospect of using combined modulation techniques to improve the efficiency of spectrum utilization will be discussed with reference to bandwidth reduction, transmitter power, interference and noise immunity, and degree of reliability.

II. DEFINITION OF SPECTRUM EFFICIENCY

There is no standardized definition of spectrum efficiency, but all proposed definitions have been based on either the ratio of the communication output to the spectrum space used to produce the output (called output/input efficiency) or the ratio of the spectrum used by an ideal system to the spectrum space actually used (called ideal/input efficiency). It has been shown that the two forms always give the same relative result, and that the output/input efficiency is easier to compute [8].

Efficiency is generally defined as the ratio of output to input and it is logical to define spectrum efficiency as the ratio of communication output to spectrum space input [8], [9]. That is,

$$\text{Spectrum Efficiency} = \frac{\text{Information delivered}}{\text{Spectrum space used}}$$

where the nature and units of the numerator depend on the type of service and the spectrum space is defined as the product of RF bandwidth, relevant physical space, and time [8]

$$\text{Spectrum Space} = (\text{Bandwidth}) \times (\text{Physical space}) \times (\text{Time}).$$

The physical space depends on the type of service. For a broadcasting service, the physical space of interest is an area. For a geostationary satellite service, the physical space is a line of the orbit, and in some cases, the physical space may be a volume. The time factor also depends on the service involved. For services which operate continuously with analog modulation, the time factor is a constant. In other services such as land-mobile radio, time sharing is of importance to efficient spectrum use.

The International Radio Consultative Committee (CCIR) defined the measure of orbit utilization efficiency for the geostationary satellite service as

$$\text{Spectrum Efficiency} = \frac{\text{Bits}}{(\text{RF bandwidth})(\text{Orbit arc time})}$$

for the case of digital modulation systems and

$$\text{Spectrum Efficiency} = \frac{\text{Information bandwidth}}{(\text{RF bandwidth})(\text{Orbit})(\text{Arc})}$$

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for analog modulation systems [10]. These are exactly the form proposed for the output/input efficiency measure.

Radio spectrum has the dimensions of frequency, time, and space. The same frequency may be used for different purposes at the same time in sufficiently separated spaces, the same frequency may be used for different purposes in the same space at sufficiently separated times, and sufficiently separated frequencies may be used at the same time and in the same space. Thus the reduction of bandwidth for transmission means more frequency bands would be available for other purposes at the same time and the same place; the reduction of physical space for transmission would allow the same frequency band to be used for different purposes at the same time in more spaces; the reduction of transmission time would allow the same frequency band to be used for more purposes in the same space. As a result, the reduction of spectrum space used to transmit a given quantity of information can increase the spectrum efficiency.

III. PARAMETERS FOR ASSESSING SYSTEM PERFORMANCES

The efficiency of spectrum use is dependent on the performance of a communication system. The performance of a system depends on the characteristics of the system and the electromagnetic environment in which it operates, and it may be evaluated based on the following important parameters:

- Information Rate (R)
- Bandwidth (W)
- Signal Power (S)
- Noise Power (N)
- Error Probability (P_e)
- Delay Time (n)
- External Considerations

The information rate (R) is the rate at which the system transmits information, and the bandwidth (W) is the bandwidth of the system. The ratio R/W represents the channel capacity per unit bandwidth (i.e., channel efficiency) of the system. It is desirable that a system transmit at a high information rate while the bandwidth occupied by the signal is small such that high spectrum efficiency can be achieved. However, as the information rate is increased, the bandwidth of the system may have to be increased to prevent the performance of the system from deteriorating. Consequently, the spectrum efficiency may not be improved.

The signal power (S) is a measure of the power of the transmitted signal, and the noise power (N) is a measure of the noise power in the electromagnetic environment of operation, and the ratio S/N represents the signal-to-noise ratio. It is required that this ratio be high enough to overcome the effects of interference and noise. Under strong interference and noise conditions, it may be necessary to raise the transmitted power, but it may not be possible to do so since the high power signals may interfere with services of other areas. The spectrum efficiency would be decreased due to the increase of physical space. Thus it is advantageous to reduce ambient noise in order to maintain the necessary S/N for reliable operations.

The error probability (P_e) is a measure of the reliability (or fidelity) of the system and is one of the most important parameters of the system. The reliability of a communication system is of primary concern.

The delay time (n) is caused by the transmitter and receiver of the system and it represents a measure of the complexity of

encoding associated with the transmitter and receiver or of the queueing time in a shared system, e.g., land mobile.

Consideration of the value of these parameters is necessary to compare the performances of systems. In addition, external considerations, such as the purpose and cost of establishing the system, allow engineers to assign relative weights or costs to these parameters. It should be noted that these parameters cannot assume arbitrary values because certain sets of values cannot be realized. The boundary between compatible and incompatible sets of parameters was investigated on a digital system operated in additive Gaussian noise [11].

The boundaries of compatible values for $n \rightarrow \infty$ can be determined based on Shannon's capacity formula, $C = W \log(1 + S/N)$, and the result that P_e can be made arbitrarily small for certain finite values of R , W , and S/N when $n \rightarrow \infty$, promised the existence of essentially error-free communication systems [12]. The boundaries of compatible values for finite values of n can be determined based on the inequalities presented by Shannon [13]. A computation technique has been developed to map out bounds on the compatible region for the parameters over a wide range of values [11]. The results of computations show quantitatively that the performance of communication systems can be improved considerably with a small amount of encoding, but to approach within a few decibels of the capacity formula in general requires extremely complicated systems. The results also give numerical information concerning the tradeoffs of the various parameters, which can provide useful references for comparison of communication systems [11].

IV. TECHNIQUES OF IMPROVING SPECTRUM EFFICIENCY

The channel capacity formula of Shannon, $C = W \log(1 + S/N)$, has set the upper limit of the channel capacity of systems and predicts that there exist coding techniques which approach the theoretical limit [12], [13].

It should be noted that the channel capacity formula developed by Shannon was based on the assumptions that (i) the transmitted signal and noise are white and limited in bandwidth to W Hz, (ii) the transmitted signal and noise are from statistically independent, stationary random processes and add linearly in the channel, (iii) the received signal is limited in average power.

The channel capacity formula is very useful for comparison purposes even if the actual systems do not satisfy these restrictions because it sets an upper bound on the channel capacities. If the noise in the channel is neither Gaussian nor white in the bandwidth W , then it will have an entropy power N_1 which is less than its actual average power N . The channel capacity is then bounded by

$$W \log [(S + N_1)/N_1] \leq C \leq W \log [(S + N)/N_1]$$

and the bounds approach one another for large signal-to-noise ratios.

Various techniques for improving the efficiency of spectrum utilization are being studied on the basis of communication theory [14]–[18]. Some of the techniques which have been considered as promising approaches are: (i) development of coding techniques, (ii) bandwidth- S/N tradeoffs in PCM systems, (iii) spread spectrum techniques (iv) mathematical modeling of systems and components, and (v) combined modulation techniques.

A. Development of Coding Techniques

The development of coding techniques to save the spectrum or transmission time of information has been extensively

studied [19]. System efficiency can be improved by using M -ary coding techniques in which the pulses are represented by different values of amplitude, frequency or phase, or combinations of these.

There are two important objectives to be achieved by coding: (i) In the case of discrete noiseless channel (under conditions of high signal-to-noise ratio, transmission error becomes negligible and the noiseless condition is approached), coding is required to match the information source to the channel in order to reduce the redundancy that may exist in the source. This type of coding is referred to as minimum-redundancy coding. (ii) For the case of a discrete channel with noise, coding is also required to combat the effects of noise and is brought about by introducing redundancy of channel symbols. This type of coding is referred to as error-correcting coding.

A number of codes such as bitternary codes, ternary block codes, Bose-Chandhuri codes, convolutional codes, fast-correcting codes, etc., may be used to increase the efficiency of spectrum utilization [20]–[23], even though this was not their primary interest when those codes were developed. It is anticipated that more new codes with a view to efficient utilization of the spectrum will be developed in the future.

B. Bandwidth- S/N Tradeoff Techniques

The bandwidth- S/N tradeoff in PCM systems deserves attention because this concept can serve a useful purpose under certain conditions. The channel capacity of an additive white Gaussian channel is given by the Shannon-Hartley theorem

$$C = W \log_2 (1 + S/N)$$

where

- W is the channel bandwidth,
- S/N is the signal-to-noise ratio,
- N is the ηW , in which $\eta/2$ represents the two-sided power spectral density.

This theorem deals with Gaussian channels, but it also provides a lower bound on the performance of a non-Gaussian channel. For a zero-noise Gaussian channel (i.e., $S/N = \infty$), the channel capacity becomes infinite. However, the channel capacity does not become infinite as the bandwidth becomes infinite because the noise power also increases with bandwidth. Thus, the channel capacity approaches an upper limit with increasing bandwidth for a fixed signal power.

It can be seen that we may tradeoff bandwidth for S/N and vice versa while maintaining the same channel capacity. So, one can save bandwidth by a moderate increase of signal power for low-noise channels and save signal power by increasing bandwidth for high noise channels with a view to achieving efficient spectrum use.

To accomplish effective tradeoffs it is necessary to encode the message into a channel signal which comes as close to being white, band limited, and Gaussian as possible, that is, an efficient coding scheme tends to make the signal look like random noise.

C. Spread-Spectrum Techniques

Spread-spectrum techniques [24] are of considerable interest due to the ability of overcoming interference and noise by special coded signals (i.e., digital pseudorandom signals) and by correlation detection techniques. When codes are properly designed for low cross correlation, a single receiver or a group of receivers may be addressed by assigning a given reference

code to them, whereas others are given a different code. Consequently more than one signal can be unambiguously transmitted at the same frequency and at the same time. Thus selective addressing and code-division multiplexing for multiple access can be achieved by the coded modulation format and the wide signal bandwidth used. Thus spread-spectrum techniques can achieve efficient spectrum utilization under certain circumstances along with the possibility of overcoming interference and noise. The use of spread-spectrum system deserves attention from the standpoint of efficient spectrum utilization under appropriate electromagnetic environment.

D. Mathematical Modeling Techniques

Mathematical modeling of a communication system and its components with a view to optimizing its parameters for efficient utilization of the spectrum is an area of considerable interest [25]–[32]. The modeling study is aimed at finding a logical combination of parameters such as the bandwidth, receiver sensitivity, antenna gain, propagation attenuation, etc., to improve the efficiency of spectrum utilization.

E. Combined Modulation Techniques

The idea of using combined modulation has been intensified recently in search of making a more efficient use of the spectrum [1]–[6]. Combined modulation techniques can increase the channel efficiency and permit more efficient use of the spectrum and transmitted power. A combined modulation (also called multiparameter modulation) involves two or more carrier parameters to be modulated. Consequently, the carrier becomes a carrier of multichannel information. Thus it has been shown that certain combined modulations can improve the capacity of a digital communication system [2], [5], [7]. It has been pointed out also that the best type of carrier is a pulse train having a number of parameters which can be used to carry information.

V. EFFICIENCIES OF DIGITAL MODULATION SYSTEMS

The efficiencies of various digital modulation systems are compared in terms of data rate per unit bandwidth (channel efficiency) and probabilities of error at given signal-to-noise ratios to demonstrate that multiparameter modulation systems can achieve more efficient uses of the spectrum and the transmitted power than single-parameter modulation systems.

A. Single-Parameter Modulation

The achievable channel efficiency, as measured by the channel capacity per unit bandwidth, for amplitude-shift keying (ASK), phase-shift keying (PSK), and frequency-shift keying (FSK) systems at a given signal-to-noise ratio (S/N) and probability of error (P_e) in the presence of additive Gaussian noise have been well known [33]–[35].

Fig. 1 shows the channel efficiency versus S/N for various digital modulation systems [33]. The most efficient system in terms of data rate per unit bandwidth for fixed error rate and bandwidth is the single sideband ASK (SSB-ASK). Although the data rate per unit bandwidth in FSK systems can be maximized for fixed RF bandwidth, error rate and signal-to-noise ratio [33], [36], [37], the FSK systems are still the most insufficient at large S/N . The differences with other systems are not considerable when S/N is less than 12 dB. The efficiency of PSK systems lie between the SSB-ASK and the FSK systems due to the fact that PSK systems can utilize bandwidth

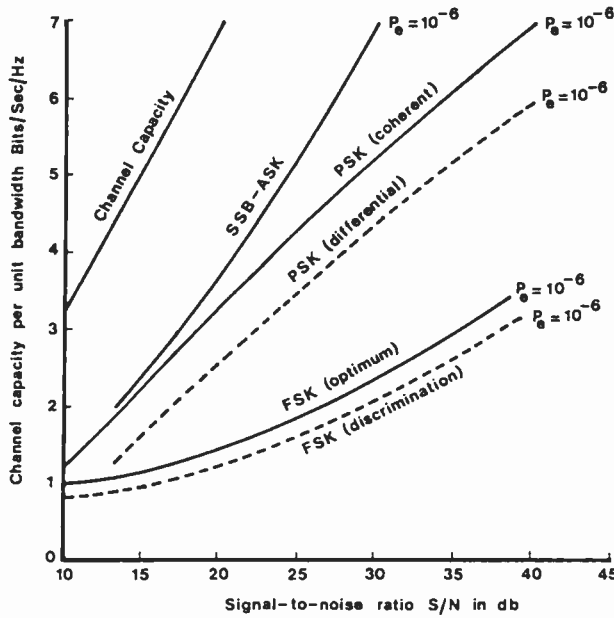


Fig. 1. Channel efficiency versus S/N for various digital modulation systems.

more efficiently than FSK systems, but not as efficient as SSB-ASK. The efficiencies of double sideband suppressed-carrier ASK (DSB-ASK) systems and PSK system are essentially the same since PSK is also a DSB-ASK system.

Multiphase PSK systems are generally used when high data rates are desired or where bandwidth limitations require M -ary systems. One of the most commonly used M -ary PSK systems is quadriphase phase-shift keying (QPSK) systems, which may be thought of as two binary phase-shift keying (BPSK) systems in parallel and their carriers are in phase quadrature. The error probability of QPSK system is greater than that of BPSK systems, but the data rate of QPSK system is twice that of the BPSK system for the same available bandwidth [38].

B. Multiparameter Modulation

A multiphase PSK system produces essentially constant amplitude, but it is predicted by Shannon's theorem that a Gaussian amplitude distribution should provide maximum channel capacity when the signal is average-power limited. Thus the concept of using combined amplitude and phase modulation (APSK) was developed as a promising form of digital modulation. The performance of APSK communication systems have been analyzed for the asymptotic case of high S/N in the presence of band-limited white Gaussian noise [1], [4], [5]. It has been shown that, compared with PSK systems, APSK systems can save power when the information content per symbol is greater than 3 bits and can make more efficient use of the spectrum for S/N greater than 11 dB [7].

The typical transmitted signal of an APSK system is shown in Fig. 2. The amplitude and phase of the transmitted signal may assume values chosen from a discrete set of m amplitude levels and n phase positions during each pulse length of T seconds. Each combination of an amplitude level and a phase position represents a transmitted symbol, and the total number of such combinations is called the alphabet size $r = mn$ of the transmitted signals. One type of APSK system is where the same number of phase positions are available regardless of the amplitude level. Thus the amplitude and phase channels are independent as shown in Fig. 3. A transmitted symbol may

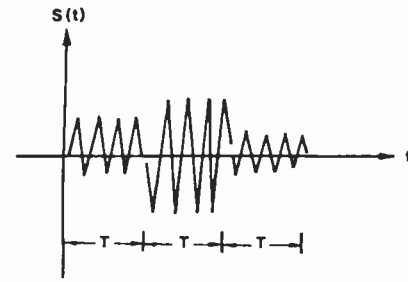


Fig. 2. Digital amplitude and phase modulation (APSK).

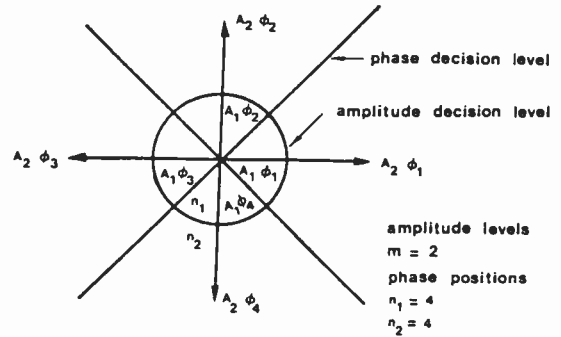


Fig. 3. Decision levels in an APSK system (the phase and amplitude channels are independent).

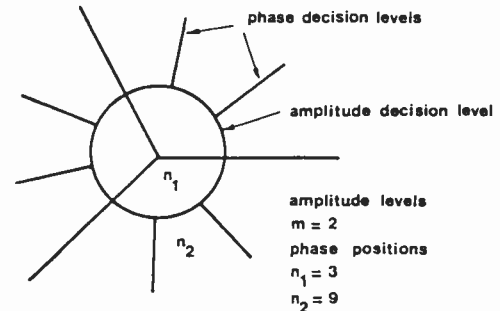


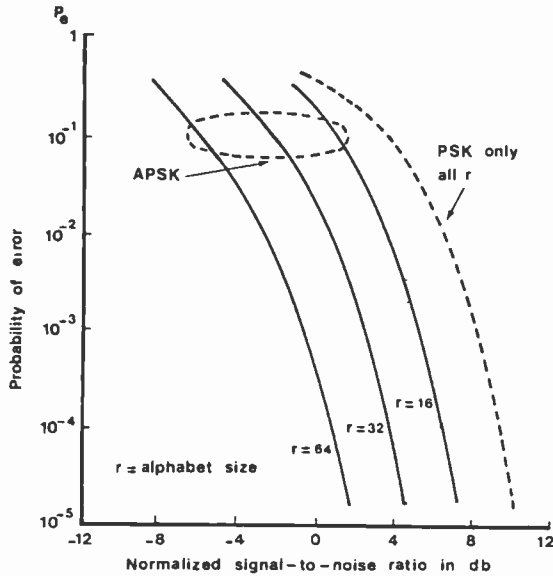
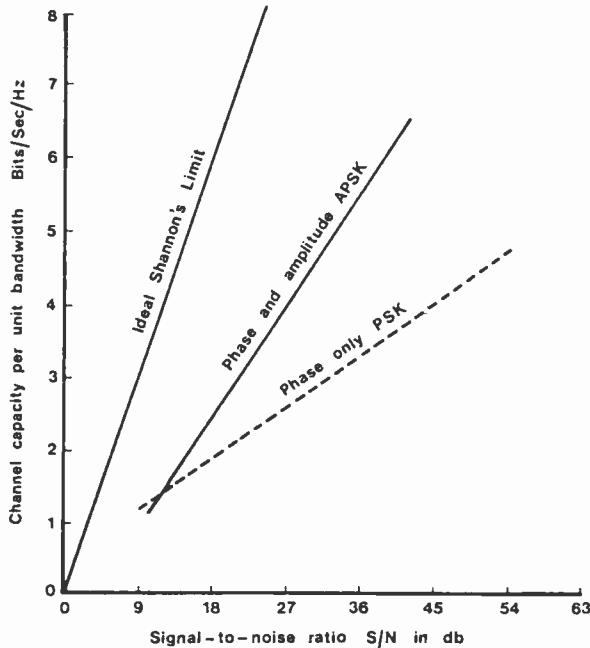
Fig. 4. Decision levels in an APSK system (the phase and amplitude channels are dependent).

be expressed as $A_i \phi_j$, where A_i and ϕ_j may be chosen independently from separate sets of A 's and ϕ 's.

Another type of APSK system, which is considered a more efficient system, is where the amplitude and phase channels are dependent upon each other. The probability of phase error reduces with increasing amplitude levels, it is therefore possible to increase the number of phase positions available with higher amplitude levels, while maintaining a constant probability of phase error. Fig. 4 shows a typical APSK of this kind, where the number of phase positions vary with amplitude levels. This type system is theoretically superior, but the first type system is much easier to instrument. The minimum probability of error attainable for a given average power and alphabet size of the system is given by [7]

$$P_e = \frac{2 \exp [-P/(8/9r - 4/3)]}{\sqrt{\pi} \frac{P}{8/9r - 4/3}}$$

where r is the alphabet size and P is the average power. It should be noted that because the average power has been normalized on the basis of unity noise power, here P is equivalent to the average signal-to-noise ratio. The probability of


 Fig. 5. Probability of error versus S/N for APSK and PSK systems.

 Fig. 6. Channel efficiency versus S/N for APSK and PSK systems.

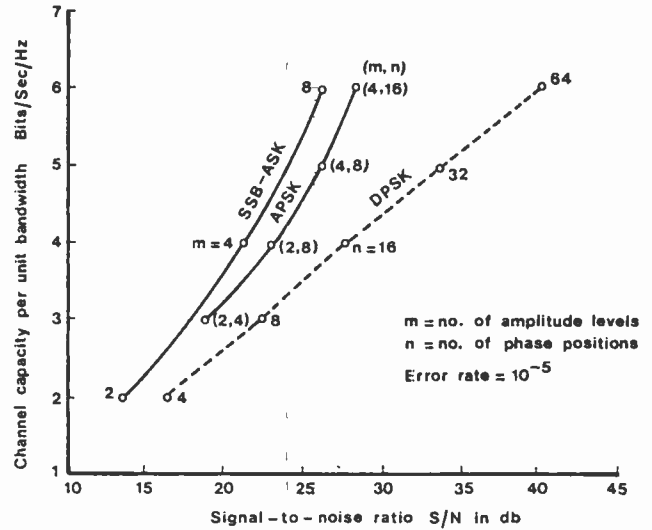
error for PSK systems at high S/N in the presence of Gaussian noise is given by [1]

$$P_e = \frac{\exp(-S/N \sin^2 \pi/n)}{\sqrt{\pi S/N} \sin \pi/n}$$

where S/N is the signal-to-noise ratio and n is the number of phase positions and the alphabet size $r = n$ for PSK systems.

Fig. 5 compares the probabilities of errors of APSK and PSK systems versus normalized S/N (i.e., normalized on the basis of unity noise power), based on their expressions for P_e , respectively. It is clearly shown that the signal-to-noise improvement obtained by APSK systems is a function of the alphabet size [7]. The improvement increases approximately 3 dB every time the alphabet size is doubled.

Fig. 6 shows the channel capacities of these two systems and Shannon's theoretical upper limit [7] plotted against signal-to-


 Fig. 7. Theoretical channel efficiency versus S/N for various digital modulation systems.

noise ratio for unit bandwidth. We see that the APSK systems make more efficient use of the channel for S/N greater than 11 dB than PSK alone. Below this power there is no advantage to the APSK system over the PSK only system [7]. At this crossover point of 11 dB the optimum alphabet size for the two systems is about 8 symbols each. Fig. 7 shows a comparison of the theoretical channel efficiencies for SSB-ASK's, PSK's, and APSK systems. [5].

The foregoing comparisons which were made based on the available results of analyses over additive white Gaussian noise channels, have demonstrated that combined (or multiparameter) modulation systems can achieve more efficient use of the spectrum and the transmitted power than single-parameter modulation systems for signal-to-noise ratios greater than certain levels. However, it must be cautioned that the same conclusion may not be drawn for non-Gaussian channels until results of analyses on non-Gaussian channels become available.

IV. CONCLUSIONS

Efficient spectrum utilization may be realized by improving the characteristics of communication systems based on such techniques as coding, bandwidth- S/N tradeoffs, and combined modulation under certain conditions. The use of spread spectrum systems and mathematical modeling techniques deserve more attention with a view to effective spectrum utilization under adverse electromagnetic environments.

It has been indicated, based on the available results of analyses over additive Gaussian noise channel, that APSK systems can make significant power savings over PSK systems when the information content per symbol is large and that APSK systems can achieve more efficient use of the spectrum for signal-to-noise ratios greater than certain levels.

However, the performances of APSK systems were analyzed based on additive Gaussian noise channels. The results may not be true over non-Gaussian channels, thus, the most efficient system over Gaussian channels may not be so over non-Gaussian channels. More studies are necessary for the cases of non-Gaussian channels before drawing definitive conclusions.

It should be noted that a system which may be the most efficient over certain signal-to-noise ratios may not be the most efficient at lower signal-to-noise ratios. In addition, the purpose and complexity of establishing the system should be

taken into consideration in evaluating the efficiency of the system.

It is generally believed that combined modulation techniques can improve the channel efficiency and/or save transmitted power compared with single-parameter modulation techniques, but complexity and cost of implementation may be a factor of importance. As technology advances, this factor may no longer exist.

There are other considerations in choosing one type of system over another. For some channels, where the channel gain or phase characteristics (or both) are perturbed by randomly varying propagation conditions, a noncoherent system may be dictated because of the near impossibility of establishing a coherent reference at the receiver under fading conditions. In other situations, the choice of a coherent system may be demanded by considerations other than power savings.

REFERENCES

- [1] C. R. Cahn, "Combined digital phase and amplitude modulation communication systems," *IRE Trans. Commun. Syst.*, vol. CS-8, pp. 150-155, Sept. 1960.
- [2] S. S. Suividenko and M. Joachin, "Information transmission with a combination of different types of modulation in radio communication systems," *Telecommun. J.*, vol. 41, no. X, pp. 613-617, 1974.
- [3] M. Simon and J. Smith, "Hexagonal multiple phase-and-amplitude shift-keyed signal sets," *IEEE Trans. Commun.*, vol. COM-21, pp. 1108-1115, 1973.
- [4] G. R. Welts, "Pulse amplitude-and-phase modulation," in *Proc. Coll. Int. Telecommun. Numeriques par Satellite* (Paris, France), pp. 208-217, Nov. 1972.
- [5] J. Salz *et al.*, "Data transmission by combined AM and PM," *Bell Syst. Tech. J.*, vol. 50, no. 7, pp. 2399-2419, Sept. 1971.
- [6] G. B. Lockhart, "Hybrid modulation," *IEEE Trans. Commun.*, vol. COM-21, pp. 790-800, Aug. 1973.
- [7] J. C. Hancock and R. W. Lucky, "Performance of combined amplitude and phase-modulated communication systems," *IRE Trans. Commun. Syst.*, vol. CS-8, pp. 232-237, Dec. 1960.
- [8] L. A. Berry, "Spectrum metrics and spectrum efficiency—Proposed definitions," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, pp. 254-260, Aug. 1977.
- [9] —, "Output oriented measure of spectrum efficiency," in *Proc. Int. Symp. Electromagnetic Compatibility* (Washington, DC), pp. 59-61, July 1976.
- [10] "The effect of modulation characteristics on the efficiency of use of the geostationary satellite orbit," Documents of the XIIIth Plenary Assembly, ITU, CCIR Report 559, Geneva, 1974.
- [11] D. Slepian, "Bounds on communication," *Bell Syst. Tech. J.*, pp. 681-707, May 1963.
- [12] C. E. Shannon, "A mathematical theory of communications," *Bell Syst. Tech. J.*, vol. 27, pp. 379-424 and 623-657, July and Oct. 1948.
- [13] —, "Probability of error for optimal codes in a Gaussian channel," *Bell Syst. Tech. J.*, vol. 38, pp. 611-656, May 1959.
- [14] E. Bedrosian, "Spectrum conservation by efficient channel utilization," *IEEE Commun. Soc. Mag.*, pp. 20-27, Mar. 1977.
- [15] CCIR, Rep. AF/1, Conclusion of the Interim Meeting of S.G.I. (Geneva, Switzerland), pp. 77-89, May 19-June 1976.
- [16] *Ibid.*, Question 11-1/1, "Diversity systems for maximizing the efficiency and utility of spectrum use."
- [17] *Ibid.*, Rep. 525, "Provisional signal-to-interference protection ratios required for spectrum utilization investigations."
- [18] S. S. Sviridenko, "Spectrum utilization problems," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, pp. 260-262, Aug. 1977.
- [19] CCIR XIIIth Plenary Assembly (1974) vol. 1, Question 18-1/1, "System design for maximizing the efficiency and utility of spectrum use," Study Programme 18A/1, Communication Theory, ITU (Geneva, Switzerland), 1975.
- [20] A. P. Brogle, "A new transmission method for pulse-code modulation communication systems," *IRE Trans. Commun. Syst.*, vol. CS-8, pp. 155-160, Sept. 1960.
- [21] J. L. Massey, "Coding and modulation in digital communications," in *Proc. Int. Seminar on Digital Communications* (Zurich, Switzerland), pp. E2(1)-E2(4), 1974.
- [22] J. Salz, "Communications efficiency of certain digital modulation systems," *IEEE Trans. Commun. Technol.*, vol. COM-18, pp. 97-102, 1970.
- [23] P. D. Shaft, "Bandwidth compaction codes for communications," *IEEE Trans. Commun.*, vol. COM-21, pp. 687-695, 1973.
- [24] R. C. Dixon, Ed., *Spread Spectrum Techniques*. New York: IEEE Press, 1976.
- [25] CCIR XIIIth Plenary Assembly (1974), Vol. 1-Question 44/1, "System models for the evaluation of compatibility in spectrum use," ITU, Geneva, Switzerland, 1975.
- [26] *Ibid.*, Rep. 519, "Coherent receiver performance model."
- [27] *Ibid.*, Rep. 520, "Non-coherent receiver performance model."
- [28] *Ibid.*, Rep. 521, "Receiver RF non-linear modelling."
- [29] *Ibid.*, Rep. 522, "A procedure for modelling receiver intermodulation characteristics."
- [30] *Ibid.*, Rep. 523, "System models for the evaluation of interference. A mathematical model for determining the adjacent channel interference in radio transmission systems with amplitude modulation."
- [31] *Ibid.*, Rep. 524, "System models for the evaluation of interference, co-site analysis model."
- [32] J. O'Donnel, "Communication receivers interference modelling," presented at Int. Conf. Communications, United States, June 1972.
- [33] J. Salz, "Communications efficiency of certain digital modulation systems," *IEEE Trans. Commun. Technol.*, vol. COM-18, pp. 97-102, Apr. 1970.
- [34] R. W. Lucky, J. Salz, and E. J. Weldon, *Principles of Data Communication*. New York: McGraw-Hill, 1968.
- [35] W. R. Bennett and J. R. Davey, *Data Transmission*. New York: McGraw-Hill, 1965.
- [36] J. E. Mazo and J. Salz, "Theory of error rate for digital FM," *Bell System Tech. J.*, vol. 45, pp. 1511-1535, Nov. 1966.
- [37] J. E. Mazo, H. E. Rowe, and J. Salz, "Rate optimization for digital FM," *Bell Syst. Tech. J.*, vol. 48, pp. 3021-3030, Nov. 1969.
- [38] R. E. Ziemer and W. H. Tranter, *Principles of Communications*. New York: Houghton Mifflin, 1976.

Spectrum Metrics and Spectrum Efficiency: Proposed Definitions

LESLIE A. BERRY

Abstract—A spectrum metric—a unit of measure of spectrum-space use—is defined and used to define a measure of spectrum efficiency as the ratio of communications output to spectrum-space input. It is shown that this efficiency measure is easier to compute than another candidate, and gives the same relative result. Several examples of the application of this measure are given. Implications of a definition of spectrum efficiency are mentioned.

I. INTRODUCTION

SPECTRUM efficiency is much discussed. For example, the Office of Telecommunications Policy (OTP) was commissioned to (among other things) “help attain coordinated and efficient use of the electromagnetic spectrum” [1]. The Joint Technical Advisory Committee was tasked in 1964 to “recommend ... procedures that would ... increase the effective and efficient use of the radio spectrum” [2], and numerous Federal Communications Commission (FCC) Dockets include spectrum efficiency as an important consideration.

But there is no generally accepted definition of spectrum efficiency, or measure of spectrum efficiency. The International Radio Consultative Committee (CCIR) has called for such a definition [3], and it is likely that one will be adopted at the next Plenary Assembly. If a definition is adopted, present CCIR recommendations, and even International Radio Regulations, may be changed to call for “maximum spectrum efficiency,” rather than for minimum necessary bandwidth as they now do. Even if international considerations are disregarded, a measure of spectrum efficiency could be used by U.S. frequency managers and regulators to compare the relative efficiency of different proposals, and even to set minimum standards of spectrum efficiency. It is therefore important that the definition be realistic and computable.

Several definitions have been proposed [4]–[12]. Some of these are for specific applications; others are generally applicable; but all can be cast in one of two general forms. One form is the ratio of the communications output to the spectrum space used to produce the output, which will be called the output/input efficiency. The other form is the ratio of the spectrum space used by an “ideal” system to the spectrum space actually used, which will be called the ideal/input efficiency.

In Section III B it will be shown that the two forms always give the same *relative* result, and that the output/in-

put measure is easier to compute. However, a measure of the spectrum-space input must be defined first, and this is done in Section II.

II. DEFINING A METRIC FOR SPECTRUM-SPACE USE

A. The Components of Spectrum Space

It is generally, but not universally, agreed that the components of spectrum space should be radio-frequency bandwidth, physical space (such as area or volume), and time [4]–[11]. There have been suggestions that other quantities, such as polarization and modulation, are also dimensions of spectrum space [13]. The argument for including these quantities is that systems using values of the parameters that are “orthogonal” or nearly orthogonal do not interfere with each other. For example, horizontally polarized antennas do not respond well to vertically polarized radio waves. However most of these proposed quantities such as polarization and modulation, do not fit well into a metric for spectrum space. So they will be excluded from the proposed measure of *spectrum-space* use, although their influence will show up in the measure of *spectrum efficiency*.

The physical space included in the definition of the spectrum-space metric will depend on the service that is involved. For many terrestrial services such as broadcasting and land mobile, the space of interest is two dimensional, and area is used as a factor as proposed by Gifford [4] and Powers [5], for example. The critical physical space for geostationary satellites is a line—the geostationary orbit. So measures of spectrum space for this service usually include degrees of arc (a linear metric) in the product [10], [14], [15]. In some cases, the relevant physical space is volume [16], and for point-to-point services it may be angle around a pivot point.

The importance of the dimension of time varies with the service. Many services operate continuously with analog modulation (for example, point-to-point microwave, some broadcasting, navigation services) so the time factor is a constant. In other services, such as land-mobile radio, time sharing is of vital importance to efficient spectrum use.

It is proposed that the spectrum metric—the unit of measure of spectrum-space use—be defined as the product

$$(\text{bandwidth}) \times (\text{relevant physical space}) \times (\text{time})$$

that is denied to other potential users.

B. “Used” means “Denied to others”

The area around a transmitter in which a usable reliable signal can be received is almost always smaller than the area

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in which the same transmitter can cause unacceptable interference. For purposes of spectrum management and efficiency, it is clearly the area that is denied to other potential users that is important. This is the area that is related to spectrum saturation. Similarly, it is the bandwidth and time that are *denied* to other users that is critical in frequency assignment [2], [7].

There are two ways in which these dimensions can be denied. The space is *physically denied* if it is filled with sufficient power to interfere with other proposed operations. This is the denial of interest to spectrum engineering [2], [7]. In Section C, definitions of a spectrum metric based on physical denial are developed.

Frequently, the spectrum space is *administratively denied* [7]. That is, frequency managers make rules or frequency assignments denying space to other users even if that space is not filled with interfering radiation. Administrative denial is sometimes a practical upper bond to physical denial imposed to account for the statistical variability of radio system performance and to make management of the spectrum simpler. In other cases, administrative denial is related to the spectrum space used by the receiver, also covered in Section C.

C. The Complementary Nature of Spectrum-Space Use by Receivers and Transmitters¹

Traditionally, radio transmitters have been considered the users of the spectrum resource. They use the spectrum space by filling some portion of it with radio power—so much power that receivers of other systems cannot operate in certain locations, times, and frequencies because of unacceptable interference. Notice that the transmitter denies the space to *receivers* only. The mere fact that the space contains power in no way prevents another transmitter from emitting power into the same location; that is, the transmitter does not deny operation of another transmitter (unless the coupled strength is so great that improper transmitter operation, e.g., intermodulation, occurs).

On the other hand, receivers use spectrum space because they deny it to transmitters. The mere physical operation of the receiver interferes with no one (except as it inadvertently acts as a transmitter or power source). Even then, the space used physically is small. However, the authorities deny licenses to transmitters in an attempt to guarantee interference-free reception. The protection may be in space (separation distance, coordination distance), in frequency (guard bands), or even in time (in the United States, some MF broadcasting stations are limited to daylight operation). This denial constitutes “use” of the space by the receiver, and is closely related to administrative denial. The radio astronomy bands are a familiar example of the recognition of receiver use of the spectrum space.

Thus receiver and transmitter usage of the spectrum resource results in complementary denial: transmitters deny use of a time-frequency-geographic region to receivers wishing to receive another signal, and a protected receiver denies

a time-frequency-geographic region to transmitters whose operation would interfere with it. An obvious way to incorporate these facts into a unit of measure of spectrum space is to partition the resource into two spaces—the transmitter space and the receiver space—and define dual units to measure the usage of each space. For administrative simplicity, the two units can be recombined into a single measure of system use.

D. Calculation of Physical Denial

For the purpose of calculating its spectrum use, a transmitter can be characterized by its location in geography and frequency, and by its *emission power density function* $\epsilon(\phi, f; f_T)$ which has the units W/Hz. This function shows the spectral power density at frequency f radiated in the azimuthal direction ϕ , when the transmitter is tuned to frequency f_T . (Area will be used as the physical space in this development.)

In most practical problems the power density emission function of the transmitter can be approximately separated into the product of a function of frequency and a function of azimuth

$$\epsilon(\phi, f; f_T) \sim p(f; f_T)g_T(\phi) \quad (1)$$

where $p(f; f_T)$ is the spectral power density at the antenna terminals, and $g_T(\phi)$ is the transmitting antenna gain function (at its normal design frequency).² The function $p(f; f_T)$ includes all power emitted, including spurious emissions and transmitter noise.

Similarly, a receiver can be characterized by its location and its *admission function* $\alpha(\phi', f; f_R)$, which is the fraction of the power density at frequency f arriving from direction ϕ' , that will reach the demodulator of a receiver tuned to frequency f_R . It has no units.

The receiver admission function can be approximately separated

$$\alpha(\phi', f; f_R) \sim \frac{g_R(\phi')}{q(f; f_R)} \quad (2)$$

where $q(f; f_R)$ is the selectivity function of the receiver, and $g_R(\phi')$ is the receiver antenna gain pattern.

Much of the power emitted by the transmitter does not reach the receiver. The difference between emitted power and received power is the basic transmission loss—defined to be the loss between isotropic antennas, and denoted by $l(f, d)$ where d is the distance between the transmitter and receiver [17]. It is assumed here that $l(f, d)$ represents the basic transmission loss for average conditions for the frequency of interest.

A general expression for the power coupling between a

¹ Sections C and D are consensed from [7].

² Editor's Note: This assumption appears reasonable in the vicinity of the carrier frequency, but may result in substantial error at harmonic and other spurious frequencies far removed from the carrier.

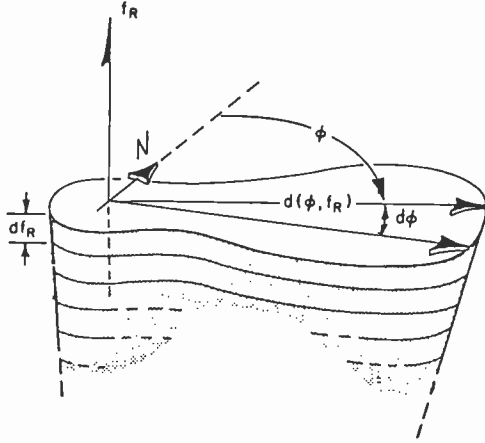


Fig. 1. Representation of the (bandwidth $\times$ area) volume denied to a receiver by a transmitter with a directional antenna.

transmitter T and a receiver R is

$$P = \int_0^\infty \left[\frac{\epsilon(\phi, f; f_T)}{l(f, d)} \right] [\alpha(\phi', f; f_R)] df \quad (3)$$

$$\sim g_T(\phi) g_R(\phi') \int_0^\infty \frac{p(f; f_T)}{l(f, d) g(f; f_R)} df(W)$$

In this equation, ϕ is the azimuth angle from T to R and ϕ' is the azimuth angle from R to T . On a flat surface, $\phi' = \phi + \pi$. The first factor in brackets is the spectral power density arriving at the receiver having suffered basic transmission loss $l(f, d)$. The second factor in brackets is the fraction of that power density admitted by the receiver so that the product is the spectral power density received. Integration over all frequencies with nonzero power density yields the total received power, P .

Suppose now that transmitter T and receiver R are not in the same system, so that there is a potential for interference. For any receiver there is some threshold amount of power in an unwanted signal that will interfere with acceptable reception of the wanted signal. Denote this threshold power level of receiver R by P_R .

By setting $P = P_R$, and assuming that all characteristics of the transmitter and receiver are fixed, (3) can be used to determine the minimum noninterfering separation $d = d(\phi, f_R)$ of T and R .

1) *The Situation-Specific Denial Metric*: Often, only a few types of systems compete for assignments in a particular frequency band and geographic region. The spectrum space that a system denies to each competing system can be calculated and is called the *situation-specific* metric. The combined spectrum space that a system denies to all competing systems is the measure of its spectrum-space usage.

The transmitter is characterized by its spectral density function $p(f; f_T)$ and its antenna pattern $g_T(\phi)$. Suppose the typical receiver R in a competing system has selectively function $q(f; f_R)$, antenna pattern $q_R(\phi')$, and interfering power threshold P_R . Solve (3) for $d(\phi, f_R)$, the minimum noninterfering distance separation in direction ϕ from T for a receiver tuned to frequency f_R . Fig. 1 is a plot of

$d(\phi, f_R)$ for an illustrative transmitter with a directional antenna. It can be seen from Fig. 1 that the geographical area that T denies R is given by

$$A(f_R) = \int_0^{2\pi} 1/2 d^2(\phi, f_R) d\phi. \quad (4)$$

The spectrum-space "volume" used at frequency f_R is $A(f_R)df_R$ (see Fig. 1). The denied areas for each frequency f_R can be computed and the resulting incremental volumes are summed. The result multiplied by τ_T (the time the transmitter operates) is the situation-specific metric M_T for the spectrum space used by transmitter T

$$M_T = \tau_T \int_0^\infty A(f_R) df_R$$

$$= \tau_T \int_0^\infty \int_0^{2\pi} 1/2 d^2(\phi, f_R) d\phi df_R \quad (5)$$

where $d = d(\phi, f_R)$ satisfies (3).

Similarly, the spectrum space denied to a transmitter by a receiver R operating τ_R h/day is

$$M_R = \tau_R \int_0^\infty \int_0^{2\pi} 1/2 d^2(\phi', f_T) d\phi' df_T \quad (6)$$

where $d = d(\phi', f_T)$ must satisfy (3) for the admission function of the evaluated receiver and the emission function of the denied transmitter.

Formally, the only difference between the metrics M_R and M_T is the interchange of admission and emission functions, but it is likely that the numerical values are different. At any rate, the space measured is different; receiver space is denied to transmitters and transmitter space is denied to receivers.

2) *The Uniform Denial Metric*: The numerical value of the situation-specific metric depends on the relative locations and specific emission and admission characteristics of the competing systems. Thus the value for a fixed system could be changed by the introduction of a new system in the same band or area. The *uniform metric* avoids this undesirable feature by using idealized reference transmitters and/or receivers. Spectrum space *used* is now considered to be the spectrum space *denied* to such *reference receivers* and *transmitters*. Equations (5) and (6) are still used to define the uniform metrics; however, (3) now has simplified forms.

For the transmitter metric, define an idealized "probe" receiver which has an isotropic loss-free antenna ($g_R(\phi') = 1$), and a perfect narrow selectivity function, so that $q(f; f_R) = 1$ if $f_R - b/2 \leq f \leq f_R + b/2$ and $q(f; f_R) = \infty$ otherwise. The bandwidth of the reference receiver b is chosen small enough that the spectral density $p(f; f_T)$ of the transmitters is essentially constant over it.

With these assumptions on the referenced receiver, the power coupling (3) becomes

$$P_R = g_T(\phi) p(f_R; f_T) b / l(f_R, d) \quad (7)$$

where P_R is the interference power threshold of the reference receiver. Recall that (7) must be solved for $d = d(\phi, f_R)$ to evaluate (5) for the transmitter metric.

The power threshold P_R of the reference receiver in (7) is somewhat arbitrary. However, it may logically be related to the average ambient noise power density since this is the power that would “use” the space in the absence of any system. Specifically, choose P_R/b to be the average ambient noise power density [18], [19].

An analogous definition can be made of the space denied to a reference transmitter by a particular receiver R . In this case, assume that the reference transmitter has an isotropic antenna ($g_T(\phi) = 1$), and a perfect narrow spectral density function. Specifically, $p(f, f_T) = 0$ unless $f_t - b/2 \leq f \leq f_T + b/2$, and with this interval $p(f, f_T) = P_T/b$, where P_T is the emitted power of the reference transmitter.

With these assumptions (3) becomes

$$P_R = \frac{P_T g_R(\phi')}{g(f_T; f_R) l(f_T, d)} \quad (8)$$

where P_R is the interference threshold of the evaluated receiver. Again, (8) must be solved for $d = d(\phi', f_T)$ to evaluate (6) for the uniform metric for receiver R .

Equation (8) shows, explicitly, what is intuitively obvious—that the space denied by a receiver to a transmitter depends on the power P_T emitted by the reference transmitter. In this case there is no “natural” reference level to use as there was in the case of a reference receiver, so the choice will have to be arbitrary.

For many applications, the desired information is the amount of spectrum space used by a receiver *relative* to the spectrum space used by other receivers. It can be shown [7] that if the transmission loss $l(f, d)$ is proportional to a power of distance d , then the *relative* value of the uniform metric is independent of the choice of P_T . This condition holds for free-space loss which is proportional to d^2 (for frequency fixed) and for some other cases. However, in general, even the relative value of the spectrum space used by receivers depends on the choice of P_T , because loss near the earth's surface is not proportional to a power of d for all distances. Thus the “best” choice for P_T remains an open question. Once a choice has been made, however, this measure of spectrum-space use depends only on the characteristics of the evaluated receiver, including its power threshold.

3) Simple Metric for Idealized Transmitters and Receivers: The uniform metric for a transmitter assumes that the reference receiver has a rectangular bandpass (i.e., selectively function). Similarly, the uniform metric for a receiver assumes that the reference transmitter has a rectangular power spectral density function. In both cases the emission (or admission) function of the *evaluated* equipment (transmitter or receiver) is arbitrary; it does not need to be “rectangular”.

Suppose, on the other hand, that a transmitter has a perfect power spectral density function of bandwidth B . Then, the uniform metric $M_T = \tau_T B A(f_T)$ where $A(f_T)$ is the area (4) denied to a competing receiver with tuned frequency $f_R = f_T$ [7]. Analogously, if we want to evaluate the metric for

a receiver with a perfect rectangular bandpass of bandwidth B , then the uniform metric is $M_R = \tau_R B A(f_R)$ where $A(f_R)$ is the area denied to a competing transmitter. That is, the uniform metric reduces to a simple (time) (area) (bandwidth) product for “perfect” equipment characteristics.

The metrics above measure the amount of spectrum space denied by *individual* transmitters and receivers. If a system has, say, multiple receivers and the spectrum-space volumes denied by these receivers overlap, then the amount of spectrum used by the system is not simply the sum of use by its component parts. Rather, it should be the union of spectrum-space volume denied, and the measure of system use should be less than the sum of the use of component receivers. An analogous situation may occur with a system having transmitters. (See [7] for examples.)

E. Final Choice of Metric Spectrum Efficiency Definition

The idea incorporated in the situation-specific metric are often used in electromagnetic compatibility and spectrum engineering analyses because they accurately describe the interactions in a real situation. However, for ease in extending the metric to a definition of spectrum efficiency, it is recommended that the simplification commonly used in frequency allocation and assignment be adopted. This simplification required defining a bandwidth–area–time product in which each factor is an upper bound (usually a conservative upper bound) of the factors that would be computed by using the simplified metric in Section D-3, and taking the union of spectrum space used by all transmitters and receivers in the link, system, or aggregate systems being evaluated.

III. DEFINING A MEASURE OF SPECTRUM EFFICIENCY³

The concept of quantifying efficiency by the ratio of desired output to valued input is familiar to people in all walks of life. A current example is a measure of personal transportation efficiency: miles/gallon. This example illustrates several features of generally accepted measures of efficiency. The numerator is the desired output of interest—even though it may not represent the entire output or system function. The denominator is a measure of the critical input to produce the output. Notice that the numerator and denominator need not be the same kind of quantity, and that the units of the resultant ratio may not make “sense”—the units of miles/gallon turn out to be inverse area.

This measure of efficiency, which does not include all of the technical detail that an engineer might want, is useful because it communicates desired significant information to the nonengineer—to the consumer, the policy maker, and the government regulator. To be valuable and accepted, a measure of spectrum efficiency also should be understood and usable by nonengineers—by the lawyers, economists, and nonspecialists who make final decisions about spectrum use in the International Telecommunication Union (ITU); and in the United States, the FCC, and the OTP.

³ Some of this section appeared in [20].

A measure of spectrum efficiency that has these characteristics would be the general form

$$\frac{\text{communications achieved}}{\text{spectrum space used}} \quad (9)$$

or more generally (to accommodate radar, navigation systems, radio control, etc.)

$$\frac{\text{information delivered}}{\text{spectrum space used}} \quad (10)$$

The nature and units of the numerator will depend on the type of service provided. The denominator was discussed in Section II.

A. Examples of Input/Output Measure of Spectrum Efficiency

Engineers addressing practical problems of interest to them have defined input/output ratios naturally. A notable example is the measure of "orbit utilization efficiency," defined by CCIR Study Group 4 in 1974, for the geostationary satellite service [10], and still under study [15]. For digital modulation, they defined efficiency as

$$\frac{\text{bit rate}}{(\text{RF bandwidth})(\text{orbit arc in degrees})} \quad (11)$$

Since bit rate is bits/s, (11) can be written

$$\frac{\text{bits}}{(\text{RF bandwidth})(\text{orbit arc})(\text{time})} \quad (12)$$

This is precisely the form recommended for the output/input efficiency measure in (9). The numerator is the amount of information transferred (measured in bits), and the denominator is the product of bandwidth, time, and geometric space. In this case, the critical geometric space is the geostationary orbital arc—a line.

For analog communications satellites, the orbit utilization was defined to be

$$\frac{\text{information bandwidth}}{(\text{bandwidth})(\text{orbit arc})}$$

In this case the information delivered is not quantified. Instead, the surrogate quantity, information bandwidth, is used because it is proportional to the potential rate of information transfer. This example illustrates one of the practical compromises that can be made in implementing the general form of the definition.

In a study aimed at maximizing the utility of microwave point-to-point networks in a dense urban environment, Tillotson, Ruthroff, and Prabhu [6] defined the "communication capacity" as

$$\frac{(\text{no. of usable channels})(\text{channel information bandwidth})}{(\text{radio bandwidth required})}$$

They specified the number of *usable* channels (instead of the number of channels) because they were calculating the amount of information delivered in the presence of interference, and only usable channels deliver information. Thus the numerator is analogous to the one defined by the CCIR [10]—it represents the communications capacity assuming that all channels are carrying information. However, the denominator contains only one dimension of the resource used—bandwidth. Their model has a fixed geographic area with a fixed (but quasi-random network) crossing it; and they apparently assumed full-time denial by the network. This latter assumption is true for many, but not all, applications.

More recently, Hatfield [11] reviewed measures of spectral efficiency proposed for comparing land-mobile radio systems and concluded that the most useful definition of spectral efficiency is

$$\text{erlangs/MHz/mi}^2.$$

Since an erlang is a measure of traffic per unit time, this ratio can be rewritten

$$\frac{\text{traffic}}{(\text{bandwidth})(\text{area})(\text{time})}$$

which is precisely the output/input ratio for spectrum efficiency (9).

Starting with the general form in (9), but not including time as a factor, Vinogradov [16] developed an explicit formula for the spectrum efficiency for a point-to-point radio link. Considerations used to derive the formula include the antenna gains and sidelobe power, the transmitter power and emission bandwidth, polarization, receiver sensitivity, and path length.

B. Another Candidate: The Ideal Measure of Efficiency

One proposed definition of "spectrum efficiency" has the form [2], [9]

$$\frac{\text{spectrum space used by an "ideal" system}}{\text{spectrum space used by the system being evaluated}}$$

The denominator of this ratio is intended to be the same as the denominator of the output/input ratio; namely, the product of bandwidth, geometric space, and time denied to other users. The numerator is the product of the same three factors that an "ideal" or "perfect" system performing the same function would deny to other users.

The "ideal" measure conforms to the traditional engineering concept of efficiency—a dimensionless number between 0 and 1. However, to nonspecialists it may have a parochial flavor—a preoccupation with conserving spectrum space as an end in itself. Returning to the miles/gallon analogy, would consumers want to replace the miles/gallon measure with one which compared the amount of fuel used by an

"ideal" automobile with the amount used by a particular model? Such a measure does allow ranking of different systems, but gives no guidance as to what the customer gets for his input of gasoline. Since many decisions which impact spectrum use are made by nonspecialists (for example, by congressmen, FCC commissioners, and ITU delegates) it is advantageous to have a measure of spectrum efficiency that they intuitively grasp.

Other advantages of the output/input ratio are that it is less subjective, takes fewer steps to compute, and gives the same relative answer as the ideal measure of spectrum efficiency. For example, suppose that the spectrum efficiency of a point-to-point microwave link must be computed. The link must carry a fixed number of telephone circuits m miles a given percentage of the time. This is the "output" which is the numerator of the output/input efficiency ratio: X circuit miles for p percent of the time. To complete the calculation of the efficiency, the spectrum space used (bandwidth $\times$ area $\times$ time) the link denied to other users must be computed. Although this calculation is not trivial, it is not necessary for the present comparison because both measures have exactly the same denominator. Thus the input/output measure of spectrum efficiency is computed.

Now consider the calculation of the ideal efficiency measure. The calculation of the denominator is the same as before. Also the output (X circuit miles with reliability p) must still be specified, else how can the ideal system be determined? And what is the amount of spectrum space used by the "ideal system?" The transmission could be via coaxial cable or by waveguide which would use almost zero spectrum space. Is this the ideal system? Or the system could use antennas with very narrow main beams and very low sidelobes. What is the pattern of the "ideal" antenna? Other parameters which would reduce the required spectrum space would have to be specified; e.g., receiver noise figure, modulation index, and modulation type. The necessity of answering these questions makes the "ideal" measure of spectrum efficiency difficult to compute and somewhat subjective. In practice, the ideal system is usually abandoned, and replaced by some other reference system [9].

If the purpose of a measure of spectrum efficiency is to compare systems, then nothing is gained from the additional difficulty of computing the ideal/input measure, because both measures give the same relative result. Let C stand for the output specified in the example above (X circuit miles with reliability p). Suppose system A uses S_A spectrum space to provide the output, system B uses S_B spectrum space to do it, and an ideal system uses S_I spectrum space. The ideal efficiency measure for system A is S_I/S_A , and for system B it is S_I/S_B . Then system A is

$$\frac{S_I/S_A}{S_I/S_B} = S_B/S_A \quad (13)$$

times more efficient than system B . Using the output/input measure, the efficiency for system A is C/S_A and for system B

it is C/S_B . Using this measure system A is

$$\frac{C/S_A}{C/S_B} = S_B/S_A \quad (14)$$

times better than system B , which is the same result obtained before.

IV. CONCLUDING REMARKS

A spectrum efficiency measure of the form (communications achieved)/(spectrum space used) is advocated in this paper because

- it will be better understood by nonspecialists who make or, at least, influence decisions about use of the spectrum resource;
- it is easier to calculate and less subjective than another candidate, the ideal/input measure.

Its potential practicality has been illustrated by examples of its use by engineers concerned with particular real-world problems. It should be further tested by converting the general form into specific definitions for many more applications such as broadcasting, point-to-point microwave links, and radar. This should not be considered to be merely an academic exercise because the CCIR will probably adopt some definition of spectrum efficiency soon. The resulting change in international regulations will impact radio system planners, designers, and operators.

REFERENCES

- [1] The Office of Telecommunications Policy, "The radio frequency spectrum: United States use and management," Jan. 1973.
- [2] Joint Technical Advisory Committee, "Spectrum engineering—The key to progress," IEEE, 1968.
- [3] CCIR Question 47/1, "Definition of efficiency and utility of spectrum use," Documents of the XIIIth Plenary Assembly, ITU, Geneva, 1974.
- [4] R. P. Gifford, "EMC revisited—1966," *IEEE Trans. Electromagnet. Compat.*, vol. EMC-8, no. 3, pp. 123–129, Sept. 1966.
- [5] K. Powers, "Diversity of broadcasting," *Science and Technology*, pp. 32–40, Apr. 1968.
- [6] L. C. Tillotson, C. L. Ruthroff, and V. K. Prabhu, "Efficient use of the radio spectrum and bandwidth expansion," *Proc. IEEE*, vol. 61, no. 4, pp. 445–452, Apr. 1973.
- [7] D. R. Ewing and L. A. Berry, "Metrics for spectrum-space usage," Office of Telecommunications Report 73-24, U.S. Department of Commerce, Boulder, CO, NTIS Accession no. COM 75-10837/AS, Nov. 1973.
- [8] O. L. Luk'yanova, "Characteristics of the utilization of the radio-frequency spectrum by a particular system," *Telecommunications & Radio Engineering*, vol. 28/29, no. 4, pp. 41–45, Apr. 1974 (Russian: *Elektrosvyaz*, Apr. 1974).
- [9] C. Colavito, "On the efficiency of the radio frequency spectrum utilization in fixed and mobile communication systems," *Alta Frequenza*, vol. XLIII, no. 9, pp. 640–651, Sept. 1974.
- [10] "The effect of modulation characteristics on the efficiency of use of the geostationary satellite orbit," Documents of the XIIIth Plenary Assembly, ITU, CCIR Report 559, Geneva, 1974.
- [11] D. N. Hatfield, "Measures of spectral efficiency in land mobile radio," *IEEE Vehicular Technology Group Conference Record*, pp. 23–26, 1975; also in this issue, pp. 266–268.

Definition of a Measurement Capability for Spectrum Managers

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Abstract—This paper defines a spectrum measurement capability that will be directly useful to the managers of the radio-frequency spectrum. The proposed uses of such a capability are categorized as measurements to 1) determine spectrum occupancy, 2) check for and document compliance with assignment rules, regulations, and standards, and 3) facilitate electromagnetic compatibility (EMC) among the various systems using the radio spectrum by helping solve specific EMC-related problems. Both general and specific requirements are identified. The hardware and software for a spectrum measurement system (SMS) which can satisfy these requirements are described at the functional level.

I. INTRODUCTION

THIS PAPER defines a radio-frequency spectrum measurement capability which will provide a flexible "diagnostic" tool that can be used by spectrum managers to check for, and document spectrum usage and compliance with, standards and assignment rules and to provide measurement support for the solution of electromagnetic compatibility (EMC) problems. Such a capability is one of several tools required by managers of the radio-frequency spectrum [1]–[6] (see Fig. 1).

The complete cycle must be considered. This includes the definition of spectrum management problems, and data collection, processing, and analysis, to generate information useful for their solution. The relationship of the measurement capability to the radio environment and to other tools of the frequency manager is shown in detail in Fig. 2 for each of the categories defined to bound the problem.

In order to specify possible alternative configurations for a measurement system, general requirements have been defined. Two distinct ways to categorize the general requirements emerged: first, the dichotomy of *short-term* (problem-solving) and *long-term* (planning) functions and, second, the trichotomy of occupancy, compliance, and compatibility. A generalized measurement scenario (GMS) with dimensions of frequency, space, and time was developed, and specific example scenarios were provided by the Office of Telecommunications Policy (OTP). Three such scenarios were developed in considerable detail in [4, Appendix C].

Since the work described in [1]–[5] was completed in the late 1960's and early 1970's, spectrum measurement systems of the general type described in this paper have been implemented by the Federal Communications Commission [7], and by the U.S. Department of Commerce for OTP [8] and the U.S. Army [9].

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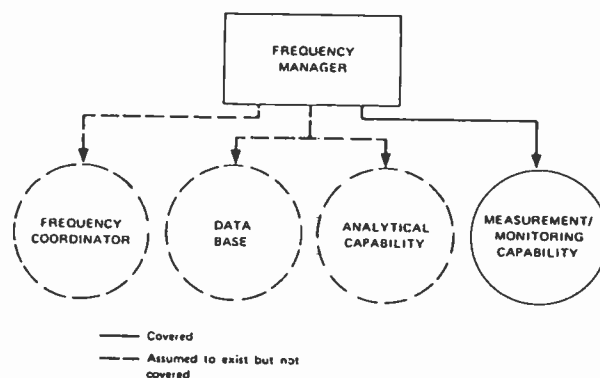


Fig. 1. Tools of the frequency manager.*

II. GENERAL REQUIREMENTS

Introduction

The basic factor pertinent to the general requirement for measurement capability is its utility toward efficient management of the radio spectrum [1], [6]. As indicated previously there are both short- and long-term requirements.

Short-Term Requirements

Short-term requirements are generally problem-solving in nature. Examples of short-term requirements are as follows.

1) A serious EMC problem has been modeled analytically and the apparent solution to the problem entails a management decision. The measurement capability can be used to check the results of the model calculations to give added confidence to the subsequent decision.

2) A complaint is made by a foreign country that the United States is not in compliance with an international agreement. The measurement capability could be deployed to help determine the validity of the complaint.

Long-Term Requirements

Long-term requirements are generally associated with planning to accommodate new users of the spectrum or with a planned or required change in spectrum assignment or allocation policy.

Examples of long-term requirements are as follows.

1) Large-scale civil or government events can severely congest certain parts of the frequency spectrum, for example, riots, other civil disturbances, and large-scale military

* Note: There will be considerable interaction among these tools (not indicated here). Also, a tradeoff will exist in the management process between the use of measurements and coordination to accomplish the management task. This tradeoff is discussed in [1], and is not treated further.

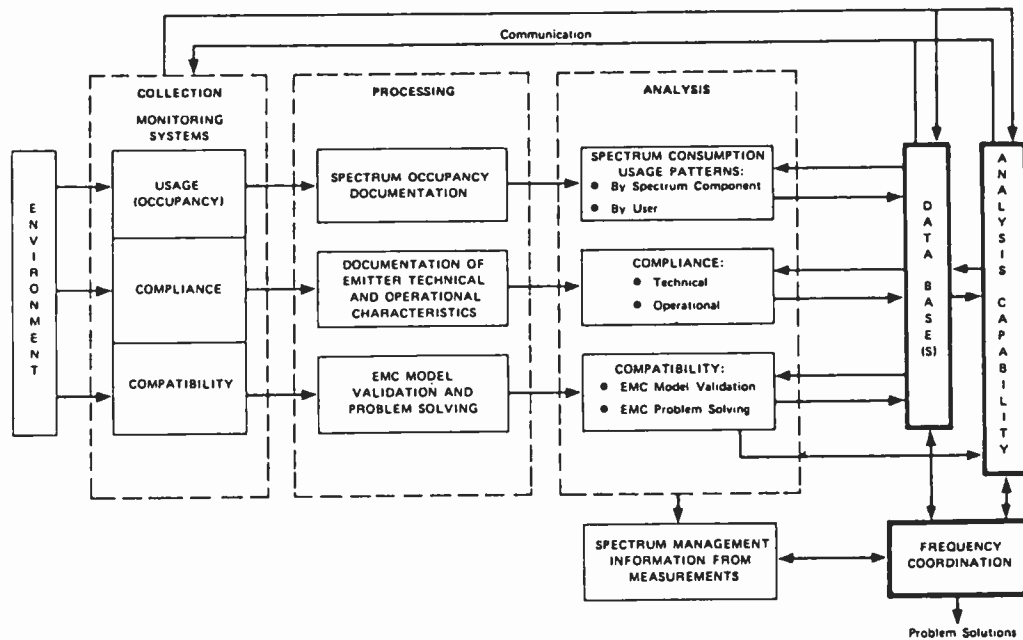


Fig. 2. Relationship of the generic types of monitoring to the frequency manager's other tools.

maneuvers. In such emergencies, the government spectrum manager might want to employ the measurement capability to define frequency usage better. The data obtained would be useful in helping to determine future frequency requirements.

2) Spectrum occupancy models would be most useful in planning for future spectrum usage. Use of the digital computer has greatly increased the feasibility of developing mathematical models (currently available only in a rudimentary phase of development) that predict the frequency, time, and space occupancy of a given radio system or group of systems, or band or group of bands. Validation of the accuracy of these analytical models may become an increasingly important function of the measurement capability.

Telecommunications System Characteristics

The radio systems currently using [10] (and planning to use [11]) the spectrum are major factors in determining the general requirements for spectrum management measurements as well as the specific requirements for the measurement system and knowledge of radio-system technical characteristics. Each task initiated by the spectrum manager will require a problem statement for the measurement which includes some of the characteristics of the specific radio systems of interest. An initial effort in defining a problem statement, then, is to determine the technical and operational characteristics of the pertinent radio systems. For each system, the parameters defined should include:

- function
- frequency band(s)
- effective radiated power
- modulation type
- modulation parameters
- spatial characteristics
- receiver characteristics
- usage and other operational characteristics

assignment guidelines
operational standards.

In general, the parameters of radio systems must be considered in terms of how they combine to produce observable signal energy in frequency, space, and time. The frequency characteristics of a radio system include its frequency assignment(s), its bandwidth, and its modulation. The spatial characteristics are determined by such factors as the power into the transmitting antenna, the antenna gain and directivity, the antenna scanning characteristics and propagation characteristics, and the mobility of the radio system. The time characteristics are determined by the transmission statistics (off-on, PRF, etc.), the antenna scanning patterns (if any), and the mobility of the radio system.

Some of the operational characteristics of radio systems may affect the use of the measurement system more than the radio system's configuration. One must determine characteristics such as the probable transmission statistics (message lengths, etc.) of communication systems and the scan rates of radars. The transmission from a radio system can vary from short and irregular (e.g., certain dispatch messages) to continuous (e.g., beacons or lengthy coordination messages). One of the requirements for specifying the problem statement will be to determine (or estimate) the transmission characteristics for each radio system in the area to be monitored. Also, the characteristics of each radio system may be considered in terms of the length of the measurement period required to obtain a statistically valid representation of that system's occupancy (see the discussion in [12]), compliance, or compatibility with other systems. Some radio systems, such as HF trunks, use multiple frequencies in the course of their operations; for such systems, occupancy, compliance, and compatibility must be determined for all the frequencies used.

Certain radio systems (such as radars) may produce repetitive signal energy as observed at a monitoring point, but

the actual occupancy, compliance, and compatibility (in space, frequency, and time) may be very complex and difficult to extrapolate from a single monitoring point to an area or to other time periods—particularly when multiple systems are used.¹ In the evaluation of such environments, it will be necessary to determine the best positions in time and space to intercept the radiated energy. These positions must be chosen so that the measured results are useful for the purposes described in the next subsection.

III. PURPOSES OF MEASUREMENT

Purposes of measurement—occupancy, compliance, and compatibility—may require different capabilities, both operationally and technically. In this section, the effects of each of these uses on capability are discussed.

Occupancy

For the purposes of this discussion, three potential uses of occupancy data are considered:²

- 1) Study of channel or band loading.
 - a) occupancy summaries at an observation point.
 - b) determination of occupancy correlation distance (i.e., the distance from the point where occupancy data are taken to a point at which these data can be extrapolated with a required degree of confidence).
- 2) Verification of the accuracy of mathematical models that predict occupancy at a point or predict signal intensity contours in an area.
- 3) Study of the assignment of new users or systems (for both short-term assignment and long-range planning) for sharing,³ reassignment, or reallocation.

The occupancy data can provide the documentation of spectrum utilization in a given region or area. Such data will illustrate the consumption of the spectrum resource. Over time, the data will show trends of utilization (growth or decay). They can provide an input to the assessment of the impact of spectrum management changes (such as the use of a regional center [15]) on frequency usage.

Occupancy must be specified in several ways that might, at various times, be required by the spectrum manager. At one extreme is the need to determine the time intervals when the energies in selected frequency bands exceed specified thresholds. Although this measurement is relatively simple, the

volume of data required to provide meaningful occupancy statistics is usually large and necessitates consideration of the tradeoff of frequency scanning (making measurements on many frequency bands, in effect, at the same time) with the amount of time required to gather sufficient data. At the other extreme are requirements comparable to some of those for an electronic intelligence gathering operation:

- identification of emitters
- analysis of modulation
- location of emitters
- measurement of signal characteristics
- measurement of operational characteristics.

For the first use, it is necessary only that the signals from radio systems be detected by the measurement system. The principal application of the data would be to evaluate the loading of channels assigned to equivalent radio systems. This application would indicate the distribution of users across the channels and identify any saturated channels.⁴

The complexity of the measurement may be increased if the data are to be compared with the outputs of mathematical models. Models can be developed to predict certain levels of signal energy at given locations and distances from the radio system being modeled. The position of the measurement system must, therefore, be known relative to the positions of the radio systems being measured, and the amplitude data must be so calibrated that valid comparisons can be made with the signal energy predictions of the models. Some additional "monitors" on the systems of interest (as described in [1]) may be required to identify which systems are in use and when—at least during initial checkout of an occupancy model. Additional measurement system complexity will be required if the occupancy data are to be used to assign new users or systems into the frequency, space, and time domains [16]. The measurement system must acquire data of sufficient accuracy and density to determine that a proposed radio system will not create, or receive, harmful interference.

Measurements are also needed to help determine noise levels [17]–[19]. Knowledge of this form of spectrum occupancy (pollution) is necessary in order to set meaningful thresholds for determining occupancy by *bona fide* transmissions. The noise levels are also needed to compute the coverage area for a given system.

Compliance

Compliance relates to the use of measurements to assist in identifying—and documenting for enforcement purposes—unauthorized transmissions or improper authorized transmissions. Measurement for compliance by authorized users requires that the measurement system directly measure specific signal characteristics (in frequency, space, and time) and determine whether the measured signal energy is within some required bounds (e.g., see [20]). If usage is noted on an unassigned channel, it can be flagged and reported to the

¹Radars produce pulse signals of considerable complexity when viewed in the frequency, time, and space domains [8], [13]. They often employ antennas that can scan azimuth, elevation, both azimuth and elevation (including helical search), and other modes. A single radar can present a complex monitoring problem; a mix (or net) of radar systems can present an extremely difficult monitoring problem—both in the space and time dimensions of the measurement and in the processing and interpretation of the monitored data.

²Standard definitions of terms pertaining to spectrum occupancy do not currently exist. The papers by Spaulding and Hagn [12] and by Hagn and Dayharsh [14] contribute to filling this void, but much work in this area remains to be done.

³Knowledge of "user profiles" is important for defining sharing criteria, and occupancy measurements can provide valuable data regarding such profiles (e.g., data on transmission lengths can be related to message lengths [14] which, in turn, indicate the difference between users performing a dispatch function from those performing a coordination function).

⁴This part of the measurement process depends on a definition of saturation. A given channel can be saturated spatially as well as temporally. No standard definition of saturation currently exists, although several have been proposed, e.g., [14].

appropriate enforcement authority for action. Other specific checks can be made as required. The joint use of measurement systems for occupancy and enforcement work has been recently studied by the Georgia Institute of Technology for the FCC [21].

Two general types of compliance guidelines will require validation through measurement: technical and operational. The former will require that the measurement system's position and technical parameters (relative to the radio systems being measured) be accurately known, while the latter will require precise measurements of operational parameters [22].

Minimum standards based on international agreement apply to all systems [23]. The U.S. government has developed standards for certain basic parameters (e.g., frequency tolerance and spurious emissions) as well as for certain types of systems (e.g., large, fixed radars) [24] and maintains a continuing effort for developing and revising these standards for both governmental [24] and nongovernmental [25] systems. A study performed in 1969 [26] provided a detailed review of standards and made recommendations relative to the development, application, improvement, and enforcement of standards.

The standards will, in general, spell out standard measurement techniques. More explicit standards will, no doubt, be developed in the future. As a guide for the type of measurements and procedures that might be required in the future, we can look to some of the existing FCC and Department of Defense (DoD) standards on EMC, such as MIL-STD-449C, -461, -462, and -463. It should be recognized that these standards are not current with the state of the art (some, like -461, are currently being updated) and should be used only to provide minimum guidelines for some of the measurement system specifications. The measurement capability can, when procured, be used to obtain some of the data needed to improve standards, as well as to check for compliance with them.

Compatibility

Compatibility pertains to the application of measurements to increase the EMC of systems sharing the radio spectrum, by the following means:

- 1) Assist in solution of high-priority problems (e.g., identification of the source of a problem and, when appropriate, description and documentation of the problem).
- 2) Validation of models of EMC problem situations; occupancy; figures of merit [27]; sharing criteria; and the like.
- 3) Standardization of definitions (e.g., usage versus occupancy), parameters to be measured, equipment and procedures.

The achievement of compatibility between two similar or dissimilar systems depends on minimizing the effects of harmful interactions from radio systems occupying the same frequency, space, and time domains. A compatibility use of measurement data requires that the measurement system be able to distinguish the signals emanating from various radio systems. The system can distinguish these signals by any of several signal characteristics that provide some degree of orthogonality. Among these characteristics are frequency and

modulation characteristics, information such as call signs, temporal characteristics, signal level, and angle of arrival. Any discrimination techniques for signal characteristics will require increased complexity in the measurement system equipment, operation, or data processing.

The solution of EMC problems, including the validation of EMC models, extends the system requirements beyond those necessary for occupancy measurements. Occupancy measurements relate to systems and their use of the spectrum resource, whereas EMC measurements relate to the interaction of similar or dissimilar systems in their respective use of the spectral resource. EMC measurements may be both active (using transmitters) and passive (using receivers). In defining the scope of the measurement capability, we have restricted our consideration to passive measurement.

IV. GENERAL MEASUREMENT SCENARIO

Previous sections have identified the important variables—radio systems, uses of measurement data, and dimensions of the operation—that must be described to quantify a measurement problem. In designing and employing a measurement system, three primary dimensions will allow flexibility: frequency, space, and time; i. e., the measurement system will have frequency range and bandwidth flexibility, can operate at a fixed point or on a line in space while in motion, and can monitor for some period of time. It is logical, therefore, to formalize the problem statement of spectrum measurements into these three dimensions. The term general measurement scenario (GMS) is a convenient one to use; it is defined as being a synthesis of the general characteristics of a measurement requirement, having the dimensions of frequency, space, and time.

The three general purposes of measurement (occupancy, compliance, and compatibility) can easily be viewed in the context of the GMS by considering their relationships in the frequency, space, and time domains. The interrelationships of these three categories of monitoring are depicted in Fig. 3. As illustrated in this figure, Systems *A* and *B* each produce signal energy that occupies certain parts of the frequency, space, and time domains. If the signal energy from these two systems is measured independently, occupancy data are developed. When it is desirable to determine whether the signal energy measured is consistent with assignment rules or certain technical and/or operational standards, the frequency/space/time measurement is used to determine compliance. Finally, if it is desirable to determine whether identical (*A/A*) or dissimilar (*A/B*) systems can share the same frequency/space/time domains, compatibility is determined. Hence, the GMS is useful in illustrating the meaning of occupancy, compliance and compatibility (see also [4, Appendix A]).

V. SPECIFIC MEASUREMENT DATA REQUIREMENTS

A list of specific types of data to be obtained by the SMS is given in Table I. The trichotomy of occupancy, compliance, and compatibility is arbitrary and somewhat artificial. Many of the data items are potentially applicable to more than one of

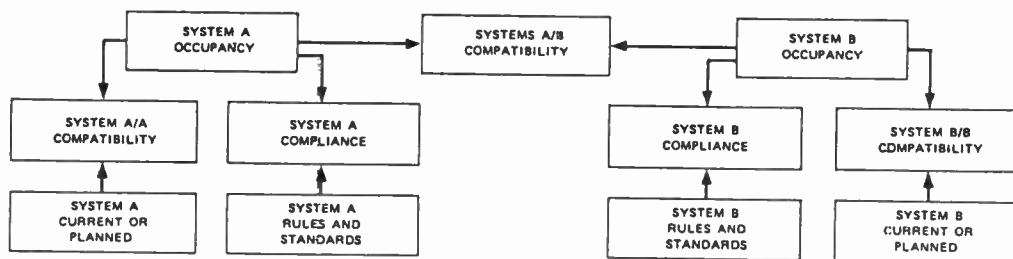


Fig. 3. Basic relationships of occupancy, compatibility, and compliance for two radio systems.

TABLE I
DATA TO BE OBTAINED BY THE SPECTRUM MEASUREMENT
SYSTEM AS A FUNCTION OF PURPOSE

Type of Data To Be Obtained	Purpose for Measurement		
	Occupancy	Compliance	Compatibility
Relative Occupancy versus Channel	X		
Relative Occupancy versus Frequency Band	X		
Occupancy versus Channel Bandwidth	X	X	
Occupancy versus Assignments	X	X	
Identification of Unauthorized Users	X	X	X
Emitter Identification (call sign)	X	X	X
Emitter Location	X	X	X
Frequency (tolerance and stability)		X	X
Effective Radiated Power		X	X
Power-Flux Density		X	X
Field Strength		X	X
Signal Envelope Characteristics		X	X
Modulation Type		X	X
Emission Bandwidth		X	X
Pulse Density, Length, PRF	X	X	X
Spurious Emissions (frequency, absolute and relative level)		X	X
Harmonic Radiation (frequency, absolute and relative level)		X	X
Cochannel Interference	X	X	X
Adjacent Channel Interference		X	X

these categories, as indicated in the table. This list is based, in part, on the specific scenarios of [4]. Many of the compliance items pertain to rules and procedures given in [24], [25], and to various standards as discussed in [26].

VI. DEFINITION OF A SPECTRUM MEASUREMENT SYSTEM (SMS)

Introduction

Prior to a discussion of specific hardware and software requirements, it is appropriate to consider requirements for frequency coverage, level of automation, and the like.

Frequency Coverage: The design goal is to provide a system capable of monitoring the frequency range for which allocations exist (10 kHz to 300 GHz in the U.S.). This range covers, not only those bands receiving major usage to date—say up to 18 GHz, but also the region for which one might expect major breakthroughs in hardware development. Propagation limitations of the earth's atmosphere [28], [29] might prove to be a deterrent to development of part of the millimeter wave bands for certain applications, even though hardware breakthroughs continue to occur [30].

Level of Automation: The spectrum measurement system can be developed in a number of configurations, ranging from a completely manual system to a fully automated one. The type of measurements to be performed (e.g., occupancy, compliance, compatibility) will determine the peripheral equipment required in addition to a basic receiver and will dictate the complexity of the control software required for a fully automated system. In some cases, it may be advantageous to use a manual system (for compliance and compatibility measurements), because the development costs of an automatic system capable of performing the required measurements would be prohibitive. On the other hand, a manual system will generally not be capable of economically acquiring sufficient data for occupancy determinations. In some cases, a semi-automatic system may prove to be the best.

The Influence of Measurement and Data Processing Time: Measurement and data processing time are important criteria in developing a measurement system. When measurements must be performed over a sector of the spectrum, sufficient data must be acquired so as to obtain a reasonable statistical sample. For certain measurements (e.g., occupancy), the time required to determine certain statistical parameters to a given confidence will depend on the data themselves, as discussed in [12]. This sample can be acquired by rapidly scanning a receiver over the frequency range of interest and recording the received signal strength (or other parameters of interest) or by using a large number of fixed-frequency receivers and monitoring their outputs. Obviously, the former method is the more economical form of instrumentation, if adequate sweep speeds can be obtained. Refined frequency-sweep techniques, such as those employed in compressive receivers, should be considered [31].

Measurements of compliance and compatibility do not usually have to be performed as rapidly as those of occupancy,

but the data must be acquired sufficiently rapidly for them to be relevant at the completion of the data processing. The fact that the usefulness of the data obtained by the measurement system may be time-perishable must be considered.

Data recording and processing requirements will vary with the type of measurements to be performed. For example, to minimize computer storage, the data for occupancy measurements could be recorded on digital magnetic tapes in an unprocessed form, and then processed later with a second pass of the control/processing computer or on a remote computer. It would be desirable, if not mandatory, to process data for compliance and compatibility in real time so as to have the results immediately available for analysis. The use of spectrum displays in the field (e.g., [13]) may be advantageous when it is necessary to record only part of the incoming data or when real-time determination of measured parameters is important.

Degree of Modularity: The ideal measurement system would be a unit sufficiently compact to be easily adaptable to any mounting platform (i.e., permanent structure, mobile van, shipboard, or aircraft). The measurement system will be of modular construction so that only the equipment required to perform the desired measurement task needs to be mounted on the platform required by a particular scenario. This construction will minimize the space and equipment weight required to perform a particular monitoring task—a distinct advantage when airborne or other mobile platforms are used.

If modular construction is assumed, each block may indicate one or more physical modules (several separate demodulator modules may make up the demodulator block), and possibly two or more blocks may make up an actual physical module (the scanning filter and demodulator may be contained in the receiver module). Modular construction also allows the system capabilities to be extended gradually as funds become available, instead of requiring the entire system to be purchased with the initial cash outlay. As the state of the art advances, modules may be replaced with more modernized and refined modules, so that the measurement system does not become obsolete because one of its components becomes obsolete.

Hardware System Requirements

Method of Approach: Equipment to make the detailed measurements for compliance and compatibility exists within the federal government inventory, but equipment that would be readily adaptable to occupancy measurements did not exist in the early 1970's when the study of [4] was conducted.

A system functionally configured as shown in Fig. 4 could collect occupancy data. The requirement to scan many different bands for different systems implies that the filter resolution bandwidth must be adjustable over large ranges. This consideration tends to argue economically against multiple scanning filters. Hence, a simple scanning filter arrangement was selected as the basic data collection device.

The important parameters of this device are:

- W frequency band to be searched
- f_0 nominal (center) frequency

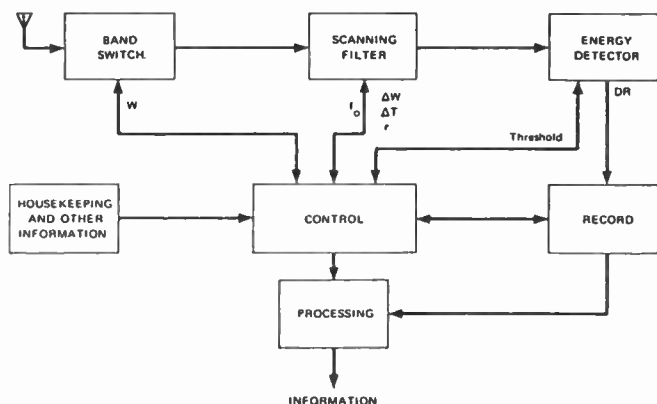


Fig. 4. Functional block diagram of the occupancy monitoring collection system.

$\Delta W f_0$ resolution of filter in frequency (bandwidth)

ΔT resolution of filter in time

r rate of scan

DR dynamic range.

These will determine other system parameters and allow system specification to begin; the requirements for these parameters are discussed in detail in [4].

The maximum and minimum values of these parameters must be determined by examining typical systems assigned to each frequency band. Ultimately, the size of the adjustable frequency steps must also be determined.

Next, increasingly more complex systems capable of accomplishing more and more of the total measurement/monitoring task are defined. A total capability (ideal system) would comprise monitoring subsystems able to supply every measurement desired—to the degree of accuracy required—as automatically as possible. Fig. 5 shows the general configuration of a complete monitoring system.

The hardware complements of the monitoring systems will include the antennas, amplifiers, and bandswitching gear necessary to monitor each RF band of interest. Also included as hardware will be some form of scanning filter to determine channel occupancy data and other (incrementally implementable) equipment to measure parameters such as signal modulation type; baseband spectrum; and emitter direction, which is required to resolve EMC problems, as well as to monitor for compliance. Some automatic control and processing functions, such as receiver tuning, band selection, and energy-density measurements, will also be implemented as hardware. The primary difference in the three general functional configurations will, in fact, show up in the division of the control function between manual and automatic equipment.

Software System Requirements

General Constraints: Two groups of monitoring software are identifiable: the software for the SMS and that for the central processing unit. The data processing and analysis requirements of the monitoring program will depend upon the information needed by the spectrum manager. Furthermore, the software developed in connection with the monitoring

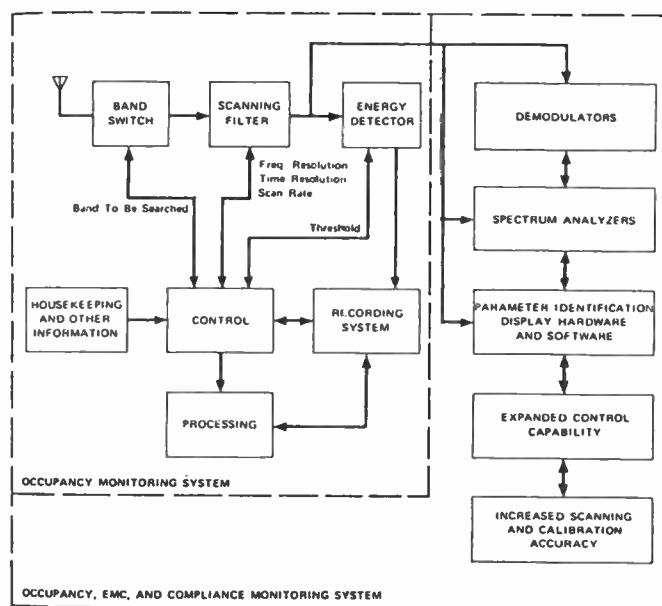


Fig. 5. Functional block diagram of the spectrum measurement system.

program should be compatible with the current *and planned* electronic data processing capability. The allocation of data processing tasks between the SMS and a central processing facility involves management decisions clearly beyond the scope of this paper. The approach here is to define software package and calibration/maintenance algorithms clearly associated with the SMS. Algorithms for occupancy, compliance, and compatibility are also defined. These algorithms can necessitate substantial processing and may or may not be performed in the field. Communication and remote-control algorithms are not considered here. The description of the software is at a functional level.

Basic Software Package: The basic software package will have two parts: one for control of the measurement functions and one for basic preprocessing, recording, and display.

System control functions: a key element of automatic system operation is efficient control of system functions. For a monitoring capability, control of the receiving system will include selection of:

- frequency
- antenna and RF filter
- gain
- resolution and sweep rate
- detector function
- digitization.

The relationship of these control functions to the system hardware is shown in Fig. 6. The control will provide the means to obtain a digital representation of selected and possibly processed samples of the radio-frequency (RF) environment. The control of the different functions should be essentially independent.

The control of frequency, as well as that of some of the other functions, may involve multiple operations. For example, reception on a selected frequency may require selection of the proper antenna, tuning of a preselector, and tuning

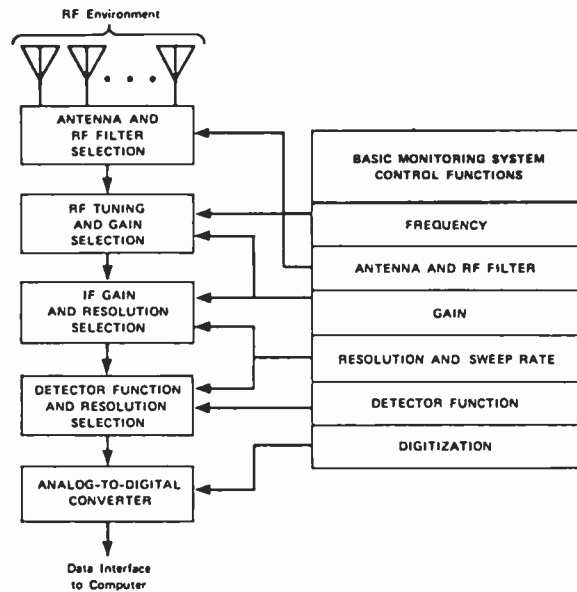


Fig. 6. The relationship between the basic monitoring system control functions and the monitoring system hardware.

of one or more local oscillators. One should also be able to tune frequency, in both a step mode and a linear sweep mode, at a selected sweep rate. The system gain control will serve two functions: to prevent system overload at any of several stages and to provide a signal of the appropriate level to the input of the digitizer. To perform these functions, the software must allocate the appropriate gain among the various receiver stages. The resolution function is concerned primarily with pre-detection and postdetection bandwidths. There is, however, a possible software coupling with sweep rate. The relationship between the resolution bandwidth and the corresponding optimum sweep rate has been discussed in [4]. The control of the detector function is related to the purpose of measurement or monitoring. For occupancy monitoring, an energy detection may be desirable. For other measurements, a synchronous detection or perhaps an FM discrimination may be desirable. For many measurements, digital control of the detector function is unnecessary. Control of the digitization process can be specified in terms of a sampling rate, a start time, and a stop time. For synchronization with the sampling rate, timing commands must be provided to transfer the digitized samples into the computer or an intermediate data storage.

Basic data handling: As part of the control function of the basic software package, the function of transferring the digitized samples of the data into the computer has been included. It is desirable to be able to do several things with the data. First, it should be possible to display the data to the operator in either a processed, intermediate, or an unprocessed form. Some minimal processing is appropriate for the basic software package. This will enable the operator to validate the data collection process in the field and will provide a useful data output independent of subsequent processing. Finally, it should be possible to record the data on magnetic tape or some other suitable medium. In addition to the data-handling functions, it is desirable to be able to incorporate into the data record such logging information as the

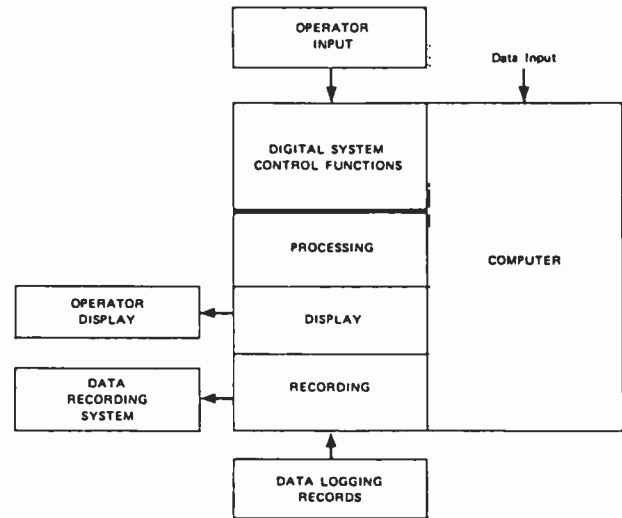


Fig. 7. Data-handling operations for the basic software package.

status of various control functions, the time, and the date. The data-handling functions of the basic software package are shown in Fig. 7.

The basic software package will be designed for processing occupancy data. One of the simplest occupancy measures is derived by comparing the signal energy, measured in a selected frequency channel (or band) and over a selected time interval, with a threshold that can be set. If the signal energy exceeds the threshold, the frequency channel (or band) may be assumed to have been occupied at that time. If the threshold is not exceeded, the channel (or band) may be assumed to have been unoccupied (see [12] for a more detailed discussion of the definition of occupancy). Software for compliance and compatibility have been treated in [4].

VII. CONCLUDING REMARKS

As mentioned earlier, several systems of the type described in this paper have now been implemented (e.g., [8]), and their use to help verify the accuracy of spectrum management records [10] has been discussed by Hailey [32]. The FCC has recently used one of its systems to help study the UHF bands [33], and the Canadian and Iranian governments have acquired (or will acquire) such systems. It will take spectrum managers some time to learn how to use these new tools fully, but the benefits can be great.

ACKNOWLEDGMENT

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REFERENCES

- [1] *JTAC, Spectrum Engineering—The Key to Progress*. Joint Technical Advisory Committee, IEEE, New York, Mar. 1968.

- [2] T. I. Dayharsh, T. J. Yung, and W. R. Vincent, "A study of land mobile spectrum utilization," Part A, Final Rep. Contract RC-10056, SRI Project 7379, Stanford Research Institute, Menlo Park, CA, July 1969. (Available from NTIS, Springfield, Va, as PB 182917).
- [3] W. R. Vincent and T. I. Dayharsh, "A study of land mobile spectrum utilization, Part B: Analysis of the spectrum management problem." Final Report., FCC Contract RC-10056, SRI Project 7379, Stanford Research Institute, Menlo Park, CA, July 1969. (Available from NTIS, Springfield, VA, as PB 182918).
- [4] G. H. Hagn, S. C. Fralick, H. N. Shaver, and G. E. Barker, "A spectrum measurement/monitoring capability for the federal government," Final Rep., Contract OEP-SE-70-102, Stanford Research Institute, Menlo Park, CA, May 1971. (Available from NTIS, Springfield, VA, as PB-203 062).
- [5] G. H. Hagn, T. I. Dayharsh, G. E. Barker, and S. C. Fralick, "A concept for the US Army Communications-Electronics Installation Agency's operational electromagnetic compatibility program," Final Letter Rep., SRI Project 2120, Contract DAE A 18-71-A-0204, Stanford Research Institute, Menlo Park, CA, p. 64, Aug. 14, 1972 (Available from NTIS, Springfield, Va, as AD-A-045 099).
- [6] D. M. Jansky, *Spectrum Management Techniques*. Don White Consultants, Inc., vol. 11, Multi-volume EMC Encyclopedia Series, Gaithersburg, MD, 1977.
- [7] J. H. McMahon, "Capability of the FCC mobile monitoring van," in *1973 IEEE Vehicular Technology Group Symposium Record*, IEEE Cat. No. 73CH0817-7VT-A-2, IEEE, New York, 1973.
- [8] R. J. Matheson, "A radio spectrum measurement system for frequency management data," this issue, pp. 225-230.
- [9] P. C. Minor and L. E. Wood, "A new state of the art in EMC field measurement instrumentation," this issue, pp. 230-231.
- [10] G. W. Garber, "U.S. Federal Government spectrum management data bases," this issue, pp. 204-212.
- [11] L. A. Buss, "Spectrum planning for U.S. Federal Government systems," this issue, pp. 196-199.
- [12] A. D. Spaulding and G. H. Hagn, "On the definition and estimation of spectrum occupancy," this issue, pp. 269-280.
- [13] W. R. Vincent, "Examples of signals and noise in the radio-frequency spectrum," this issue, pp. 241-253.
- [14] G. H. Hagn and T. I. Dayharsh, "Land mobile radio communication channel occupancy, waiting time, and spectrum saturation," this issue, pp. 281-284.
- [15] D. King, "Chronology of the national spectrum management program," FCC Rep. SMTF 76-01, Federal Communications Commission, Washington, DC, Aug. 1976.
- [16] T. I. Dayharsh, T. J. Yung, V. E. Hatfield, R. C. Kunzelman, B. M. Sifford, K. Fukushima, and G. E. Barker, "Incorporation of monitoring data in the frequency assignment process of the FCC spectrum management task force," Final Rep., Contract FCC-0039, Stanford Research Institute, Menlo Park, CA, Jan. 1976. (Available from NTIS, Springfield, VA, as PB 234 530.)
- [17] CCIR, "World distribution and characteristics of atmospheric radio noise," Rep. 322, International Radio Consultative Committee, International Telecommunication Union, Geneva, Switzerland, 1963.
- [18] CCIR, "Man-made noise," Rep. 258-2, International Radio Consultative Committee, International Telecommunication Union, Geneva, Switzerland, 1976.
- [19] A. D. Spaulding, "Man-made noise: The problem and recommended steps toward solution," OT Rep. 76-85, U.S. Department of Commerce, Office of Telecommunications, Boulder, CO, Apr. 1976.
- [20] D. L. Means, "Microwave mobile monitoring techniques," this issue, pp. 236-240.
- [21] FCC, Contract FCC-0194-6, Georgia Institute of Technology, Engineering Experiment Station, Atlanta, GA, 1976.
- [22] J. Crenca, W. Cothran, and B. Pritchard, "Spectrum characteristics analysis and measurement (SCAM) equipment study," Rep. FAA-RD-72-131, Atlantic Research Corp., Alexandria, VA, Apr. 1973. (Available from NTIS, Springfield, VA, as AD 774 652.)
- [23] ITU, "Edition of 1976 radio regulations and additional radio regulations, appendices, resolutions and recommendations," International Telecommunication Union, Place des Nations, CH 1211, Geneva 20, Switzerland, 1976.
- [24] OTP, "Manual of regulations and procedures for radio frequency management," Office of Telecommunications Policy, Washington, DC, May 1977, and updated periodically. (Available from US Government Printing Office, Washington DC.)
- [25] FCC, "Rules and regulations," Federal Communications Commission, Washington DC, 1977.
- [26] C. L. Frederick, C. O. Forbes, and D. A. Durst, "Standards and measurements for improved spectrum utilization," Final Rep., Contract OEP-SE-68-104, Melpar, Falls Church VA, Apr. 1969.
- [27] M. N. Lustgarten, (Chairman,) and W. G. Duff, G. H. Hagn, J. S. Hill, R. J. Mohr, R. B. Schulz, and N. H. Shepherd, "Special Issue: Final Report of Ad Hoc Committee on an Electromagnetic Compatibility Figure of Merit (EMC FOM) for Single-Channel Voice Communications Equipment," *IEEE Trans. Electromagnetic Compatibility*, vol. EMC-17, no. 1, pp. 1-45, Feb. 1975.
- [28] B. R. Bean and E. J. Dutton, *Radio Meteorology*. US Department of Commerce, National Bureau of Standards, Boulder, CO, Mar. 1966.
- [29] CCIR, "Propagation in non-ionized media (Study Group 5)," in *Documents of the XIIIth Plenary Assembly*, vol. V, International Radio Consultative Committee, Geneva, Switzerland, 1974. (Available from NTIS, Springfield, VA, as PB 244 005.)
- [30] R. E. Smith and H. W. Nurdyke, "Technology assessment for spectrum management," Aerospace Rep. ATR-76(7542-03)-1, Final Rep., Contract OTP-TP5AC018, The Aerospace Corporation, Washington, DC, June 30, 1976.
- [31] L. G. Hailey, "Bird-dogging the Federal Government's use of the spectrum," this issue, pp. 199-201.
- [32] H. S. Hewitt, "The microscan signal intercept and analysis system," Electromagnetic Techniques Laboratory, Stanford Research Institute, Menlo Park, CA, Apr. 1970. See also, —, "Microscan revisited: Candidate for the agile environment," *Electron. Warfare*, vol. 8, no. 5, pp. 49-53, Sept./Oct. 1976.
- [33] R. M. Wilmotte, FCC, private communication, 1977.
- [34] R. H. Stehle, SRI International, private communication, 1977.

On the Definition and Estimation of Spectrum Occupancy

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Abstract—Spectrum occupancy for channels and bands of similar channels is defined. A distinction is made between transmission occupancy and message occupancy. The measurement time required to determine if a given channel is occupied is considered as well as the time required to estimate the degree of transmission occupancy with a given statistical confidence. Nonparametric (distribution-free) statistical techniques are employed to obtain this estimate and to determine the sample size required to establish confidence bounds for a set of channel or band transmission occupancy values.

I. INTRODUCTION

THIS PAPER defines spectrum occupancy and addresses the problem of the measurement time required to estimate the occupancy of radio channels and bands to within some accuracy limits with some given degree of confidence. There are four basic questions:

- 1) What is spectrum occupancy for a channel and for a band of similar channels?
- 2) What measurement time is required to determine if a given channel is occupied? We might term this "basic detection."
- 3) What measurement time is required to estimate the degree of occupancy (percent of total time signals exist on some given channel or in a band of similar channels)?
- 4) What statistical confidence bounds can be placed upon the sample distribution obtained from a set of occupancy estimates for a channel or band of similar channels.

We address the first question from the standpoint of providing an unambiguous definition of spectrum occupancy on a channel-by-channel basis in a manner amenable to statistical description. We address the last three questions using a minimum of assumptions concerning *a priori* knowledge about the actual structure of the messages (signals) on a channel. Nonparametric (distribution-free) statistical methods are employed to the extent possible in order to avoid continual testing of distribution hypotheses.

We start by defining a random process on which we are to perform the statistical analysis. We use this process to define precisely what we are attempting to measure (or estimate), i.e., "spectrum occupancy." The simplest case (independent samples) is treated first. This case is the most efficient in terms of estimation. Sampling rates are considered, and the case of dependent sampling is also treated. Selected channel models are presented which can be used to estimate the degree of dependency in the measurements and how this might vary

with sampling rate, transmission lengths, etc. Distributions of channel transmission occupancy values for the same channel sampled at different times are considered, and these results are extended to distributions of channel occupancy for a band of similar channels. Numerical examples are given as appropriate.

II. DEFINITION OF CHANNEL TRANSMISSION OCCUPANCY

We first define the transmission occupancy of a selected channel as a two-state random process. The first state is labeled "occupied" and is defined as the event that, during an observation, the signal strength at a monitor receiver is above a given threshold. The complementary event is that the signal strength is below this threshold. Because the state of the channel is random, its state at any given measurement time cannot be predicted. However, its state can be described in terms of a probability law. Traditionally, the unconditional probability that a random sample will be above a threshold has been defined as the "occupancy" of the channel. It has also been expressed as a percent.

If we could observe the occupancy pattern of a channel continuously for an entire hour, we could state with zero error the occupancy for that hour. But if we can make only limited observations of the occupancy pattern, then we can only estimate the occupancy for that hour. It is the task of experimental design to obtain as much information as possible concerning a random process (the random process here being the dynamic occupancy pattern) with the minimum of experimental work. If we use a scanning receiver and take some number of observations of a channel during an hour, we base our estimate of the occupancy of the channel on this number of observations.

Several time scales are important for spectrum occupancy measurements with a scanning receiver. The most basic of these is the time of an individual transmission. Ideally, the scanning receiver should sweep rapidly enough so that all signals in the monitored area are observed several times per transmission. Let us use land-mobile radio as an example. It is important to sort out the undesired impulsive noise from the desired land-mobile transmissions, as well as to record all transmissions. Hence, the shortest sampling time of interest is the time interval between consecutive observations of a given channel. The next time scale of interest, after transmission length, is the time of an individual message (which is usually composed of more than one transmission). The next time of interest is the time of sampling of a given channel. Clearly, we must sample rapidly enough and long enough to resolve the variations of interest, if we can. The other scales of interest are related to trends of use of the channels, such as hourly, daily, weekly, seasonal, and annual variations.

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Fig. 1. Transmissions on a channel.

Now, let us define channel transmission occupancy in a rigorous manner. Fig. 1 depicts our arbitrary channel.

In Fig. 1, the random variable V is the transmission length, or more precisely, the length of time a signal continuously exists above some threshold level L_i during the time interval T . The random variable W is the length of time between transmissions, and T is the total time during which measurements of the channel are made. We assume that T is large compared to the mean values of V and W . The random variables V and W have distributions, but we will not specify them.

Consider the two-valued random process: $X(t) = 1$, if signal at time t is above threshold level L_i , and $X(t) = 0$, otherwise.

The process $X(t)$ has "states" 0 and 1. V is the time continuously in state 1, and W is the time continuously in state 0. Let $X(t) = x_i$ so that our sequence of measurements, $x_1, x_2, x_3, \dots, x_n$ is represented by a sequence of 0's and 1's, where 1 means the detected power in the channel exceeds a given threshold, and 0 means that the detected power in the channel does not exceed that threshold. We are interested in $\beta(L_i, T)$, the fraction of the measurement time T , that $X(t)$ is in state 1, i.e., that the detected power in the channel exceeds threshold level L_i . Since V and W are random variables, $\beta(L_i, T)$ is a random variable which we will call channel transmission occupancy.¹

We now make two simple assumptions: V and W are independent random variables, and $V + W$ has a continuous distribution.

For our purposes, it suffices to know the behavior of the zero-one process after it has been operating for a long time. Two limit theorems provide very simple answers:

$$\lim_{T \rightarrow \infty} P[X(t) = 1] = \frac{E[V]}{E[V] + E[W]} \quad (1)$$

where $E[V]$ is the expectation or mean value of V , etc.

The fraction of time $\beta(L_i, T)$ of the interval 0 to T that the process has the value 1 for threshold level L_i is asymptotically normally distributed; i.e., for every real number x ,

$$\lim P \left[\sqrt{T} \frac{\beta(L_i, T) - m}{\sigma} \leq x \right] = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-y^2/2} dy \quad (2)$$

¹ See [1] for a discussion of the difference and relationship between transmission occupancy and message occupancy. Spectrum users are more concerned with fitting into the gaps between messages which may consist of one or more transmissions.

where

$$m = \frac{E[V]}{E[V] + E[W]} \quad (3)$$

and

$$\sigma^2 = \frac{E^2[V] \text{var}[W] + E^2[W] \text{var}[V]}{\{E[V] + E[W]\}^3} \quad (4)$$

where $\text{var}[V]$ is the variance of V , etc.

The proofs of the above are quite involved,² and the details are of no interest to us. Independent of the actual distributions of V and W , we have now defined channel transmission occupancy, $\beta(L_i, T)$ (asymptotically, at least) in terms of the means and variances of V and W . From now on we will be concerned with the determination of the single number m above. We might even call m "the average channel transmission occupancy." Note that by using the artifact $X(t)$, we have been able to use two powerful results for two-valued processes and have specified our statistical estimation problem as the problem of estimating m above. Note further that $m = P[X(t) = 1] = p$. Therefore, terming p the probability of success (i.e., obtaining a 1, or a measurement of signal above our threshold), we have framed our problem to the case of estimating the probability of success in Bernoulli trials, since our sequence of measurements has been represented as a sequence of 0's and 1's. For the case of independent trials, this is the well-known case of binomial sampling, for which many results are available ([4] and the references therein).

III. INDEPENDENT SAMPLING

Our problem, that of estimating p , the probability of success, in Bernoulli trials, has been treated in detail by Crow [4] for independent trials. We start here by considering the effect of the actual measurement time. We seldom have truly "instantaneous" measurements of the energy in a channel. We require a small measurement time t_0 , and we will demonstrate that this will not have an effect on our basic results. Suppose that N transmissions occur during time period T and that they occur via the Poisson process, i.e.,

$$p(N) = \frac{(aT)^N}{N!} e^{-aT} \quad (5)$$

where a is the mean number of transmissions per unit time (seconds). The Poisson process for the occurrence of "events" arises from very basic assumptions. The assumption (5) means that the number of changes of state in $X(t)$ or transversals (0 to 1 or 1 to 0), k , in time period T is given by

$$p(k, T) = \frac{(bT)^k}{k!} e^{-bT} \quad (6)$$

where $b = 2a$. In order for the scanning receiver system to

² For proof of (1) see Parzen [2], and for (2) see Renyi [3].

detect a signal, where t_0 is the measurement time, we have that P (detection) = $P[X(t) = 1] \times P$ [zero transversals in times t_0]. So

$$P[\text{detection}] = \frac{E[V]}{E[V] + E[W]} e^{-2at_0}. \quad (7)$$

As an example, suppose the average transmission length is 10 s = $E[V]$, the average number of transmissions per hour is 20, so $E[V + W] = 3600/20$ s, then $p = 10 \times 20/3600 = 0.0556$ (5.56 percent). Let $t_0 = 1.0 \text{ ms}^3$ so that the factor due to t_0 is $\exp[-2 \times 20/3600 \times 10^{-3}] = 0.99998$. In this example, P [detection] and p are, for all practical purposes, the same.

In the above, it would appear that we have demonstrated the obvious. However, in such problems, small things like t_0 can sometimes have big effects, and it is not safe to neglect them out of hand.

We now consider our second question regarding "basic detection." The probability of m detections in M scans (or measurements) is given by

$$\binom{M}{m} (p)^m (1-p)^{M-m} \quad (8)$$

so the probability of at least one detection (success) in M trials is

$$P = 1 - (1-p)^M. \quad (9)$$

For a 0.99 probability (say) of at least one success

$$0.99 = 1 - (1-p)^M \quad (10)$$

or for M the required number of trials (measurements),

$$M = \frac{\log[1-P]}{\log[1-p]} \quad (11)$$

where P is our required confidence (0.99 above). Table I illustrates the results obtained from (11).

For example, the above tells us that if we take 4603 measurements (on a given channel) and detect no signals, then we are 99 percent confident (99 times out of 100) that occupancy is below 0.1 percent. Remember this is for *independent* samples.

³Modern spectrum monitoring systems [5]–[7] can make many measurements in a given channel in 1 ms. The Federal Communications Commission (FCC) system van [5] typically uses 0.5 ms when sampling the nongovernment land-mobile band and the Office of Telecommunications (OT) van [6] uses 0.8 ms when sampling bands in the frequency range 100–500 MHz. The OT system currently takes 40 measurements in 0.8 ms and then uses the minimum of these measurements for the channel signal level. This technique is effective in reducing erroneous measurements due to impulsive noise. The FCC system software considers three adjacent scans and states that if a signal having an amplitude at least 6 dB above threshold is received on a particular frequency preceded and followed by signals on the same frequency having amplitudes near threshold, the higher level signal is impulse noise. Samples considered to be impulse noise are not used in the occupancy computation.

TABLE I
TRIALS (MEASUREMENTS) REQUIRED TO DETERMINE WITH
99-PERCENT CONFIDENCE IF A GIVEN CHANNEL IS
OCCUPIED (INDEPENDENT SAMPLES)

Occupancy ($p \times 100$)%	M (99% confidence)
50	7
20	21
10	44
1	459
0.1	4,603
0.01	46,050

We now give a procedure for obtaining confidence limits for the estimation of the probability of success p . We use procedures that are designed to be quite accurate for $p \leq 0.1$ (i.e., channel occupancy ≤ 10 percent). The following results are valid for any value of p , but for $p > 0.1$, other techniques are available which give somewhat "tighter" confidence limits [8]. For any fixed measurement time (number of samples), the smaller p is, the less accurate our estimate of p is, so we are primarily interested in confidence limits for small p . The situation is identical for large p ; in fact, the estimation procedures are completely symmetrical about $p = 0.5$. For $p > 0.5$, the results below are applied to the complimentary event $q(q = 1 - p)$. This then, of course, establishes confidence limits for p , $p > 0.5$.

A confidence interval (or set of confidence intervals) for p is a set of random intervals such that, whatever p is, the random interval covers p with a probability at least equal to a prescribed number called the confidence level. The confidence level is denoted as $1 - 2\alpha$; that is, for a confidence level of 0.9 (90 percent), $\alpha = 0.05$. The occurrence of successes (1's) in our sequence of measurements (n samples) is governed, for independent samples, by the binomial distribution. For large n and small p (or small q), the case we have here, it is well known that the Poisson distribution provides an excellent approximation.

If we denote the number of successes by c , and the total number of samples by n , then the "best" (in terms of unbiasedness and efficiency) point estimate of p is simply

$$\hat{p} = \frac{c}{n}. \quad (12)$$

To obtain confidence limits for this estimate we use the upper (U) and lower (L) confidence factors given by Crow and Gardner [8]:

$$\left. \begin{matrix} U \\ L \end{matrix} \right\} = c \pm \frac{1}{2} + \frac{3}{8} u_{\alpha}^2 \pm u_{\alpha} \sqrt{c \pm \frac{1}{2} + \frac{1}{8} u_{\alpha}^2} \quad (13)$$

where u_{α} is the upper 100 $\alpha/2$ percentage point of the normal distribution of mean 0 and variance 1.

Values of u_{α} are given in Table II.

If we let p_U and p_L denote the upper and lower confidence limits for p , and U and L the corresponding limits for the Poisson mean [from (13) above], then Anderson and Burstein [9], [10] have given simple but accurate confidence limits

TABLE II
CONFIDENCE LIMITS (AND LEVEL OF SIGNIFICANCE)
VERSUS u_α

Confidence	α	u_α
80%	0.1	1.282
90%	0.05	1.645
95%	0.025	1.960
99%	0.005	2.576

for p ,

$$p_U = \frac{U}{n + (U - c)/2}$$

$$p_L = \frac{L}{n - (c - 1 - L)/2} \quad (14)$$

As an example, suppose $n = 4000$ measurements and c was 80 successes, then $\hat{p} = 80/4000 = 0.02$, or we would say 2 percent channel occupancy. From (13), at the 90 percent confidence level, $U = 96.3$ and $L = 65.8$, so, from (14), $p_U = 0.0240$ and $p_L = 0.0165$. That is we are 90 percent confident that channel occupancy is between 1.65 and 2.40 percent. At the 99 percent confidence level, $U = 106.2$ and $L = 58.90$, so $p_U = 0.0266$ and $p_L = 0.0148$. If $n = 400$ and $c = 8$, $\hat{p} = 0.02$, but at the 90 percent confidence level $p_U = 0.0357$ and $p_L = 0.00981$. The accuracy of our estimate depends on the number of successes, c .

Rather than an absolute confidence interval as above, we are probably more concerned with relative accuracy, especially with p unknown, in deciding how long we must measure. A percent half-length is given, for n relatively large, by

$$\text{percent(\%)} \text{ half-length} = \frac{U - L}{2c} \times 100. \quad (15)$$

The percent half-length tells us (at a given confidence level) our relative accuracy. In the above numerical example, at the 90 percent confidence level, we have, for $c = 80$, $(U - L)/160 = 0.19$, or a relative accuracy of ± 19 percent and for $c = 8$, $(U - L)/16 = 0.656$ or a relative accuracy of ± 66 percent. The results given in (13) and (15) have been used to prepare Fig. 2. This figure gives the number of successes c required to achieve a given percent half-length of accuracy. For example, to achieve ± 10 percent relative accuracy at the 95 percent confidence level, we require about 390 successes. Or, for a channel occupancy of, say 1 percent, $c/n = 0.01$, or $n = 390(100) = 39\,000$ measurements required. Fig. 3 shows, for various relative accuracies, the number of required measurements, n , for a given channel transmission occupancy.

All the above assumed independent samples, and it makes no difference whether we take one sample per year or one sample per second. However, since our actual sampling interval is less than a typical average transmission length, we can be quite confident that we will *not* have independent samples for any reasonably dense sampling scheme. This more realistic situation of dependent sampling is covered in the next section.

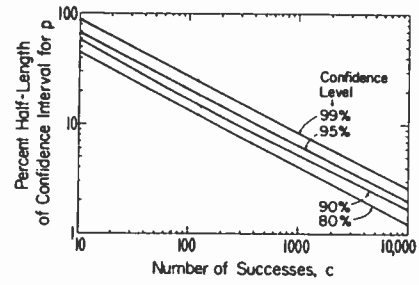


Fig. 2. Relative precision in estimating p from large samples for independent sampling.

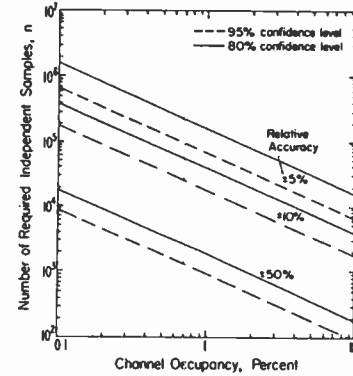


Fig. 3. Number of required independent samples versus channel occupancy.

Before proceeding however, we here mention a test to determine independence. Probably one of the easiest, and best known, tests for independent samples is the run test which is based on the *total number of runs* in a sequence of measurements. A sequence of k identical symbols that is preceded and followed by a different symbol or no symbol is called a run of length k . For example, consider the sequence

000111011010110.

There are five runs of length 1, 2 runs of length 2, and 2 runs of length 3, for a total of nine runs. The total number of runs, μ , in a sequence of independent samples is influenced by the number of 0's, N_0 , and the number of 1's, N_1 . For a large number of samples, the normal approximation of the distribution of μ is quite satisfactory:

$$E[\mu] = \frac{2N_0N_1}{N_0 + N_1} + 1 \quad (16)$$

and

$$\text{var}[\mu] = \frac{2N_0N_1(2N_0N_1 - N_0 - N_1)}{(N_0 + N_1)(N_0 + N_1 - 1)}.$$

If the observed number of runs is *less than*

$$E[\mu] = u_\alpha \sqrt{\text{var}[\mu]} \quad (17)$$

we reject the hypothesis of independence at the α significance level. Since here we use a one-sided test, μ_α is the

100 α percentage point of the normal distribution of mean 0 and variance 1. For example, if the observed number of runs is less than $E[\mu] + 2.326 \sqrt{\text{var}[\mu]}$, we reject the hypothesis of independence at the 1 percent significance level ($\alpha = 0.01$). That is we are 99 percent sure that the samples are dependent.

IV. DEPENDENT SAMPLING

In this section we will represent our sequence of 0's and 1's by a first-order Markov chain. Testing whether a sequence can be represented by a Markov chain of first order, or any order for that matter, is a special case of the problem of testing the goodness of fit of a general Markov chain, which has been discussed extensively in the statistical literature. For a summary of such tests see Crow and Miles [11]. Many more complicated mathematical models have been suggested, but for situations of interest to us here, the complex results from such complex models differ little from first-order Markov results.

By a first-order Markov chain, we mean that the probability of success on the i th trial depends on what happened on the $i - 1$ th trial, but not on the $i - 2$ nd trial, etc. We assume that the Markov process has been operating for a long time and has achieved steady-state conditions. As before, we have $P[x_i = 1] = p$, and we are interested in estimating p . We have two constant parameters

$$\begin{aligned} p &= P[x_i = 1] \\ \lambda &= P[x_i = 1 | x_{i-1} = 1] \end{aligned} \quad (18)$$

where $P[|]$ indicates the conditional probability of the event given first occurring, given that the event given second has occurred. We have the following

$$\begin{aligned} P[x_i = 0] &= 1 - p = q \\ P[x_i = 0 | x_i = 1] &= 1 - \lambda. \end{aligned} \quad (19)$$

The second relation in (19) simply says that the process must go from state 1 either to state 1 (probability λ) or to state 0 (probability $1 - \lambda$). If we let

$$\phi_{k1} = P(x_i = k | x_{i-1} = 1), \quad k, 1 = 0, 1 \quad (20)$$

then the steady-state equations for our process are

$$\begin{aligned} q &= q\phi_{00} + p\phi_{01} \\ p &= q\phi_{10} + p\phi_{11}. \end{aligned} \quad (21)$$

Solving, we obtain

$$\begin{aligned} \phi_{00} &= P[x_i = 0 | x_{i-1} = 0] = \frac{1 - 2p + \lambda p}{q} \\ \phi_{01} &= P[x_i = 1 | x_{i-1} = 0] = \frac{p(1 - \lambda)}{q}. \end{aligned} \quad (22)$$

The four ϕ_{k1} 's are termed the "transition probabilities." In the above, the probability properties of an entire sequence

of n samples are determined by p , λ , and n . Also, $\lambda = p$ means the samples are independent, and $\lambda > p$ means the 1's and 0's cluster. Our problem is now to estimate p for a given λ or to estimate both p and λ . The larger λ is, the more dependent our samples are.

As before, we first consider the question of "basic detection," and we let P denote the probability of at least one success in M trials [and p is the probability of success (signal)]. Let $n_M(1)$ be the number of 1's in M samples. Then

$$\begin{aligned} P &= \Pr [n_M(1) \geq 1] = 1 - P_r[n_M(1) = 0] \\ P &= 1 - \Pr [x_1 = 0] P_r[\text{next } M - 1 \text{ samples are zero}] \\ P &= 1 - \Pr [x_1 = 0] [p(x_i = 0 | x_{i-1} = 0)]^{M-1} \end{aligned}$$

or

$$1 - P = q \left[\frac{1 - 2p + \lambda p}{q} \right]^{M-1}. \quad (23)$$

Solving for M , we have

$$M = \frac{\log(1 - P) - \log(1 - p)}{\log \frac{(1 - 2p + \lambda p)}{1 - p}} + 1. \quad (24)$$

Previously, for independent samples, we saw that at the 99 percent confidence level and for 1 percent occupancy, M was 459. Suppose $\lambda = 0.6$. Now for $P = 0.99$, $p = 0.01$ as before, from (24), $M = 1136$. That is, now to be 99 percent confident that occupancy is less than 1 percent, we need 1136 measurements of no signal.

Obviously, λ is a function of the transmission length statistics and our sampling rate.

We now consider the problem of estimating p for the case of dependent samples. Klotz [12] derived estimates of p and λ that are consistent and asymptotically normally distributed. They are

$$\hat{p} = c/n \quad (25)$$

and

$$\begin{aligned} \hat{\lambda} &= \frac{1}{2} (c - \hat{p})^{-1} [r - c + t + (2c - t - 1)\hat{p} + \{(r - c + t \\ &\quad + (2c - t - 1)\hat{p})^2 + 4r(c - \hat{p})(1 - 2\hat{p})\}^{1/2}] \end{aligned} \quad (26)$$

where

$$r = \sum_{i=2}^n x_{i-1}x_i, \quad c = \sum_{i=1}^n x_i, \quad t = x_1 + x_n. \quad (27)$$

An intuitive estimate of λ , not making full use of the data, is the relative frequency estimate.

$$\lambda^* = \frac{r}{c - \hat{p}}. \quad (28)$$

The simplest and most appropriate confidence limits for p for cases of interest here ($p \leq 0.1$, large sample size) have been developed by Crow and Miles [11] as a modification to the Anderson-Burstein limits [9], [10] for independent samples discussed in Section III:

$$\begin{aligned} p_U &= \hat{p} + (p_{UI} - \hat{p}) \left(\frac{1 + \hat{p}}{1 - \hat{p}} \right)^{1/2} \\ p_L &= \hat{p} - (\hat{p} - p_{LI}) \left(\frac{1 + \hat{p}}{1 - \hat{p}} \right)^{1/2} \end{aligned} \quad (29)$$

where p_{UI} and p_{LI} are the Anderson-Burstein limits for independent samples, and

$$\hat{p} = \frac{\hat{\lambda} - \hat{p}}{1 - \hat{p}}. \quad (30)$$

If the p_L calculated from (29) turns out to be negative, then (29) should be replaced by

$$p_U = (p_{UI} - p_{LI}) \left(\frac{1 + \hat{p}}{1 - \hat{p}} \right)^{1/2}, \quad p_L = 0. \quad (31)$$

In terms of relative precision, for large n , the percent half-length is, from (29) or (31),

$$\frac{U - L}{2c} \times 100 = \left(\frac{UI - LI}{2c} \right) \left(\frac{1 + \hat{p}}{1 - \hat{p}} \right)^{1/2} \times 100 \quad (32)$$

where UI and LI now denote the upper and lower confidence factors for independent samples [from (13)].

In order to use the above, we need an estimate of λ . This can be obtained from the actual measurements via (26) or (28) or calculated from some assumed channel model.

Suppose we are given the maximum value of λ expected, $\lambda_{\max}$. If we let c_{ind} be the number of successes required to achieve a given relative accuracy at some confidence level for independent samples (Fig. 2), then, to achieve the same prescribed precision approximately, the number of successes required for dependent samples is given in [11] by:

$$c = c_{\text{ind}} \left(\frac{1 + \lambda_{\max}}{1 - \lambda_{\max}} \right). \quad (33)$$

The next question is that of stationarity. If it is believed that p and/or λ may change during the acquisition of data, the data should be separated into subsamples considered to be homogeneous and tested for differences between the subsamples. Crow and Miles [11] gave procedures for doing this.

An Example

Suppose we have 40 transmissions per hour and our average transmission length is 6 s, then $E[V] = 6$, $E[W] = 84$, and transmission occupancy = $E[V]/E[V + W] = 6/90 = 6.67$ percent. Suppose we want to estimate p to ± 10 percent relative

accuracy at the 95 percent confidence level. For independent samples, Fig. 2 tells us that we need 390 successes, or, for the above situation, $n = 390/0.0667 = 5850$ measurements. Let us denote our sampling time interval of τ and let $\tau \approx 4$ s.⁴ That is, any given channel has a measurement taken every 4 s. Suppose the transmission lengths above are exponentially distributed with mean value 6 s. A recent study by Lauber and Macklon [13] shows that the usually assumed exponential distribution for transmission lengths is a reasonable assumption—at least for some channels. We use this assumption here, however, only to get an estimate of λ . We have

$$p_V(v) = ae^{-av}, \quad a = 1/6$$

$$P[x_i = 1 | x_{i-1} = 1] = P[V \geq \tau] = \int_{\tau}^{\infty} ae^{-ax} dx = e^{-a\tau}.$$

The above result is independent of where, during a message, x_{i-1} occurs. This is due to the "memorylessness" property of the exponential distribution. The exponential distribution is the only distribution that has this property. [Note that, if we know that the message lengths are exponentially distributed, then we can estimate the average message length from an estimate of λ via (26) or (28). That is, $a = -(\ln \lambda)/\tau$. For $\tau = 4$ s then

$$\lambda = e^{-4/6} = 0.513.$$

If we decide this value of λ is the maximum we expect, then the required number of successes to achieve the same relative accuracy as above (± 10 percent, 95 percent confidence) is

$$c = 390 \left(\frac{1 + 0.513}{1 - 0.513} \right) = 1212$$

or $n = 1212/0.0667 = 18\,166$. At a measurement every 4 s, then, for independent samples, we require a measurement time of 6.5 h, but for dependent samples ($\lambda = 0.513$), we need a measurement of time of 20.2 h. Many channels of interest may not be stationary over such a long interval because of diurnal variations of channel usage.

Another Example

Suppose we have three bands and we can scan each band in 4 s. Suppose we want ± 10 percent relative accuracy at the 95 percent confidence level; then, for independent samples, we require 390 successes. We want to determine channel occupancy for all channels in the three bands with the above relative accuracy down to occupancy of 5 percent. We consider two options:

- 1) Scan the first band for the required amount of time and then go to the second band, etc.
- 2) Scan all three bands together.

⁴ A current procedure [6], for example, scans a band of channels such that each channel is revisited every 4 s.

Obviously, for independent samples, there is no difference between options 1) and 2). Suppose, now, we assume transmission length statistics as in the above example ($E[V] = 6$ s, etc.) and that this is true for all channels of the three bands. Under option 1),

$$\lambda = e^{-4/6} = 0.513$$

and the number of successes we require is, therefore, 1212. Then, $n = 1212/0.05 = 24\,240$ scans or a measurement time of 27 h/band for a total measurement time of 81 h.

Under option 2),

$$\lambda = e^{-12/6} = 0.135$$

so, now, the minimum number of successes required is

$$390 \left(\frac{1 + 0.135}{1 - 0.135} \right) = 512.$$

Then, $n = 512/0.05 = 10\,240$ scans, or a total measurement time of $12 \times 10\,240/3600 = 34$ h.

Suppose we want ± 10 percent relative accuracy at the 95 percent confidence level, occupancy down to 0.1 percent ($p = 0.001$). For option 1), $\tau = 4$ s and $\lambda = 0.513$. We require 1212 successes:

$$n = \frac{512}{0.001} = 512\,000 \text{ scans or } 1347 \text{ h/channel}$$

or

$$3 \times 1347 = 4040 \text{ h total measurement time.}$$

For option 2),

$$n = \frac{512}{0.001} = 512\,000 \text{ scans}$$

so total measurement time is

$$\frac{12 \times 512\,000}{3600} = 1707 \text{ h.}$$

Suppose now we want down to 0.1 percent ($p = 0.001$) occupancy but ± 50 percent relative accuracy at 80 percent confidence level, so

$$c_{\text{ind}} = 9 \text{ samples.}$$

For option 1),

$$c = 9 \left(\frac{1 + 0.513}{1 - 0.513} \right) = 28$$

$$n = \frac{28}{0.001} = 28\,000 \text{ scans or } 31 \text{ h/band}$$

total time = 3×31 or 93 h.

For option 2),

$$c = 9 \left(\frac{1 + 0.135}{1 - 0.135} \right) = 12$$

$$n = \frac{12}{0.001} = 12\,000 \text{ scans}$$

on total time = $(12 \times 12,000)/3100 = 41$ h.

One possible area of concern, statistically, is whether a little used channel would exhibit the same sort of discipline as a heavily used channel. In a crowded channel, the user is likely to use procedures to minimize actual time on the air (e.g., the "10 code"). These would tend to make transmissions shorter on heavily used channels. On the other hand, the user of a little used channel has no reason to be efficient and may feel more sure of himself if he talks a bit more. Therefore, the transmissions on a little used channel may average several times the length of those on a heavily used channel. Suppose we have $p = 0.001$ to measure, and the average transmission length is now 30 s. Then $\lambda = \exp(-\tau/30)$, so that for $\tau = 4$ s, $\lambda = 0.875$, and for $\tau = 12$ s, $\lambda = 0.670$. For option 1), 95 percent confidence, ± 10 percent relative accuracy,

$$c = 390 \left(\frac{1 + 0.875}{1 - 0.875} \right) = 5859$$

or

$$n = 5\,859\,000 \text{ scans per band}$$

so total time = $(3 \times 4 \times 5\,859\,000)/3600 = 19\,530$ h.

For option 2), 95 percent confidence, ± 10 percent relative accuracy,

$$c = 309 \left(\frac{1 + 0.670}{1 - 0.670} \right) = 1977$$

or total measurement time = $(12 \times 1\,977\,000)/3600 = 6590$ h.

The above examples show that if we insist on tight relative accuracy with high confidence for small p , the required measurement times can quickly become quite large.

The Example of Section III [Following (14)] for Dependent Samples

As in Section III, suppose n was 4000 measurements and c was 80 successes. We saw that the $\hat{p} = 0.02$ and that at the 90 percent confidence level and for independent samples, $p_{UI} = 0.0240$ and $p_{LI} = 0.0165$. Suppose now we know that $\lambda = 0.6$. Then, from (29) and (30) we have

$$\hat{p} = \frac{0.6 - 0.02}{1 - 0.02} = 0.592$$

$$p_U = 0.02 + (0.0240 - 0.02) \left(\frac{1 + 0.592}{1 - 0.592} \right)^{1/2}$$

$$p_U = 0.0279$$

$$p_L = 0.02 - (0.02 - 0.0165) \left(\frac{1 + 0.592}{1 - 0.592} \right)^{1/2}$$

$$p_L = 0.0131.$$

Or, we are 90 percent confident that p is between 1.31 and 2.79 percent. For independent samples, the relative accuracy was ± 19 percent with dependent samples from (32), the relative accuracy is

$$\pm 19 \left(\frac{1 + 0.592}{1 - 0.592} \right)^{1/2} = \pm 37.5 \text{ percent.}$$

For further examples and results, see Appendix I. An example of data obtained in two channels during the same hour are examined in Appendix II to illustrate the lack of stationarity which can be encountered in practice.

V. DISTRIBUTIONS OF CHANNEL OCCUPANCY VALUES

The previous sections have defined channel transmission occupancy as a random variable and have established confidence bounds on individual occupancy estimates obtained by sampling a channel through the use of distribution-free (non-parametric) statistics. This single value, m , is applicable only for time periods for which the channel statistics remain stationary. We do not expect stationary statistics over long time periods (daytime versus night-time, Monday versus Sunday, for example). For these long-term variations, we will have a number of occupancy values which we want to use to make statements like: The channel transmission occupancy is greater than 50 percent more than 80 percent of the time, etc. Also, we may want to discuss occupancy for a band of channels and make statements like: 62 percent of the channels in the band have occupancies greater than 40 percent etc. In short, we are interested in distributions of channel transmission occupancy values. This section will consider such distributions and a means of placing confidence limits on such distributions.

The average occupancy m of the h th channel for threshold level L_i over the j th time interval T_j , defined in the preceding sections, forms the basic building block of the cumulative distribution function of channel occupancy over the much longer time interval T_k . Over a long time interval T_k , we have η values of occupancy for a channel of interest C_h . From the previous sections, we let $m = O(C_h, L_i, T_j, T_k)$ = transmission occupancy. The η values of $O(C_h, L_i, T_j, T_k)$ computed will be rank ordered, normalized to obtain any estimate of the probability of a given occupancy level, and plotted as a function of occupancy (O_c) to generate the cumulative distribution function (CDF) for the interval T_k . The occupancy data for a given threshold over this time interval can be neatly summarized on a diagram as illustrated in Fig. 4. This process can then be repeated for the other thresholds, which can then be plotted on the same diagram. [A corresponding situation is the cumulative distribution of η values of channel occupancy for h channels forming a band of channels].

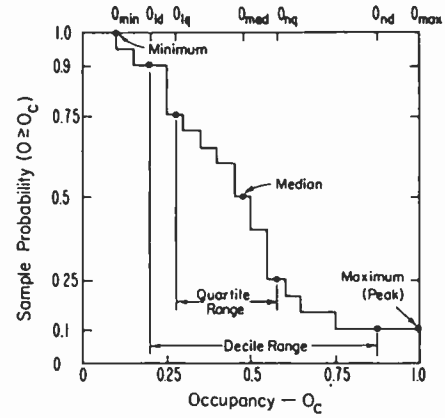


Fig. 4. Hypothetical example of sample cumulative distribution function of channel occupancy for time interval T_k , h th channel, and threshold L_i .

Such a plot is a very useful summary, because one can read directly from it the following occupancy measures for the channel for interval T_k :

peak (O_{max})

median (O_{med})

minimum (O_{min})

quartiles (O_{uq}, O_{lq})

deciles (O_{ud}, O_{ld})

quartile range

decile range.

The cumulative distribution functions also provide the vehicle, when coupled with distribution-free statistics, for putting confidence limits on the measured occupancy cumulative distribution.

One nonparametric measure of the deviation between the sample distribution $F_\eta(x)$, and the "true" occupancy distribution, $F(x)$, is the Kolmogorov-Smirnov (KS) statistic, $\sqrt{\eta}$ supremum $|F_\eta(x) - F(x)|$, [14]-[17]. The KS statistic is based on independent samples.

The KS statistic is useful for determining the sample size (η) required to approximate the occupancy cumulative distribution function, $F(x)$, by the sample distribution function $F_\eta(x)$ within a prescribed accuracy with a prescribed level of confidence. For example, if we have the hypothesis that the distributional error never exceeds ± 0.15 (± 15 percent), then $\eta > 80$ is required for the hypothesis to be accepted at the 95 percent confidence level (see Fig. 6). Tables of this statistic have been given by Massey [14] for levels of significance (α = Type I error) of 0.20, 0.15, 0.10, 0.05, and 0.01, which correspond to confidence levels of 80, 85, 90, 95, and 99 percent, respectively. Figs. 5 and 6 give the half-length confidence interval versus sample size η in terms of the confidence level ($1 - \alpha$) that the hypothesis is accepted, given that it is true.

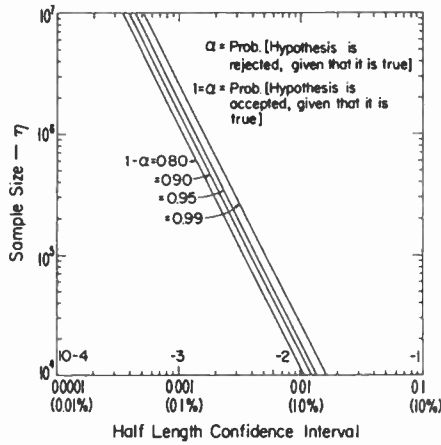


Fig. 5. Number of required samples, η , for a given half-length confidence interval for the distributional error.

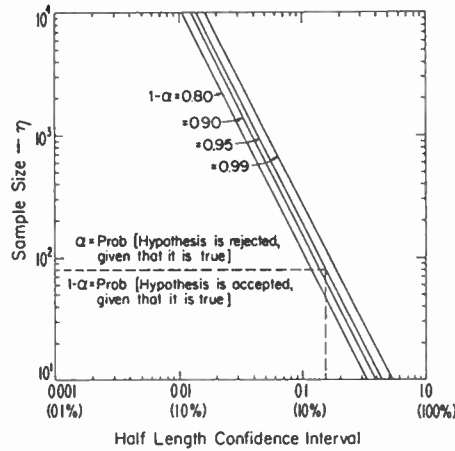


Fig. 6. Number of required samples, η , for a given half-length confidence interval for the distributional error.

When the sample size $\eta > 35$, then Smirnov's [18], [19] asymptotic forms can be used [14]:

$$\epsilon_{\eta,0.95} \cong 1.3581 \eta^{-1/2}$$

$$\epsilon_{\eta,0.99} \cong 1.6276 \eta^{-1/2}.$$

The KS statistics are applicable to independent observations with a common (unknown) continuous distribution function $F(x)$. We note in passing that the KS statistics can also be used to test the goodness of fit of a completely specified cumulative distribution [14]–[16].

Let us now consider an example CDF: a land-mobile channel in Chicago [20]. The CDF data shown in Figs. 7 and 8 were obtained for a Special Emergency channel (33.080 MHz) on the same day, at approximately 0700 and 0900. Invalid data consisting of impulsive noise (IN) samples and intermodulation products (IM) were removed, using the methods discussed by McMahon [5].⁵ At 0652 hours local time, the

⁵ The IM algorithm used a 3-dB attenuator switched in and out on alternate scans of a given channel ($\tau = 0.5$ ms). This algorithm was conservative in that it tended to reject valid data with contained amplitude fluctuations ≥ 6 dB (e.g., due to propagation) occurring during 1 ms.

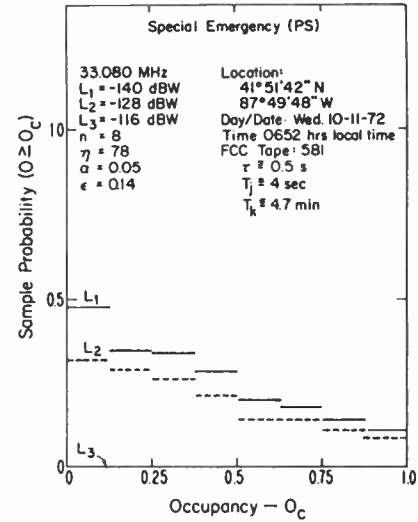


Fig. 7. CDF of lightly loaded 33-MHz channel.

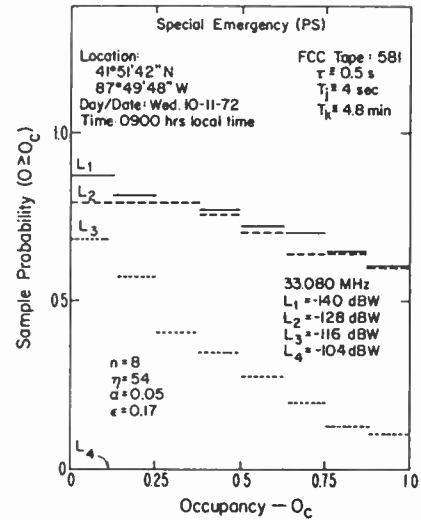


Fig. 8. CDF of relatively heavily loaded 33-MHz channel.

channel was lightly loaded, but at 0900 hours the usage of the channel had greatly increased. This can easily be seen by comparing CDF's.

At 0652 hours, there were 627 valid samples with only one case of IN and six cases of IM. The average transmission time was 2 s. The maximum observed level was -117 dBW, and the minimum observed level was -163 dBW. The mean transmission occupancy values, m , computed over the entire 4.7-min interval were 26, 24, and 19 percent for -140 , -134 , and -128 -dBW thresholds, respectively; the occupancy was zero for higher thresholds. At 0900 there were only 435 valid samples with three cases in IN and 206 cases of IM. The average transmission time was 1.7 s, and the maximum and minimum observed levels were -110 dBW and -151 dBW, respectively. For L_2 (-128 -dBW threshold), the mean transmission occupancy level for the entire 4.8-min interval was 72 percent, and it increased to only 74 percent at L_1 (the -140 -dBW threshold). The occupancy level dropped off to 35 percent at L_3 (the -116 -dBW threshold) and to only 1 percent at a threshold of -110 dBW.

About 15 percent of the data were discarded for the 0652 hours sample and about 30 percent of the 0900 hours sample. Nevertheless, the confidence bound $\epsilon_{\eta,0.95}$ (Smirnov's asymptotic form) increased only from about 0.14 to 0.17, a much better result than if whole blocks of data had been discarded because small sections were invalid.

As noted previously, the methodology for placing confidence bounds on the CDF of a channel can be used for bands of channels. For example, one might compute for the same time interval T_h the median occupancy for each of h channels in a band of similar channels. The CDF for the band occupancy could then be computed, and confidence bounds could be applied using the KS statistics. Such band occupancy statistics could be used to study the time variation of band usage over longer periods of time.

VI. CONCLUSIONS

This paper has defined channel transmission occupancy as a measure of a random process: specifically, the quantity $\beta(L_i, T)$ is the fraction of time T that the received power in the channel exceeds the threshold level L_i . We have shown how, independent of the actual statistical distributions of the individual transmission lengths (V) and the gaps between these transmissions (W), we can describe $\beta(L_i, T)$ asymptotically in terms of the means and variances of V and W over the interval T . The problem of estimating transmission channel occupancy has been reduced to the problem of estimating $p(=m)$, the probability of success in Bernoulli trials, a problem for which many results are in the literature. We have examined how long it takes to measure m to a given accuracy with a given level of confidence for both independent and dependent samples— independent of the actual transmission structure on the channel. We have discussed a method for determining the independence of the samples as well as the time stationarity of the sequence of samples. Once a minimum value of m is set, it is possible, previous to making measurements, to determine the measurement time required to determine m to within a given relative accuracy with a given level of confidence (the degree of dependence between measurement samples, λ , must also be assumed, or estimated). We have explored the tradeoffs between measurement time and measurement accuracy, and shown that if it is desired to get extremely accurate estimates of low-occupancy (or high-occupancy) channels that there may be a problem with lack of sufficient stationarity, due to the required large measurement times.

After discussing the measurement of mean transmission occupancy, m , we showed how a group of m values could be rank-ordered and normalized to form an occupancy cumulative distribution function (CDF) for a channel or for a band of similar channels. Confidence bounds on the CDF were computed using distribution-free techniques that are useful in estimating (before the measurement) the number of m samples required to estimate the occupancy distribution function to a given accuracy with a given level of confidence. Finally, it should be noted that CDF's can be generated on level for a fixed time as well as on time for a fixed level. The same statistical methods would pertain.

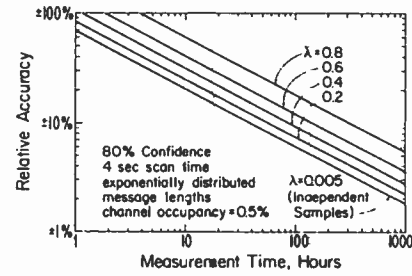


Fig. 9. Measurement time for various degrees of sample dependence, λ .

APPENDIX I

FURTHER RESULTS AND EXAMPLES

We use the results obtained previously to develop various figures that illustrate the kind of results possible. The basic results are those of Fig. 2 and all others proceed directly from the number of successes c . The first of the figures (Fig. 9) gives measurement time versus relative accuracy for various channel occupancy levels. On Fig. 9 we assume 80 percent confidence, and exponentially distributed transmission lengths with a mean of 6 s, so that, as we saw previously, $\lambda = 0.513$. The relative accuracy is given by (32). For example, for 5 percent occupancy, or $\hat{p} = 0.05$, we obtain from (30) that $\hat{\rho} = 0.487$, and then from (32) for ± 5 percent relative accuracy,

$$\left(\frac{UI - LI}{2c} \right) = 0.05 \left(\frac{1 - \hat{\rho}}{1 + \hat{\rho}} \right)^{1/2} = 0.0293 \text{ or } 2.93 \text{ percent.}$$

Then from Fig. 2, the required c is 1800; therefore

$$\text{measurement time} = \frac{\left(\frac{1800}{0.05} \right) \times 4 \text{ s}}{3600 \text{ s/h}} = 40.0 \text{ h.}$$

Notice that if we use the approximate upper bound expression (33) with $\lambda_{\max} = 0.513$, c is 2019, and the measurement times is 44.9 hr. This example points out that (33) gives an approximate result (upper bound), but (32) is somewhat easier to compute. Fig. 9 was developed via (32).

As we have seen, the required measurement time critically depends on the parameter λ , which, in turn, depends on the transmission length statistics and the rate at which we take measurements on any given channel. Using the assumption of exponentially distributed transmission lengths, for example, we have seen that

$$\lambda = \exp \left[- \frac{\text{measurement interval}}{\text{average transmission length}} \right].$$

Fig. 10 shows the effect of λ on measurement time, where we have chosen 80 percent confidence, channel occupancy of 0.5 percent ($p = 0.005$), exponentially distributed transmissions, and a 4-s scan time.

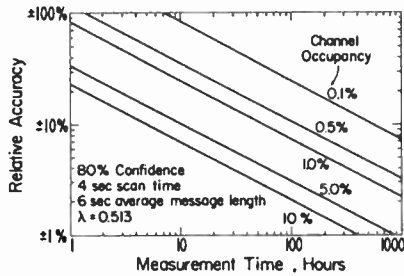


Fig. 10. Measurement time versus relative accuracy for various channel occupancies.

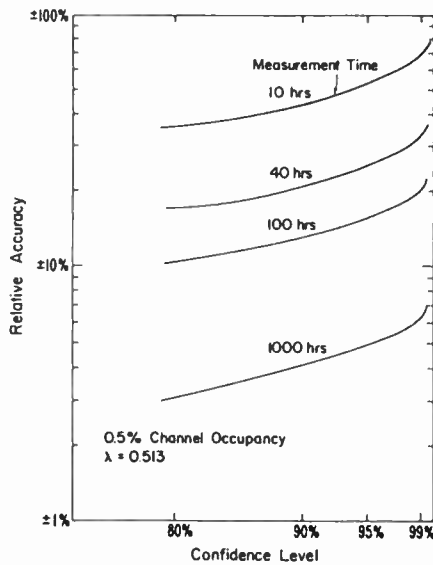


Fig. 11. Relative accuracy versus confidence level for various measurement times.

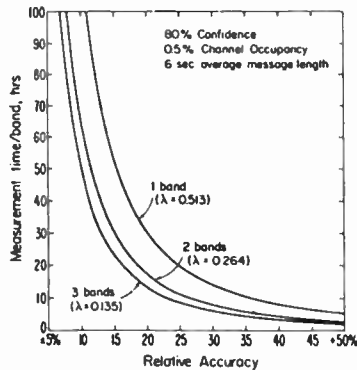


Fig. 12. Measurement time per band versus relative accuracy.

Fig. 11 shows the relationship between relative accuracy and confidence level for various measurement times. A channel occupancy of 0.5 percent ($p = 0.005$) is used with a scan time of 4 s and exponentially distributed transmissions with 6-s average length.

On Fig. 12, the difference in required measurement time between scanning one band at a time and scanning more than one band is shown. Fig. 12 shows the measurement time *per band*. As before, each band can be scanned in 4s, and exponentially distributed messages of 6-s average length are assumed. Suppose we have three bands and want ± 20 percent

relative accuracy for channel occupancies down to 0.5 percent. We see from Fig. 12 that, if each band is scanned separately, each band requires 30.5 h of measurement time, or a total of 91.5 h for all three bands. However, if all three are scanned together (so that the sampling interval for each channel is 12 s rather than 4 s) then the measurement time per band is 13.3 h, or a total required time of 39.9 h.

APPENDIX II

EXAMPLES OF CHANNEL TRANSMISSION OCCUPANCY COMPUTED OVER DIFFERENT TIME INTERVALS DURING THE SAME HOUR

Monitoring data [20] were obtained by the FCC for a period of several hours on January 17, 1973 at the City of Chicago South Water Filtration Plant, 3200 East 78th Street ($41^{\circ}45'24''N$, $87^{\circ}32'36''W$), as part of a special test. For this test we have data in 5-min simple data sets (i.e., $T_j = 300$ s) for every other 5-min period over several consecutive hours. Each channel was sampled about every 0.5 s for the period between approximately 1530 and 1720 hour local time. Data in two 150-MHz business radio channels from the first hour of observation were reduced as simple and compound data sets to illustrate the compound technique and, more importantly, to show how transmission occupancy computed for a 5-min interval can differ from that computed over longer periods up to an hour.

The two channels studied were 151.865 and 151.895 MHz. Occupancy was computed for seven thresholds for each channel for the first 5 min (simple data sets beginning at 1531 hour), after the invalid data had been removed. The results of these calculations are given in Table III. Also shown in this table are the number of valid samples, the number of invalid data (IN and IM), and the maximum and minimum observed signal levels. Next, a compound data set was formed for each channel by using the first (simple) data set for the given channel and data from the next available 5-min period (which actually began 10 min after the beginning of the first set). The transmission occupancy calculations were then repeated; they are recorded in Table III in the rows labeled 10 min. Finally, all the similar data obtained during the first hour were combined to give transmission occupancy values computed over the equivalent of a 30-min period (see Table III). These tests revealed some interesting things, as discussed below.

The 151.865-MHz channel was essentially unoccupied over the first 5 min; and the same situation existed from the 10-min sample (Table III). A relative increase in occupancy was noted for the 30-min sample. On an absolute scale, the channel was still lightly loaded, but the 5- and 10-min samples (while similar to each other) were not good estimators of the 30-min sample.

In the 151.895-MHz channel, also lightly loaded, a significant increase in activity was observed between the 5- and 10-min samples. The data taken during the 10-min sample were reasonably representative of those taken during the first hour (the 30-min sample in Table III) for thresholds above -140

TABLE III
CHANNEL TRANSMISSION OCCUPANCY FOR DIFFERENT
SAMPLE INTERVALS DURING THE SAME HOUR

Frequency (MHz)	Total Interval Scanned (min)	Total Elapsed Time (min)	Mean Transmission Occupancy vs. Threshold (percent)							No. of Samples			Signal (dBW)	
			-140 dBW	-134 dBW	-128 dBW	-122 dBW	-116 dBW	-110 dBW	-104 dBW	Valid	IN	IM	Maximum	Minimum
151.865	5	5	5.0%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	378	4	2	-127	-160
151.865	10	15	6.0	1.0	0.5	0.0	0.0	0.0	0.0	722	4	42	-124	-161
151.865	30	55	9.6	3.9	2.9	1.4	0.7	0.4	0.0	2093	31	323	-106	-161
151.895	5	5	11.0	2.0	1.0	1.0	1.0	1.0	0.0	366	8	10	-105	-159
151.895	10	15	11.5	5.0	4.0	3.5	3.0	2.0	0.0	721	18	29	-105	-160
151.895	30	55	11.1	4.1	3.9	3.3	2.5	1.4	0.4	2298	42	107	-104	-160

dBW. The data taken during the first 5 min were reasonably representative of the first hour, for the -140-dBW threshold (about 20 dB above the level of the minimum observed "signal"). This sample illustrates the need to consider threshold level when evaluating how representative data from a given 5-min interval are for the hour from which they came. One might expect greater similarity of occupancy data on lower thresholds, especially near the noise level.

A conclusion from this brief study of time stationarity (in the loose sense) is that it is important to try different groupings of the same data when evaluating the adequacy of any sampling plan that looks at each channel for only 5 min of each hour. More data should be taken over longer continuous intervals, and attention should be given to the results for channels with greater occupancy than the two cited here.

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REFERENCES

- [1] G. H. Hagn and T. I. Dayharsh, "Land mobile radio communication channel occupancy, waiting time, and spectrum saturation," this issue, pp. 281-284.
- [2] E. Parzen, *Stochastic Processes*. San Francisco, CA: Holden-Day, 1962, pp. 184-185.
- [3] A. Renyi, "On the asymptotic distribution of the sum of a random number of independent random variables," *Acta Math. Acad. Scient. Hung.*, vol. 8, pp. 193-199, 1957.
- [4] E. L. Crow, "Confidence limits for digital error rates," Office of Telecommunications, US Department of Commerce, Boulder, CO, Rep. 74-51, Nov. 1974.
- [5] J. H. McMahon, "Capability of the FCC mobile monitoring van," in *1973 IEEE Vehicular Technology-Group Symp. Rec.*, IEEE Cat. No. 73CHO817-VT-A-2, 1973.
- [6] R. J. Matheson, "A radio spectrum measurement system for frequency management data," this issue, pp. 255-230.
- [7] P. C. Minor and L. E. Wood, "A new state of the Art in EMC field measurement instrumentation," this issue, pp. 230-236.
- [8] E. L. Crow and R. S. Gardner, "Table of confidence limits for the expectation of a Poisson variable," *Biometrika*, vol. 46, Pts. 3 and 4, pp. 441-453, Nov. 1959.
- [9] T. W. Anderson and H. Burstein, "Approximating the upper binomial confidence limit," *J. Amer. Statist. Assoc.*, vol. 62, pp. 857-861, 1967.
- [10] —, "Approximating the lower binomial confidence limit," *J. Amer. Statist. Assoc.*, vol. 63, pp. 1412-1415, 1968.
- [11] E. L. Crow and M. J. Miles, "Confidence limits for digital error rates from dependent transmissions," Office of Telecommunications, US Department of Commerce, Boulder, CO, Rep. No. 77-118, Mar. 1977.
- [12] J. Klotz, "Statistical inference in Bernoulli trials with dependence," *The Annals of Statistics*, vol. 1, no. 2, pp. 373-379, 1973.
- [13] W. R. Lauber and W. E. Macklon, "A VHF spectrum occupancy pilot project," Communications Research Centre, Ottawa, Canada, Rep. 1289, 1976.
- [14] F. J. Massey, Jr., "The Kolmogorov-Smirnov test for goodness of fit," *J. Amer. Statist. Assoc.*, vol. 46, pp. 68-78, Mar. 1951.
- [15] W. C. Hoffman, "Some statistical methods of potential value in radio wave propagation investigations," in *Statistical Methods of Radio Wave Propagation*. New York: Pergamon, 1960, pp. 117-135.
- [16] A. H. Bowker and G. J. Lieberman, *Engineering Statistics*, 2nd ed., Englewood Cliffs, NJ: Prentice-Hall, 1972, pp. 452-458.
- [17] Z. W. Birnbaum, "Numerical tabulation of the distribution of Kolmogorov's statistic for finite sample size," *J. Amer. Statist. Assoc.*, vol. 47, Sept. 1952.
- [18] H. Smirnov, "Sur les Écarts de la Courbe de Distribution Empirique," *Recueil Mathématique (Matematicheskii Sbornik, N.S.)*, vol. 48, pp. 3-26, 1939.
- [19] N. Smirnov, "Table for estimating the goodness of fit of empirical distributions," *Annals of Mathematical Statistics*, vol. 19, pp. 279-281, 1948.
- [20] G. H. Hagn and T. I. Dayharsh, "Technical assistance for the FCC national and regional spectrum management program," Stanford Research Institute, Menlo Park, CA, Final Rep., Contract RC-10177, SRI Project 8652-1, Jan. 1973 (available from NTIS, Springfield, VA, as PB 243 687).

A Radio Spectrum Measurement System for Frequency Management Data

ROBERT J. MATHESON

Abstract—Since 1973, the U.S. Office of Telecommunications has been operating a Radio Spectrum Measurement System (RSMS) for the Office of Telecommunications Policy (OTP) in support of federal frequency management processes. The RSMS is a van-deployed computer-controlled receiving system designed to make many different types of measurements between 100 MHz and 12 GHz. The RSMS has been used in measurement programs on selected Federal Government communication and radar bands in many high spectrum usage areas in the United States. This paper discusses the capabilities of the RSMS van, and uses some measured data as examples of those capabilities.

I. INTRODUCTION

EFFECTIVE frequency management depends on knowing what systems are currently using the electromagnetic spectrum and what their characteristics are. Usually, most of these data come from frequency management records. In some cases, however, environmental measurements may be required to provide additional information. One major use of these measurements is to establish what sort of confidence may be placed in the accuracy of frequency management records and to show how the data in these records relate to the environment that a potential user would encounter. Radio spectrum usage, as distinct from assignments, is a particularly important type of frequency management data which is often obtained by environmental measurements. Measurements also provide data to be incorporated into models, operating standards, and frequency allocation decisions, and are used to test the accuracy of existing models and other prediction techniques.

The RSMS van was developed to provide useful data for the frequency management process [1]. Since the system was delivered in April 1973, the Office of Telecommunications (OT) has undertaken spectrum occupancy measurement programs in and around Washington, DC, Norfolk, VA, Los Angeles, CA, San Francisco, CA, and El Paso, TX, [2]–[4]. The primary objective in the communication measurements is to determine channel occupancy for each assignment and to correlate channel usage with assignment records. Several radar bands were also measured. The object in these measurements is to identify operating radars and measure their emission characteristics, comparing these observations with frequency assignments and operating standards. In addition, the RSMS has been extensively involved in collecting environmental data, emission characteristics, etc., and used in studies of several specific EMC problems, including the crowded 1030-MHz air traffic control radar beacon band and the 2700–2900-MHz radar

band. Though the details of these data will not be discussed here, some samples of measured data are included as examples of the types of measurements the system routinely makes. Sections II through V discuss the RSMS characteristics and capabilities; Sections VI and VII give examples of environmental measurements and EMC studies in which the RSMS has had a major role.

II. THE VEHICLE

The RSMS is installed in a modified motor home-type vehicle shown in Fig. 1. Copper screen was laminated into the fiberglass body for shielding, the suspension was reinforced, and strong points were provided to attach the antenna structures and racks. In addition to providing comfortable and convenient working space for men and equipment, the vehicle provides its own electrical power with two 5KVA generators (one for electronic equipment, one for air conditioning and heating). A mobile telephone and a hinged tower to support the main antenna arrays are also part of the van. Gross weight of the system is 17 300 lb with normal equipment and fuel.

III. ANTENNAS

The RSMS contains omnidirectional discone and biconical antennas covering the 30 MHz to 12 GHz range. Quadrant coverage is provided by sets of 4 conical helix antennas (150 MHz–4 GHz) and cavity-backed spiral antennas (1–12 GHz). Directional coverage (1–12 GHz)—useful for direction finding and isolating a signal for more detailed analysis—is provided by a 36-in dish antenna. A network of RF relays allows antenna selection via computer programs. Broad band noise diodes are located several places in the antenna system for automatic calibration of signal amplitude at the antenna terminals.

IV. THE RECEIVER

The RSMS is based on a Hewlett-Packard 8580 automatic spectrum analyzer system [5], augmented with antennas, specialized equipment for communication and radar measurements, and additional software routines. The major part of the RSMS is contained in three racks shown in Fig. 2. The receiver occupies most of the left and middle racks; the computer and interactive graphics terminal are contained in the right-hand rack. The 9-track tape unit, the transient digitizer, the pulse blanking system, and other equipment is contained in a 2-bay rack not shown. A block diagram of the RF/video portion of the RSMS is shown in Fig. 3. All of the instruments shown in the block diagram except those labeled with “*” are capable

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Fig. 1. Exterior view of OT Radio Spectrum Measurement System.

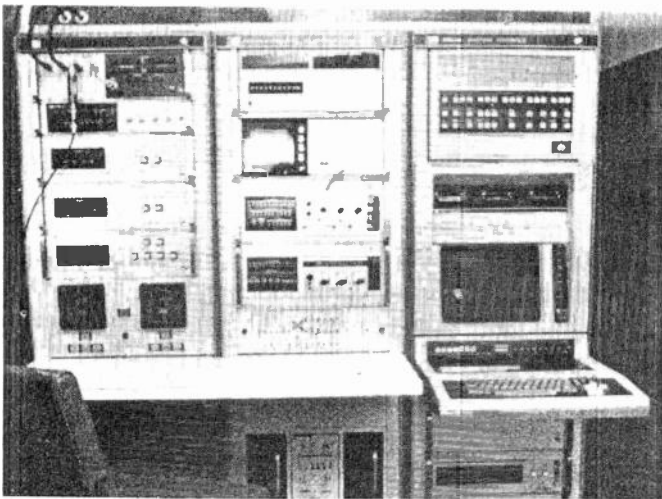


Fig. 2. Interior view of OT Radio Spectrum Measurement System.

of being controlled by the computer, functioning automatically by computer programs.

Receiver Input

An input switching unit can choose signals from the antennas or one of several calibration sources. A 0-70-dB input attenuator can reduce system sensitivity in 10-dB steps as necessary for strong signals. Preamplifier/preselector units are used to increase sensitivity and reject off-frequency signals. For frequencies above 500 MHz, a typical preselector consists

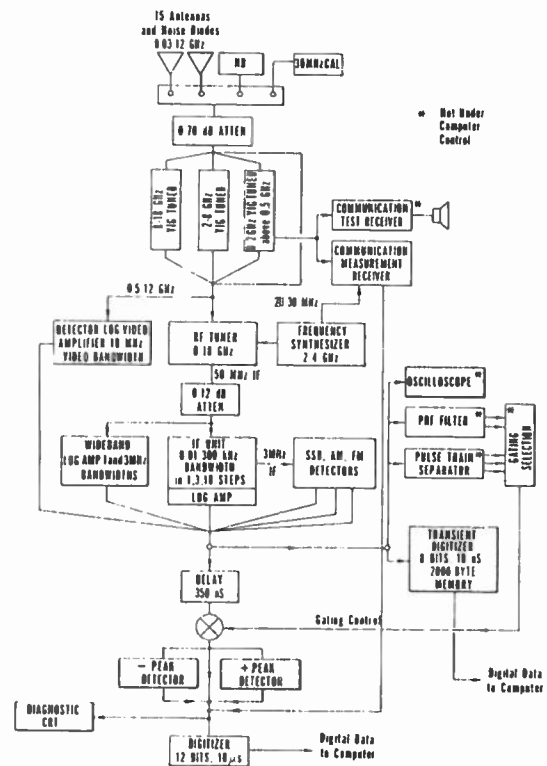


Fig. 3. RF/video block diagram of RSMS van.

of 2 stages of tracking YIG preselection, followed by a low-noise amplifier, followed by another 2 stages of YIG postselection. Fixed-tuned coaxial bandpass filters are used to isolate particular bands of interest below 500 MHz. A portion of the preamplified signal in the 5-500-MHz range is directed to a wide dynamic range communication measurement receiver and a manually tunable test receiver. The manually tuned communication test receiver enables an operator to monitor individual signals while the rest of the system continues scanning.

RF Tuning and IF Processing

The system tuning is controlled by a frequency synthesizer which allows very accurate system tuning—typically 2 parts in 10^7 for frequencies above 2 GHz. Several IF/detector units are used for various types of measurements. The narrow band IF unit allows a choice of 10 bandwidths between 0.01 and 300 kHz, in 1:3:10 steps. A 16-kHz bandwidth filter with very steep skirts is also available and is generally used for communication studies. Connected to this unit is a set of AM, FM, and SSB detectors to demodulate signals, as well as a logarithmic amplifier for amplitude measurements. The FM discriminators are dc-coupled so that frequency deviation or average center frequency of a narrow-band signal can be directly measured. A parallel wide band system provides a logarithmic amplifier output with 1- and 3-MHz bandwidths. Video bandwidths in excess of 10 MHz are available from a detector/log amplifier module driven directly from the preamplifiers. In this mode, the RF bandwidth of the system is determined by the selectivity of the YIG preselectors at the frequency of interest. Any one of these outputs can be selected for measurement by the rest of the system.

Pulse Blanking

A pulse-blanking system is used to isolate a single radar out of a multiradar environment, so that measurements may be made on that radar only. A pulse train separator and pulse repetition frequency filter provide a means of determining exactly when the desired radar pulses are present. This equipment operates with a high-speed video switch to gate only the desired radar pulses into the measurement circuits. Fig. 6 from a later paragraph illustrates the effectiveness of pulse blanking.

Digitizers

A gated signal passes through a final processing section before it is digitized. Plus and minus peak detectors are used to hold pulse-type signals for measurement. The 12-bit digitizer allows signals to be digitized every $10 \mu\text{s}$ with a resolution of 0.025 dB. Although overall system accuracy is not nearly so good, this resolution (along with short-term gain stability) enhances the usefulness of the noise diodes for system calibration.

A second digitizer is used for very high speed measurements, e.g., to measure digitally the shape of a nominal $1\text{-}\mu\text{s}$ radar pulse. The transient digitizer can be operated as fast as one measurement every $10 \mu\text{s}$. Although this device gives only 8-bit measurements, proper control of scale and offset on the digitizer can locate these 8 bits over a small portion of the system dynamic range, giving measurements to better than 0.1 dB.

V. COMPUTER/DATA PROCESSING

Hardware

The RF/video hardware is controlled and calibrated by the computer in Fig. 4. Most of the major instruments, including all of the interactive graphics terminal, are on a common two-way instrument bus system. This bus controls the instruments, accepts data and status from the instruments, and provides processed data and text for display and copying. The keyboard, control panel, and tracking ball (cursor) provide a means to interact with the particular measurement program being run by changing operating parameters from the keyboard and controlling program branching.

The HP 2100 computer operates with 16-bit words and 32K of core memory. Very flexible input/output peripheral devices greatly increase the productivity of the system. The 9-track magnetic tape operates under DMA and is used especially to record the billions of data points typically involved in measurements. The three digital cassette decks and the dual floppy discs are used extensively to store programs and data. The system also contains a thermal printer, which can be used to copy text, and a paper tape reader which can be used to input programs from paper tape.

Software

The system has been operated mainly in Basic. Although Basic is not as efficient as some other languages, it is very easy to work with. Programs are continually changed in the field, and the ease with which program changes are made and tested makes Basic an obvious choice. Although Basic runs slowly,

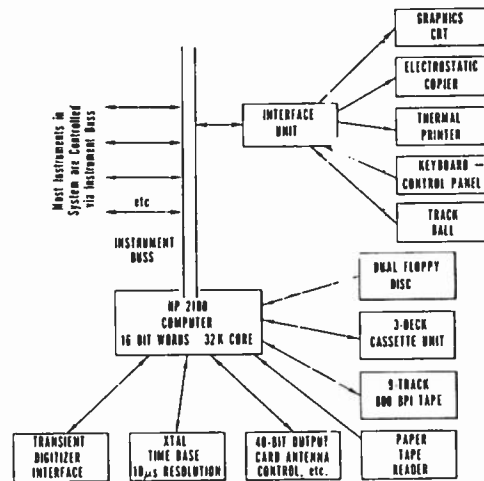


Fig. 4. Computer/data processing block diagram of RSMS van.

much of the computer time is spent waiting for measurement hardware to finish a particular task, and speeding up the software would not appreciably speed up overall system operation. When subroutines are encountered where software speed is crucial, a special subroutine may be created which is callable in Basic.

The feature of programmable hardware gives an increase in the hardware's utility. The computer enables the hardware to be automatically and rapidly calibrated. These calibration factors may be used to give results which could otherwise be measured only with hardware having much greater linearity and stability. At the same time, these calibration factors give clues which are useful in diagnosing long-time changes in system performance. Under computer control, many measurements may be made much more rapidly than before, with unbiased repeatability. Processed data may be displayed in a manner that is immediately useful to control the course of further measurements. This processed data can be well documented and labeled for immediate reporting and backed up by a magnetic tape duplicate which can be further analyzed if required. The ability of the software to operate the system in many different modes allows the same hardware to be used for widely differing measurements in the few seconds required to load a new program.

VI. EXAMPLES OF OPERATIONAL MEASUREMENTS

Calibration Routines

The standard system noise test (Fig. 5) is made on a daily basis to monitor the system noise figure and gain stability over the 0-14-GHz range. This 2-min test involves measuring system noise at 60 frequencies in this range, with and without a 22-dB excess noise source at the system input. The solid line traces the system noise figure, while the dashed line gives a system gain correction factor. Variations of this program are used to calibrate the system over narrower frequency ranges at the terminals of the antenna selected for a measurement. Other automatic routines linearize the system at 30 MHz, generating correction factors so that any system configuration can be accurately calibrated.

STANDARD SYSTEM NOISE CHECKOUT

DATE: 760427

TIME: 1858

FRONT PANEL

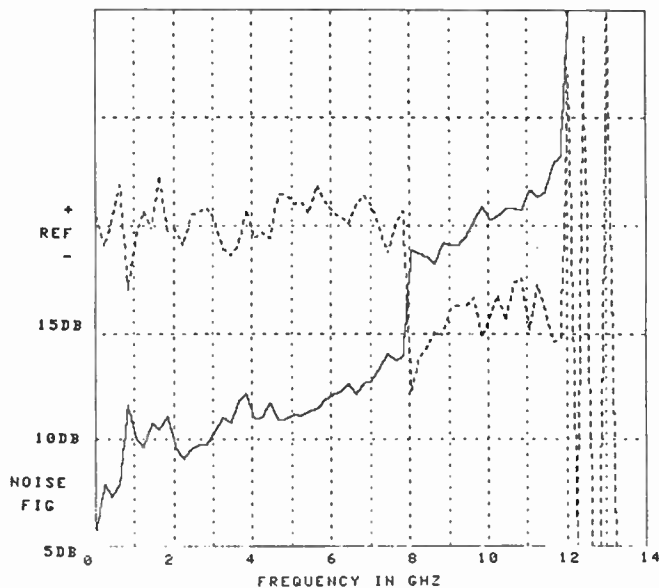


Fig. 5. Standard system noise test.

Communication Occupancy Measurements

Measurements of communication channel occupancy are made using the communication measurement receiver. This specialized hardware was designed to give the very high performance required for spurious-free measurements. Earlier measurements included many spurious signals resulting from receiver intermodulation and LO noise sidebands. The communication measurement receiver gives a 120-dB instantaneous measurement range with an 18-kHz bandwidth, while adjacent channels (25-kHz away) are suppressed 80 dB.

A typical communications measurement program includes a continuous scanning of the band of interest, stopping at each assignable frequency in the band (according to the band channelization plan). At each frequency, a burst of 40 measurements is made over an 0.8-ms period and processed to eliminate impulsive noise. The resulting single processed measurement is analyzed to give occupancy statistics at that frequency. If the signal is above an occupancy threshold amplitude, the channel is considered occupied. Statistics developed include percentage of time each channel is occupied, the average signal amplitude while the channel is occupied, and the maximum signal amplitude. This statistical data is updated as each channel is measured. About 7 ms is required to tune, measure, and analyze the data at each frequency; thus it requires about 3.6 s to measure each channel in a 500-channel band.

The accumulated statistical data is recorded on magnetic tape at the end of a 1-h measurement period. Statistical data from many 1-h blocks are combined into a single statistical file for a 1-week period and plotted and copied in a prescribed format. Data are also sorted by type of assignment and analyzed to show occupancy versus time of day and cumulative distributions of occupancy versus percentage of channels with that occupancy or greater.

DATE 750326 TIME 130120 STEPS 130 LOS ANGELES
 REMOD 513111 PINPT. 2 ANTS 111115 PORTS 211
 TOT 0 ANIM0 ANAX50 2900 131450
 +10.00

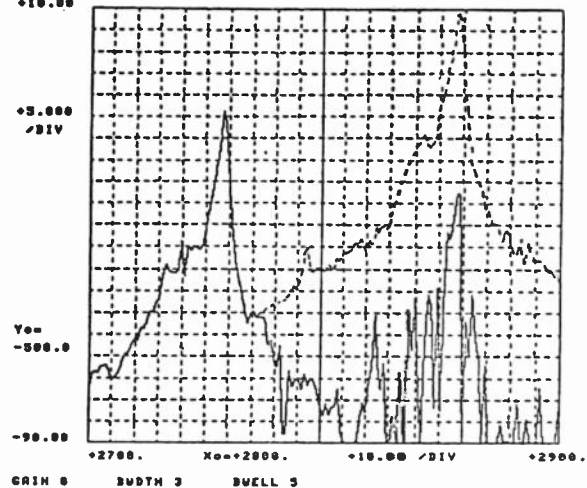


Fig. 6. Spectra of two radars. Right hand removed by blanking.

Radar Spectra Measurements

Radar spectra are measured using the pulse-blanking circuits and the plus peak detector. The system is tuned in steps across the band of interest. At each frequency the peak detector holds on to the maximum signal of interest. With conventional rotating radar antennas, this maximum will occur when the radar antenna is aimed directly at the RSMS van. If the radar antenna rotates once every 5 s, the system must remain at each frequency for at least 5 s to ensure that the radar is pointed at the RSMS van sometime during the measurement period. Since the hardware peak detector output decays too rapidly to hold a signal accurately for a 5-s period, its output is sampled every 50 ms and the largest digitized value is held in memory. Thus the peak detector is a combination of hardware and software. This peak value is plotted on the graphics CRT as it is measured. The pulse blanker, described earlier, may be used to eliminate unwanted radars from the measurements. Fig. 6 shows a measurement of two radars. The dotted line shows the radar spectra as measured without pulse blanking. The solid line shows the measured spectra with the pulse blanker adjusted to reject the higher frequency radar. Note the effective rejection of about 40 dB.

Radar Antenna Patterns

Radar antenna patterns at 0° elevation angle are interesting to EMC engineers because they suggest the amount of sidelobe and backlobe antenna response available to couple interference between ground-based radars. Fig. 7 shows a radar antenna pattern measured as the radar rotates its pattern past the RSMS van. For these measurements, a burst of 500 points was measured, timed to begin slightly before one main beam passed and to end slightly after the succeeding mainbeam passed. The highest amplitude measurement in the first 250 data points is assigned an angle of 0° ; the highest amplitude in the second 250 data points is called 360° ; and the rest of the data points are scaled to fit between. In addition, the peak amplitude of the first mainbeam is assigned a value of 0 dB, and the rest of the pattern is normalized to this value. An

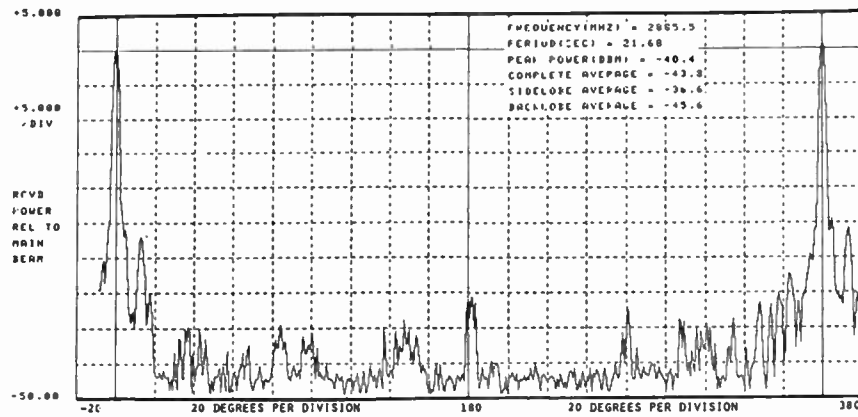


Fig. 7. Radar antenna pattern.

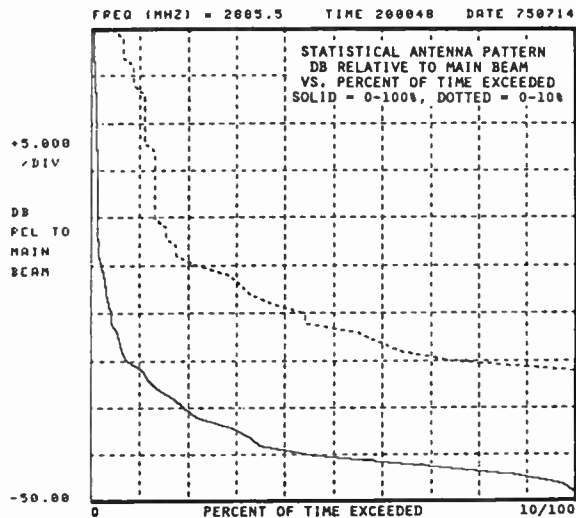


Fig. 8. Statistical radar output.

accurate timer is used to time the antenna rotation period automatically to the nearest 10 ms. Various averages are calculated, including the average antenna gain in dB below main-beam gain, averaging between 0 and 360°. The sidelobe average is similarly computed but uses only data within the range of 3 to 25° from the mainbeam. The backlobe average is taken from data points further than 25° from the mainbeam.

A statistical antenna pattern may also be plotted from the above data. In this case, all of the data points between 0 and 360° are ordered by amplitude and plotted as a cumulative distribution (Fig. 8).

VII. EMC ENVIRONMENTAL STUDIES

The mobility of the RSMS has been utilized to make measurements directed towards certain EMC problems where environmental measurements play a key role. A study was made of radar-to-radar interference in the crowded 2700-2900-MHz radar band. In the Los Angeles and San Francisco areas [6], the RSMS made measurements of the radar signal environments seen by radars which were victims of interference from other radars. Specific measurements were made on various component factors of the interference, including interferer emission spectra, interferer antenna gain pattern,

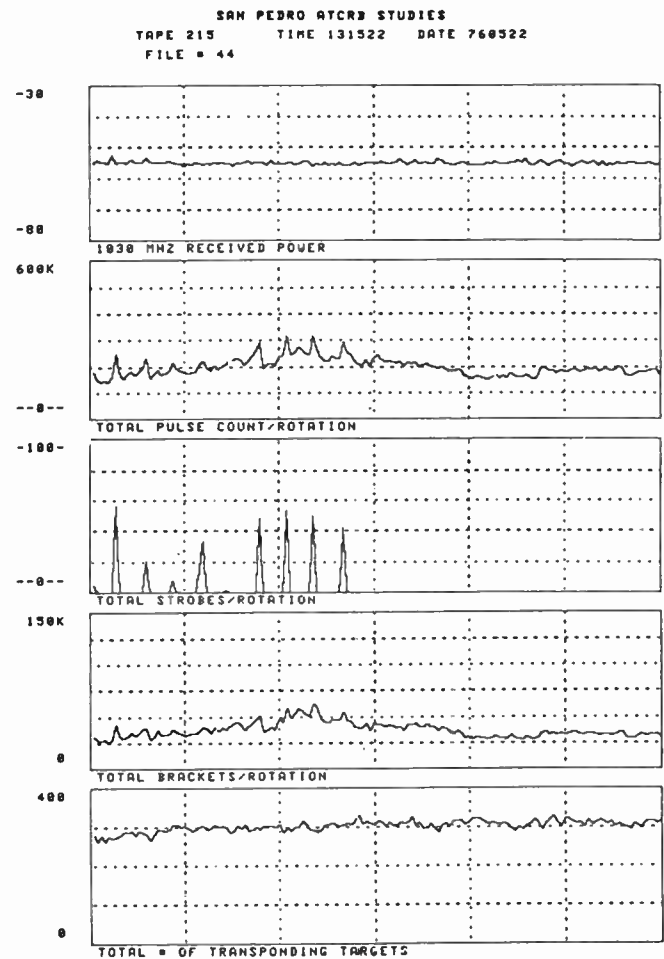


Fig. 9. RSMS measurement of ATCRBS performance.

propagation characteristics, victim radar antenna gain patterns, victim radar signal processing, etc. These data were analyzed to give a clearer understanding of which factors were most important in radar interference and were used to modify some of the existing EMC models. Eventually the data will be used in decisions in radar frequency allocations.

A study of the crowded 1030/1090 MHz Air Traffic Control Radar Beacon System (ATCRBS) was undertaken in the Los Angeles area. The RSMS was connected to the ATCRBS signal processor—the Common Digitizer (CD)—and was able to

monitor the CD while simultaneously making measurements on the 1030/1090-MHz signal environment. Specialized pulse processing hardware in the RSMS allowed many intermittent "problem signals" to be identified and related to particular system overload malfunctions on a real-time basis. Fig. 9 shows a partial set of graphs produced by the RSMS for a 30-min period. The top graph shows received signal power at 1030 or 1090 MHz, selected by PRF, interrogation modes, and direction of arrival. The lower 4 graphs show the CD response to the signal environment for a 12-s antenna rotation including total number of pulses received, number of strobes (indicative of system overload), bracket pairs received, and total number of transponding targets.

REFERENCES

- [1] G. H. Hagn, S. C. Fralick, H. N. Shaver, and G. E. Barker, "A measurement/monitoring capability for the Federal Government," Stanford Research Institute, Menlo Park, CA, Final Report, SRI Project 8410, Contract OEP-SE-70-102, May 1971. (Available from NTIS, Port Royal Road, Springfield, VA, PB 203 062.) See also, G. H. Hagn, D. M. Jansky, and T. I. Dayharsh, "Definition of a measurement capability for spectrum managers," in this issue, pp. 216-224.
- [2] L. D. Schultz, A. D. Spaulding, and A. F. Barghausen, "Radio spectrum occupancy—Signals and noise," in *1972 IEEE Int. Electromagnetic Compatibility Symposium Record*, 72CHO638-7EMC, Chicago, IL, 1972, pp. 42-49.
- [3] A. F. Barghausen, "The OT radio spectrum measurement system for frequency management support," presented at the IRAC/TSC Spectrum Management Symposium Proceedings, NASA Goddard Space Flight Center, Greenbelt, MD, Oct. 30-31, 1973.
- [4] A. F. Barghausen and L. G. Hailey, "Radio spectrum measurement system—Current applications, experience, results," in *1974 IEEE EMC Symposium Record*, 74CHO803-7EMC, San Francisco, CA, July 16-18, 1974, pp. 140-145.
- [5] *Hewlett-Packard 8580—Automatic Spectrum Analyzer User's Manual*, Hewlett-Packard Part #08580-90030, Palo Alto, CA, 1976.
- [6] R. L. Hingle, R. M. Pratt, and R. J. Matheson, "Spectrum resource assessment in the 2.7 to 2.9 GHz band. Part II: Measurements and model validation (Report No. 1)," Office of Telecommunications, U.S. Department of Commerce, Boulder, CO, Report 76-97, Aug. 1976.
- [7] R. J. Matheson, "The Office of Telecommunications radio spectrum measurement system," in *IEEE 1976 Int. Symposium in Record*, 76-CH-1104-9EMC, 1976, pp 1-12.

Frequency Assignment: Theory and Applications

WILLIAM K. HALE

Abstract—In this paper we introduce the minimum-order approach to frequency assignment and present a theory which relates this approach to the traditional one. This new approach is potentially more desirable than the traditional one. We model assignment problems as both frequency-distance constrained and frequency constrained optimization problems. The frequency constrained approach should be avoided if distance separation is employed to mitigate interference. A restricted class of graphs, called disk graphs, plays a central role in frequency-distance constrained problems. We introduce two generalizations of chromatic number and show that many frequency assignment problems are equivalent to generalized graph coloring problems. Using these equivalences and recent results concerning the complexity of graph coloring, we classify many frequency assignment problems according to the "execution time efficiency" of algorithms that may be devised for their solution. We discuss applications to important real world problems and identify areas for further work.

I. INTRODUCTION

FREQUENCY assignment problems arise in a wide variety of real world situations. Many may be modeled as optimization problems having the following form: Given a collection of radio transmitters to be assigned operating frequencies, find an assignment that satisfies various constraints and that minimizes the value of a given objective function. Informal methods, which attempt to find such assignments, have been in use since the beginning of the twentieth century when maritime applications of Marconi's wireless telegraph first appeared [1].

The first frequency assignment problems arose from the discovery that transmitters, assigned to the same or to closely related frequencies, had the potential to interfere with one another. Thus the first approach to frequency assignment was to minimize or eliminate this potential interference (i.e., potential interference was the first objective function). In this approach, the major constraints were the operating bandwidth of the transmitters, the band of the electromagnetic spectrum which the transmitters were capable of using, and, combining these two, the total number of frequencies available for assignment to the transmitters (under the assumption that frequencies should be assigned to discrete, evenly spaced points in a dedicated portion of the spectrum). A simple way to minimize interference was to assign different transmitters to different noninterfering frequencies or to come as close to this as was possible within the constraints. Such an approach to frequency assignment tied up a lot of the spectrum but remained viable so long as the growth of the usable spectrum kept pace with the growth in demand placed upon it.

Recently (1950–1980), the growth of the usable spectrum has slowed while the demand placed upon it has grown exponentially [2]. This turn of events has induced spectrum managers to consider different approaches to frequency assignment. In one such approach, the amount of spectrum tied up

by an assignment is the objective function to be minimized, and instead of eliminating unwanted interference, conditions which place acceptable upper bounds upon interference are included among the constraints which an assignment must satisfy. This approach also calls for an ongoing evaluation of the system (e.g., the constraints, conventions, regulations, policies, and procedures) that governs the way in which the spectrum is allocated, assigned, and used. In addition, the governing system may be modified if it can be demonstrated that such modifications lead to spectrum savings and that existing conditions (e.g., technologic, methodologic, and economic) make such actions feasible. This paper will provide tools for quantifying the effects on efficient spectrum use of such modifications to the governing system. For example, suppose that improvements in UHF-TV receivers allow for the relaxation of some of the UHF taboos. One can use the tools developed here to determine which taboo(s) to modify for the maximum gain in spectrum efficiency.

It is misleading to suggest that frequency assignment problems have always been formally modeled as optimization problems. In fact, investigations of formal mathematical models of assignment problems did not appear in the literature until the 1960's (e.g., [3], [4]). These early models seem to have enjoyed very limited application and together with other frequency assignment models in existence as of 1968, were not very well known, understood or accepted by the spectrum utilization experts of that day. As evidence for this conclusion, consider that the exhaustive report on spectrum engineering [2] mentions only two frequency assignment models and describes neither of these.

Since 1968, the interest in formal frequency assignment models has increased significantly as evidenced by the articles that have appeared in the literature [5]–[18]. In addition, as early as 1975, one of these approaches had been demonstrated to outperform older frequency assignment procedures on an important real world problem [13]. In spite of these developments, many policy makers, spectrum managers, and frequency assigners remain unconvinced that formal models are a viable approach to the wide range of assignment problems which arise in the real world. (For example, a 1977 encyclopedia volume [1], devoted to spectrum management techniques, does not mention a single formal frequency assignment model.) The reasons for this skepticism are clear. First of all, the existing formal models can handle only a limited range of the wide variety of real world problems. For example, the approach applied in [13] obtains significant spectrum savings over older methods when the only interference limiting constraints are cochannel constraints. However, if adjacent channel constraints are also considered, then these spectrum savings go to zero as the ratio of adjacent channel to cochannel constraints increases. There is an even more important reason for skepticism: *there exists no unifying theory which demonstrates that formal models are a viable approach to the wide range of prob-*

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lems which arise in the real world. The purpose of this paper is to provide such a unifying theory for a wide variety of real world problems.

Recent developments in the theory of computational complexity [19]–[22] allow for the classification of optimization problems according to the “execution time efficiency” of algorithms that may be devised for their solution. For example, the book [23] classifies well over 1000 combinatorial problems but not a single frequency assignment problem is included. An important feature of the theory developed here is that, for the first time, many frequency assignment problems are classified according to their complexity.

Graph coloring is perhaps the most famous optimization problem (e.g., the four-color theorem). That this problem also is one of the most intensively investigated and applied optimization problems is dramatically evidenced by the numerous books and articles that have appeared in the literature (e.g., [25]–[81]). A second important feature of the theory developed here is that a very close connection is established between each of the frequency assignment problems of this paper and graph coloring. Among the obvious benefits of this connection is the potential application of well-known graph coloring algorithms and/or heuristics to frequency assignment problems. Graph colorers will be interested to know that the theory of frequency assignment opens up new vistas in chromatic graph theory. Real world problems now make it important to find algorithms and/or heuristics for both classical and generalized graph coloring problems.

This paper is written primarily for spectrum planners, spectrum managers, and frequency assigners. We hope it will also be read by operations researchers, computer scientists and applied mathematicians. The mathematical (i.e., graph theory, optimization theory, complexity theory) and the spectrum engineering backgrounds of members of this audience are likely to range all over the scale. For this reason, we have attempted to provide motivation for formal definitions, describe the meanings of theorems, and to illustrate concepts with examples. We have proved theorems in their least general (but most understandable) form, while only stating or mentioning more general theorems which have the same proof.

In this paper, a frequency assignment is a *function* which assigns to each member of a set of transmitters an operating frequency from a set of available frequencies. Therefore, if A is an assignment for the set of transmitters V and if v is a transmitter belonging to V , then $A(v)$ denotes the frequency assigned to v by A . In a typical frequency assignment problem, one attempts to find a frequency assignment (i.e., a function from a given set of transmitters into a given set of frequencies) that satisfies certain constraints (e.g., a collection of interference limiting rules) and that minimizes the amount of spectrum tied up by the assignment.

It is sometimes convenient to differentiate between two types of frequency assignment problems. If the assignments are confined to discrete, but not necessarily evenly spaced frequencies and we wish to emphasize this fact then the problem is called a *channel assignment problem*. We sometimes conserve space and write assignment instead of channel (or frequency) assignment. It is important to differentiate between two types of interference limiting constraints. One type of constraint specifies that if the distance between two transmitters is less than a prescribed minimum number of miles then certain combinations of assignments to this pair of transmitters are taboo or forbidden. Such constraints employ

both frequency and distance separation to mitigate interference and are called *frequency-distance (F^*D) constraints*. An assignment problem in which the interference limiting constraints are all F^*D constraints is called a *frequency-distance constrained assignment problem*. The paper [82] discusses the origin and application of an elaborate set of F^*D constraints called the UHF-TV taboos. A second type of interference limiting constraint specifies that certain combinations of assignments are forbidden for a given pair of transmitters. Superficially at least such constraints employ only frequency separation to mitigate interference and are called *frequency (F) constraints*. An assignment problem in which the interference limiting constraints are all frequency constraints is called a *frequency constrained assignment problem*. The papers [10], [18] investigate such problems.

We have mentioned that an assignment should not needlessly tie up spectrum. Traditionally, this has meant that the span of an assignment for a given set of transmitters must be minimized (where the span of an assignment is the largest frequency assigned to a transmitter in the set minus the smallest frequency assigned to a transmitter in the set). An assignment problem in which our objective is to minimize the span of an assignment is called a *minimum span assignment problem*. The papers [9], [13], [17], [18] investigate such problems.

Can a minimum span assignment waste spectrum? The answer is yes for channel assignment problems with interference limiting constraints other than cochannel constraints. That is, for such problems it is not uncommon for a minimum span assignment to assign transmitters to more frequencies than does a second assignment which may or may not be a minimum span assignment. In fact, for many common instances of assignment problems it is impossible to find a minimum span assignment which actually uses the minimum number of frequencies required. (See Examples One and Two in Section III for details). This potentially useful phenomenon makes it important to formalize a new type of assignment problem. The number of frequencies that an assignment actually uses is called its *order* and an assignment problem in which our objective is to minimize the span of an assignment subject to the additional constraint that its order is minimized is called a *minimum-order assignment problem*.

In Section II, we set down our conventions, notations, and other preliminary definitions. In Section III, we develop the elementary theory of frequency-distance constrained channel assignment problems (both minimum span and minimum order). Section IV presents a parallel development for the more general frequency constrained channel assignment problems. Section V presents other more complicated assignment problems and indicates how to develop a theory which parallels that of Section III for these problems. We also discuss other optimization problems some of which appear to be related to frequency assignment problems. In Section VI, guided by our efforts in Sections III, IV, and V, we formulate and investigate generalized graph coloring problems and, once again, indicate how to develop a theory for these problems that parallels that of Section III. In Section VII, we show that each of the assignment problems of Sections III, IV, and V is equivalent to a generalized graph coloring problem. Using these equivalences, we are able to classify many real world assignment problems according to their computational complexity. In Section VIII, we conclude with a summary and a discussion of real world applications of our findings. In addition, we suggest topics for further study.

II. DEFINITIONS AND NOTATION

This paper contains the following notations and terminology. X is a subset of Y , $X \subseteq Y$; X is a proper subset of Y , $X \subset Y$; A is a function from X into Y (or A is an assignment of members of X to members of Y). $A: X \rightarrow Y$; the cardinal number of the set X , $|X|$; the empty set $\{\}$; the integers Z ; the rationals Q ; the positive integers, rationals and reals, respectively Z^+ , Q^+ , and R^+ ; the nonnegative integers, rationals and reals, respectively Z_0^+ , Q_0^+ , and R_0^+ ; the absolute value of the number a , $|a|$; the largest number in X , a finite nonempty subset of Z_0^+ , $\max X$; the smallest number in X , a nonempty subset of Z_0^+ , $\min X$; the greatest lower bound of X , a nonempty subset of Q_0^+ , $\inf X$; the Euclidean distance between u and v , two points in the plane $D(u, v)$. If $A: X \rightarrow Y$ and x belongs to X , then $A(x)$ is the element of Y that A assigns to x and $A(X)$ equals $\{A(x) | x \text{ belongs to } X\}$. If a and b belong to Q then, $(a, b)_Q$ equals $\{c | c \text{ belongs to } Q \text{ and } a < c < b\}$ and $[a, b]_Q$ equals $\{c | c \text{ belongs to } Q \text{ and } a \leq c \leq b\}$.

If V is a finite set and E is a specified set of two element subsets of V , then $G = (V, E)$ is a *graph* with *vertex set* V and *edge set* E . To simplify notation, the two element subset $\{u, v\}$ belonging to E is denoted by uv . If $G = (V, E)$ and uv belongs to E then u and v are *adjacent vertices* in G . The graph $G = (V, E)$ is *complete* if uv belongs to E whenever $u \neq v$. The graph $G' = (V', E')$ is a *subgraph* of the graph $G = (V, E)$ if $V' \subseteq V$ and $E' \subseteq E$. If $G = (V, E)$, $V' \subseteq V$, and $E' = \{uv | uv \text{ belongs to } E, u \text{ and } v \text{ belong to } V'\}$, then the graph (V', E') is denoted $\langle V' \rangle$ and is called the *subgraph of G induced by V'* . If H is a complete subgraph of G and H is not properly contained in a complete subgraph of G , then H is a *clique* of G . The *clique number* of G is the number of vertices in the largest clique of G and is denoted by $W(G)$. The *chromatic number* of G is denoted by $X(G)$ and is the minimum number of colors necessary to color the vertices of G such that no two adjacent vertices receive the same color. A graph G is *perfect* if $X(H) = W(H)$ for every induced subgraph H of G .

A graph $G = (V, E)$ is called an *intersection graph* for F , a family of sets, if there exists a one-to-one correspondence, $f: V \rightarrow F$, such that uv is an element of E if and only if $f(u)$ and $f(v)$ have nonempty intersection. Conversely, F is called an *intersection model* for G if G is an intersection graph for F . If F is a finite collection of intervals on the real line then an intersection graph for F is called an *interval graph*. If F is a finite collection of arcs on a circle then an intersection graph for F is called a *circular-arc graph*. If, in addition, no arc in F contains another arc, G is called a *proper circular arc graph*.

III. FREQUENCY-DISTANCE CONSTRAINED CHANNEL ASSIGNMENT PROBLEMS

Complex frequency assignment problems are most easily discussed in terms of formal models. In this paper, all assignment problems are modeled as optimization problems. All but three of these are combinatorial optimization problems called search problems [23]. For our purposes, it is not necessary to give a rigorous definition of "search problem." The concept will be amply illustrated by many examples. In this section, we investigate cochannel, adjacent channel, and more complex frequency-distance constrained channel assignment problems. We assume that everything is uniform. That is, the terrain is uniform; the receivers are uniform; the transmitters are omni-

directional and all have the same power and operating bandwidth. Spectrum managers sometimes make these assumptions when taking a nationwide or regional approach to an assignment problem (e.g., UHF-TV as in [82]). We investigate the traditional minimum span approach to channel assignment and show that for some situations a new approach called the minimum-order approach may be more desirable. We show that the distinction between the minimum span approach and the minimum-order approach is lost on the cochannel assignment problem. In addition, we develop a theory which relates the two approaches and their common subproblem. Finally, for the reader who does not wish to work through the proofs of theorems, there is a summary at the end of this section in which we present an informal discussion of the theory.

A. The Frequency-Distance Constrained Cochannel Assignment Problem

The paper [13] discusses the following search problem called the *F*D constrained cochannel assignment problem* (*F*D-CCAP*). Given V a finite subset of the plane and d a positive rational number, the problem is to find an assignment $A: V \rightarrow Z^+$ which satisfies the conditions

$$\max A(V) \text{ is as small as possible and} \quad (1)$$

$$\text{if } u \text{ and } v \text{ are elements of } V, u \neq v \text{ and } D(u, v) \leq d \text{ then } A(u) \neq A(v). \quad (2)$$

The set V may be thought of as the locations of radio transmitters and $A: V \rightarrow Z^+$ as an assignment of channels to these transmitters. Thus the assignment A assigns the channel $A(v)$ to the transmitter located at v . Condition (2) requires that transmitters assigned to the same channel (i.e., cochannel transmitters) be separated by a distance greater than d . For this reason, condition (2) is called a *cochannel constraint*. An assignment $A: V \rightarrow Z^+$ which satisfies (2) is called a *feasible assignment for V and d* . The condition (1) is motivated by our desire to conserve spectrum; and if $A: V \rightarrow Z^+$ is a feasible assignment for V and d which satisfies (1) then A is called an *optimal assignment for V and d* and $\max A(V)$ is denoted $m(V, d)$. Thus $\{1, 2, \dots, m(V, d)\}$ is the smallest set of channels which will accommodate an assignment of channels to the transmitters in V , which does not violate the cochannel constraint.

Throughout the rest of this paper we will use a standard format for specifying search problems. A restatement of F*D-CCAP illustrates this format.

*F*D-CCAP* (problem name)

INSTANCE: V a finite subset of the plane and $d > 0$ a rational number.

FIND: $A: V \rightarrow Z^+$ a feasible assignment for V and d such that $\max A(V)$ is as small as possible.

The standard format consists of three parts: the first part is the problem name, the second part specifies a generic instance of the problem, and the third part describes, in terms of the generic instance, the object(s) of the search. For each of the search problems of this paper, we establish that the search will not be fruitless; i.e., for each generic instance there exists at least one object of the search. Therefore, for our purposes, an algorithm (or computer program) is called a *solution of the search problem S* if it accepts as input any generic instance of the problem S and returns as output an object of the search. A search problem is *undecidable* if it is impossible to specify

any algorithm which is a solution. An algorithm runs in polynomial time if it always terminates within a number of steps which is bounded above by some polynomial in the size of the input. A solution of a search problem is called an efficient solution if it runs in polynomial time. For example, given $V = \{v_1, v_2, \dots, v_n\}$ and d an instance of F*D-CCAP, let $F(V, d)$ consist of all $A: V \rightarrow \{1, 2, \dots, n\}$ which are feasible assignments for V and d . $F(V, d)$ is not empty since $A: V \rightarrow \{1, 2, \dots, n\}$ defined $A(v_i) = i$ for $i = 1, \dots, n$ is feasible. An exhaustive search of the finite set $F(V, d)$ will yield an optimal assignment for V and d . This exhaustive search can be formalized as an algorithm which solves F*D-CCAP. Therefore F*D-CCAP is decidable. For future reference we formalize these conclusions.

Theorem 1: If V is a finite subset of the plane and $d > 0$ is a rational number, then there exists $A: V \rightarrow \{1, \dots, m(V, d)\}$ an optimal assignment for V and d .

Theorem 2: F*D-CCAP is decidable.

Exhaustive search algorithms are inefficient and, in practice, can only be applied to "small" problems. The likelihood of our finding an efficient solution for F*D-CCAP will be discussed in Sections VII and VIII. The reader who is interested in learning more about search problems and their computational complexity is referred to [23].

B. The Frequency-Distance Constrained Adjacent Channel Assignment Problem (F*D-ACAP)

The paper [13] discusses the following assignment problem. Let V be a finite subset of the plane and let $D = \{d(0), d(1)\}$ where $d(0) > d(1) > 0$ are rational numbers. If $A: V \rightarrow \mathbb{Z}^+$ satisfies the condition, if u and v are elements of V ,

$$u \neq v \text{ and } D(u, v) \leq d(i)$$

then

$$|A(u) - A(v)| \neq i, \quad \text{for } i = 0, 1, \quad (3)$$

then A is called a feasible assignment for V and D . When $i = 0$, (3) becomes a cochannel constraint and requires that cochannel transmitters be separated by a distance greater than $d(0)$. When $i = 1$, equation (3) becomes an adjacent channel constraint and requires that transmitters assigned to adjacent channels be separated by a distance larger than $d(1)$. An adjacent channel constraint is required, in practice, when a receiver tuned to a transmitter in V cannot tolerate the interference generated by adjacent channel transmitters which are "close" (in distance) to the receiver.

If A is a feasible assignment for V and D , then we say that $L = \max A(V)$ accommodates V and D and the smallest such L , denoted $m(V, D)$, is called the minimum span of a feasible assignment for V and D . If $A: V \rightarrow \{1, \dots, m(V, D)\}$ is feasible for V and D , then A is called a minimum span assignment for V and D .

F*D-ACAP

INSTANCE: V a finite subset of the plane and $D = \{d(0), d(1)\}$ where $d(0)$ and $d(1)$ are positive rational numbers.

FIND: $A: V \rightarrow \{1, \dots, m(V, D)\}$ a minimum span assignment for V and D .

Traditionally (see [9], [13], [17], and [18]), minimum span assignments have been regarded as mathematically optimal from the point of view of minimizing spectrum waste. Can a minimum span assignment waste spectrum?

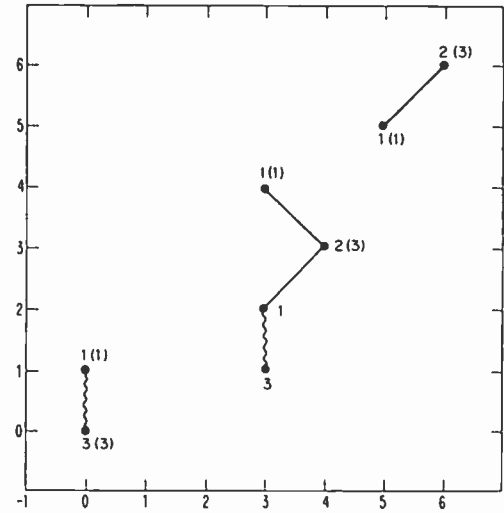


Fig. 1. Graphical depiction of the set of transmitter locations, the forbidden combinations of channel assignments, the minimum span assignment A , and the minimum-order assignment B of Example One.

C. Example One: A Minimum Span Assignment That Wastes Spectrum

Let $V = \{(0, 0), (0, 1), (3, 1), (3, 2), (3, 4), (4, 3), (5, 5), (6, 6)\}$ and $D = \{d(0), d(1)\}$ where $d(0) = 1.415$ and $d(1) = 1$. One can show by exhaustive search that $A: V \rightarrow \{1, 2, 3\}$ defined by $A(0, 0) = A(3, 2) = A(3, 4) = A(5, 5) = 1$, $A(0, 1) = A(3, 1) = 3$, and $A(4, 3) = A(6, 6) = 2$ is a minimum span assignment for V and D . However, $B: V \rightarrow \{1, 2, 3\}$ defined by $B(4, 3) = B(6, 6) = 3$ and $B(v) = A(v)$ otherwise is feasible for V and D . In addition, B uses only two channels whereas A uses three. Thus minimum span assignments may waste spectrum. Notice that B is also a minimum span assignment for V and D . One can show that no feasible assignment for V and D uses fewer than two channels. Therefore B is called a minimum order feasible assignment for V and D (where the order of an assignment is the number of channels actually used by the assignment). Fig. 1 depicts this example graphically. In this figure, transmitters separated by a distance equal to or less than the adjacent channel distance requirement ($d(1) = 1$) are connected by a wavy line and cannot be assigned the same or adjacent channels. The transmitters separated by a distance larger than the adjacent channel distance requirement but equal to or less than the cochannel distance requirement ($d(0) = 1.415$) are joined by a smooth line and cannot be assigned the same channel (but may be assigned adjacent channels). The numerals adjacent to the transmitter locations (but not in parentheses) constitute the minimum span assignment A . The numerals in parentheses constitute the minimum-order assignment B . Can it be that all of the minimum span assignments, for a particular problem, waste spectrum?

D. Example Two: All Minimum Span Assignments Waste Spectrum

Let $V = \{(2, -2), (2, 0), (2, 1), (2, 3), (3, 2), (4, 0)\}$ and $D = \{d(0), d(1)\}$ where $d(0) = 3$ and $d(1) = 2$. One can show by exhaustive search that six is the minimum span of a feasible assignment for V and D and that each of the minimum span assignments for V and D has order five or six. However, $A: V \rightarrow \{1, 2, \dots, 7\}$ defined by $A(2, -2) = 3$, $A(2, 0) = 7$, $A(2, 1) = 5$, $A(2, 3) = 1$, $A(3, 2) = 3$ and $A(4, 0) = 1$ is a feasible assignment for V and D that uses only four channels. Therefore,

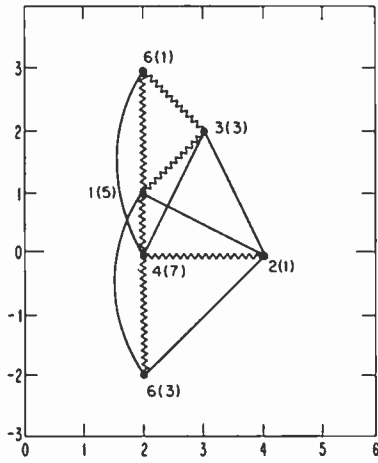


Fig. 2. Graphical depiction of the set of transmitter locations, the forbidden combinations of channel assignments, a minimum span assignment and the minimum order assignment A of Example Two.

in certain situations, A is more desirable than any minimum span assignment for V and D (since each of the minimum span assignments uses more channels). Fig. 2 depicts this example graphically.

The distinction between minimizing the span of an assignment versus minimizing the order is lost on F*D-CCAP since every minimum span assignment for an instance of F*D-CCAP is also a minimum-order assignment (see Theorems 15 and 26 below). However, the majority of real world assignment problems are more complex than F*D-CCAP. And for these more complex problems it is easy to find examples like the ones above. That is, minimum span assignments which fail to have minimum order abound in the real world. It is important that we investigate this potentially useful phenomenon. Before defining the search problems which capture the essence of minimum span and minimum order, we present another example to further motivate the following definitions and theory.

E. Example Three: UHF-TV

F*D constraints, other than cochannel and adjacent channel are often imposed in practice. For example, if V is a set of locations of UHF-TV transmitters in the Eastern U.S., then $A: V \rightarrow Z^+$ is a feasible assignment of channels for V if and only if the following condition is satisfied.

If u and v are elements of V , $u \neq v$, and $D(u, v) \leq M(i)$ then

$$|A(u) - A(v)| \neq i, \quad \text{for } i = 0, 1, 2, 3, 4, 5, 7, 8, 14, \text{ and } 15. \quad (4)$$

Where, $M(0) = 155$, $M(1) = 55$, $M(2) = M(3) = M(4) = M(5) = M(8) = 20$, $M(7) = M(14) = 60$ and $M(15) = 75$ are mileage separations required of transmitters assigned to channels separated by 0, 1, 2, 3, 4, 5, 8, 7, 14, and 15 channels, respectively. There is no mileage separation requirement for transmitters separated by 6, 9, 10, 11, 12, 13, 16, 17, $\dots$ channels. Let $R = \{(T(i), d(i)) | i = 0, 1, 2, 3, 4\}$ where $T(0) = \{0\}$, $T(1) = \{0, 15\}$, $T(2) = \{0, 7, 14, 15\}$, $T(3) = \{0, 1, 7, 14, 15\}$, $T(4) = \{0, 1, 2, 3, 4, 5, 7, 8, 14, 15\}$, $d(0) = 155$, $d(1) = 75$, $d(2) = 60$, $d(3) = 55$ and $d(4) = 20$. The following condition is a convenient way to express (4). If u and v are elements of V , $u \neq v$, and $D(u, v) \leq d(i)$, then

$$|A(u) - A(v)| \text{ is not an element of } T(i), \quad \text{for } i = 0, 1, 2, 3, 4. \quad (5)$$

The pair $(T(0), d(0))$ is called UHF-TV's cochannel constraint, since for $i = 0$, (5) requires that cochannel stations be separated by more than 155 mi. Similarly, the pair $(T(1), d(1))$ is called UHF-TV's 15th adjacent channel constraint since for $i = 1$, (5) requires that transmitters assigned to channels separated by exactly 15 channels be separated by more than 75 mi; the pair $(T(2), d(2))$ is called UHF-TV's 7th and 14th adjacent channel constraint since for $i = 2$ (5) requires that transmitters assigned to channels separated by exactly 7 or 14 channels be separated by more than 60 mi, etc. The pairs $(T(i), d(i))$ for $i = 1, 2, 3, 4$ are F*D constraints related to the UHF-TV receiver rejection characteristics. The paper [82] discusses this relationship and the possibility that improvements in receiver rejection characteristics may allow for the relaxation of some of these constraints.

The UHF-TV assignment problem is more involved than F*D-CCAP or F*D-ACAP and once again a minimum span assignment may fail to be a minimum-order assignment. To illustrate, let $V = \{v_1, v_2, v_3, v_4, v_5\}$ where $v_1 = (20, 10)$, $v_2 = (75, 100)$, $v_3 = (100, 80)$, $v_4 = (120, 80)$, and $v_5 = (100, 150)$. One can show by exhaustive search that $A: \rightarrow \{1, 2, 3, 4, 5, 6, 7\}$ defined by $A(v_1) = 4$, $A(v_2) = 3$, $A(v_3) = 1$, $A(v_4) = 7$, and $A(v_5) = 2$ is a minimum span assignment for V subject to the UHF taboos. Similarly $B: V \rightarrow \{1, 2, 3, 4, 5, 6, 7\}$ defined by $B(v_1) = 2$ and $B(v_i) = A(v_i)$ for $i = 2, 3, 4, 5$ is a minimum-order assignment for V which is more desirable than A . Fig. 3 depicts this example graphically. In this figure, transmitters separated by any distance d that is equal to or less than the cochannel distance requirement ($d(0) = 155$) are connected by a line and this line is labeled with $T(i)$ if $d(i+1) < d \leq d(i)$. Thus, if two transmitters v_i and v_j are connected by a line that is labeled with $T(i)$ then any feasible assignment A must have the property $|A(v_i) - A(v_j)|$ is not an element of $T(i)$ (e.g., $|A(v_2) - A(v_5)|$ cannot belong to $\{0, 7, 14, 15\}$, $|A(v_2) - A(v_5)|$ cannot belong to $\{0, 1, 7, 14, 15\}$, etc.). The numerals adjacent to the transmitter locations constitute the minimum span assignment A . The numerals in parentheses constitute the minimum-order assignment B .

F. A General Minimum Span Channel Assignment Problem (F*D-CAP)

If $d(0) > d(1) > \dots > d(m) > 0$ are rational numbers and $\{0\} = T(0) \subset T(1) \subset \dots \subset T(m)$ are finite subsets of Z_0^+ then $R = \{(T(i), d(i)) | i = 0, \dots, m\}$ is called a set of F*D-constraints. If $k \geq 0$ and k is an element of $T(j)$ but k is not an element of $T(j-1)$, then the pair $(T(j), d(j))$ is called R 's k th-channel constraint, and $d(j)$ is called R 's k th-channel distance constraint. R 's 0th-channel constraint is also called R 's cochannel constraint; R 's 1st-channel constraint is also called R 's adjacent channel constraint; and for $k \geq 2$, R 's k th channel constraint is also called R 's k th adjacent channel constraint.

Let V be a finite subset of the plane and let $R = \{(T(i), d(i)) | i = 0, 1, \dots, m\}$ be a set of F*D constraints. If $A: V \rightarrow Z^+$ satisfies: $|A(u) - A(v)|$ is not an element of

$$T(i) \text{ whenever } u \neq v \text{ and } D(u, v) \leq d(i), \quad \text{for } i = 0, 1, \dots, m, \quad (6)$$

then A is called a feasible assignment for V and R . Thus, if the distance between two transmitters u and v is less than or equal to $d(i)$, then certain combinations of assignments to this pair of transmitters are taboo. In particular, any assignment in which $|A(u) - A(v)|$ is an element of $T(i)$ is forbidden by condition (6).

Let $F(V, R)$ denote the set of all feasible assignments for V and R . Let ℓ belong to Z^+ and let $F(V, R, \ell)$ denote $\{A \mid A \text{ is an element of } F(V, R) \text{ and } \max A(V) \leq \ell\}$. If $|V| = n$, then let $M = 1 + \max \{T(i) \mid i = 0, \dots, m\}$ and let $M(V, R) = 1 + (n - 1)M$.

Theorem 3: If $\ell \geq M(V, R)$, then $F(V, R, \ell)$ is not empty.

Proof: Let $v_1, v_2, \dots, v_n$ be a list of V and define $A: V \rightarrow \{1, 2, \dots, \ell\}$ by $A(v_i) = 1 + (i - 1)M$ for $i = 1, 2, \dots, n$. It is easy to see that A is feasible for V and R and that $\max A(V) = M(V, R)$. Q.E.D.

Since $F(V, R, \ell) \subseteq F(V, R)$ for each ℓ , we have the following result as a corollary to Theorem 3.

Theorem 4: $F(V, R)$ is not empty.

If A is an element of $F(V, R)$ then we say that $\ell = \max A(V)$ accommodates V and R . The smallest such ℓ is denoted $m(V, R)$ and is called the *minimum span of a feasible assignment for V and R* . Thus $m(V, R) = \min \{\max A(V) \mid A \text{ is an element of } F(V, R)\}$ and the following results are immediate.

Theorem 5: $F(V, R, \ell)$ is not empty if and only if $\ell \geq m(V, R)$.

Theorem 6: $m(V, R) \leq M(V, R)$.

If A is an element of $F(V, R)$ and $\max A(V) = m(V, R)$ then A is called a *minimum span assignment for V and R* . We now formulate a general minimum span search problem called the *F*D constrained channel assignment problem*.

F*D-CAP

INSTANCE: V a finite subset of the plane, and R a set of F*D constraints.

FIND: $A: V \rightarrow \{1, \dots, m(V, R)\}$ a minimum span assignment for V and R .

Recall that an algorithm solves F*D-CAP if, given V and R as input, it returns a minimum span assignment for V and R . Since $F(V, R, \ell)$ is finite and nonempty (where $\ell = M(V, R)$) an exhaustive search will yield a minimum span assignment for V and R .

Theorem 7: If V is a finite subset of the plane and R is a set of F*D constraints, then there exists $A: V \rightarrow \{1, \dots, m(V, R)\}$ a minimum span assignment for V and R .

Theorem 8: F*D-CAP is decidable.

Example Four: An algorithm which solves F*D-CAP also solves any subproblem of F*D-CAP. Each of the minimum span search problems discussed earlier in the section are subproblems of F*D-CAP and may be obtained from F*D-CAP by restricting the form of R . For example, F*D-CCAP is obtained when R is restricted to have the form $\{(\{0\}, d(0))\}$; F*D-ACAP is obtained when R is restricted to have the form $\{(\{0\}, d(0)), (\{0, 1\}, d(1))\}$; and F*D-UHF is obtained when $R = \{(\{0\}, 155), (\{0, 15\}, 75), (\{0, 7, 14, 15\}, 60), (\{0, 1, 7, 14, 15\}, 55), (\{0, 1, 2, 3, 4, 5, 7, 8, 14, 15\}, 20)\}$.

G. A General Minimum-Order Assignment Problem with Limited Bandwidth (F*D-CAPOL)

If A is an element of $F(V, R)$, then $|A(V)|$ is called the order of A and is denoted $o(A)$. Thus $o(A)$ is the number of channels actually used by A . If $\ell \geq m(V, R)$ and $L = \{1, 2, \dots, \ell\}$, then $\min \{o(A) \mid A \text{ is an element of } F(V, R, \ell)\}$ is called the *minimum order of a feasible assignment for V and R in L* and is denoted $o(V, R, \ell)$. Let $m_0(V, R, \ell)$ denote $\min \{\max A(V) \mid A \text{ is an element of } F(V, R, \ell) \text{ and } o(A) = o(V, R, \ell)\}$. If A belongs to $F(V, R, \ell)$, $o(A) = o(V, R, \ell)$, and

$\max A(V) = m_0(V, R, \ell)$, then A is called a *minimum-order assignment for V and R in L* . We are now ready to formulate a minimum-order search problem called the *F*D-constrained minimum-order channel assignment problem with limited bandwidth*.

F*D-CAPOL

INSTANCE: V a finite subset of the plane, R a set of F*D-constraints and $\ell \geq m(V, R)$.

FIND: $A: V \rightarrow L = \{1, 2, \dots, \ell\}$ a minimum-order assignment for V and R in L .

By Theorem 5, $F(V, R, \ell)$ is not empty when $\ell \geq m(V, R)$. Therefore, by exhaustive search there is a feasible assignment $A: V \rightarrow L$ which uses exactly $o(V, R, \ell)$ channels and no assignment A' which is an element of $F(V, R, \ell)$ uses fewer than $o(V, R, \ell)$ channels. Again by exhaustive search (this time on the nonempty finite set $\{A \mid A \text{ is an element of } F(V, R, \ell) \text{ and } o(A) = o(V, R, \ell)\}$) there is a feasible assignment $A: V \rightarrow \{1, 2, \dots, m_0(V, R, \ell)\}$ which uses exactly $o(V, R, \ell)$ channels and $m_0(V, R, \ell) \leq \ell$ is the smallest number of channels that will accommodate such an assignment. We formalize these results as theorems.

Theorem 9: If $\ell \geq m(V, R)$, then there exists $A: V \rightarrow L = \{1, 2, \dots, \ell\}$ a minimum-order assignment for V and R in L .

Theorem 10: F*D-CAPOL is decidable.

An algorithm which solves F*D-CAPOL also solves any subproblem of F*D-CAPOL including F*D-CCAPOL, F*D-ACAPOL, and F*D-UHFOL (where these subproblems are obtained by restricting the form of R exactly as was done in Example Four). In Example One above, A is a minimum span assignment for V and R but is not a minimum-order assignment for V and R in $L = \{1, \dots, 6\}$. Therefore, F*D-ACAP is not equivalent to F*D-ACAPOL. We shall see (Theorem 15 below), however, that F*D-CCAPOL is equivalent to F*D-CCAP.

If $R = \{(T(i), d(i)) \mid i = 0, \dots, m\}$ is a set of F*D constraints, then let R_c denote $\{(T(0), d(0))\}$, R 's cochannel constraint. Let $m_c(V, R)$ denote $\max A(V)$ where A is an optimal assignment for V and R_c . Notice that V and R_c is an instance of F*D-CCAP and that $\{1, \dots, m_c(V, R)\}$ is the smallest set of channels which will accommodate a feasible assignment for V , when only R 's cochannel constraint must be satisfied. We will show that for every $\ell \geq m(V, R)$, $m_c(V, R)$ is a lower bound on the minimum order of a feasible assignment for V and R in L .

Theorem 11: If A is an element of $F(V, R, \ell)$, then $o(A) \leq \max A(V)$.

Proof: $A(V) \subseteq \{1, \dots, \max A(V)\}$ therefore $o(A) \leq \max A(V)$. Q.E.D.

Theorem 12: If A is an element of $F(V, R, \ell)$ and $\max A(V) = m_c(V, R)$, then A is an element of $F(V, R_c)$ and $o(A) = m_c(V, R)$.

Proof: If A is an element of $F(V, R, \ell)$, and u and v are elements of V , then $|A(u) - A(v)|$ is not an element of $T(i)$ whenever $u \neq v$ and $D(u, v) \leq d(i)$ for each $i = 0, 1, \dots, m$. Therefore, $|A(u) - A(v)| \neq 0$ whenever $u \neq v$ and $D(u, v) \leq d(0)$ since 0 is an element of $T(i)$ for each $i = 0, \dots, m$. In other words, A is an element of $F(V, R_c)$. By Theorem 11, $o(A) \leq \max A(V) = m_c(V, R)$. Assume that $o(A) \neq m_c(V, R)$ and therefore that $o(A) < m_c(V, R)$. It follows that $A(V)$ is a proper subset of $\{1, \dots, m_c(V, R)\}$. Therefore, let M be the largest element of $\{1, \dots, m_c(V, R)\}$ which is not in $A(V)$

and define $A: V \rightarrow \{1, \dots, M\}$ by $A'(v) = M$ if $A(v) = m_c(V, R)$ and $A'(v) = A(v)$ otherwise. Now A' is an element of $F(V, R_c)$ since if u and v are elements of V and $u \neq v$:

Case 1: If $A(u) \neq m_c(V, R)$ and $A(v) = m_c(V, R)$, then $A'(u) = A(u)$ is an element of $A(V)$, $A'(v) = M$ is not an element of $A(V)$ and therefore $A'(u) \neq A'(v)$:

Case 2: If $A(u) = A(v) = m_c(V, R)$, then $D(u, v) > d(0)$;

Case 3: If $A(u) \neq m_c(V, R)$ and $A(v) \neq m_c(V, R)$, then $|A'(u) - A'(v)| = |A(u) - A(v)| \neq 0$ since A is an element of $F(V, R_c)$.

Therefore, we have A' is an element of $F(V, R_c)$ and by definition of A' , $\max A'(v) = M < m_c(V, R)$. This is impossible since by definition $m_c(V, R) = \min \{\max A(V) | A \text{ is an element of } F(V, R_c)\}$. Therefore $o(A) = m_c(V, R)$. Q.E.D.

Theorem 13: If A is an element of $F(V, R, \ell)$ and $\max A(V) = m_c(V, R)$, then $A(V) = \{1, 2, \dots, m_c(V, R)\}$.

Proof: $A(V) \subseteq \{1, 2, \dots, m_c(V, R)\}$ by Theorem 11, and inclusion cannot be proper since otherwise $o(A) < m_c(V, R)$ which is impossible by Theorem 12. Q.E.D.

Theorem 14: If A is an element of $F(V, R, \ell)$ and $\max A(V) = m_c(V, R)$, then $o(A) = m_c(V, R) = o(V, R, \ell) = m_0(V, R, \ell)$.

Proof: By Theorem 12, $o(A) = m_c(V, R)$ and by definition $o(V, R, \ell) \leq o(A) = m_c(V, R)$. Suppose that, $o(V, R, \ell) < o(A)$ and let A' be an element of $F(V, R, \ell)$ such that $o(A') = o(V, R, \ell)$. Let C_i , $i = 1, \dots, o(A')$ be an indexing of $A'(V)$ and define $A'': V \rightarrow \{1, 2, \dots, o(A')\}$ by $A''(v) = i$ if $A'(v) = C_i$. Now A'' is an element of $F(V, R_c)$ and $\max A''(V) = o(A') < m_c(V, R)$ which is impossible. Therefore $o(A) = o(A') = o(V, R, \ell)$. We now have A is an element of $F(V, R, \ell)$ and $o(A) = o(V, R, \ell)$, therefore, by definition of $m_0(V, R, \ell)$, $\max A(V) \geq m_0(V, R, \ell)$. But $m_c(V, R) = \max A(V) > m_0(V, R, \ell)$ is impossible since if A^* is a minimum-order assignment for V and R in L , then A^* is an element of $F(V, R_c)$ (by Theorem 12) and $\max A^*(V) = m_0(V, R, \ell) \geq m_c(V, R)$ by definition of $m_c(V, R)$. Q.E.D.

The following result is an immediate corollary.

Theorem 15: F*D-CCAP is equivalent to F*D-CCAPOL.

Theorem 16: If A is an element of $F(V, R)$, then $m_c(V, R) \leq o(A)$.

Proof: Suppose $o(A) < m_c(V, R)$ and let C_i , $i = 1, \dots, o(A)$, be an indexing of $A(V)$. Define $A': V \rightarrow \{1, 2, \dots, o(A)\}$ by $A'(v) = i$ if $A(v) = C_i$. Clearly A is an element of $F(V, R_c)$ and $\max A'(V) = o(A) < m_c(V, R)$ which is impossible. Q.E.D.

As promised, we have the following result as a corollary.

Theorem 17: If $\ell \geq m(V, R)$, then $m_c(V, R) \leq o(V, R, \ell)$.

By Example One, $m_c(V, R)$ is the best possible lower bound. Taking into account Theorem 15, we say that A an element of $F(V, R)$ is a minimum-order feasible assignment for V and R if $o(A) = m_c(V, R)$. Let $F_0(V, R)$ denote the set of all such assignments. Let ℓ be an element of Z^+ and let $F_0(V, R, \ell)$ denote $\{A | A \text{ is an element of } F_0(V, R) \text{ and } \max A(V) \leq \ell\}$. Let $M = 1 + \max \{\max T(i) | i = 0, \dots, m\}$ and let $M_0(V, R) = 1 + (m_c(V, R) - 1)M$.

Theorem 18: If $\ell \geq M_0(V, R)$, then $F_0(V, R, \ell)$ is not empty.

Proof: By Theorem 1, there exists A' an element of $F(V, R_c)$ such that $A': V \rightarrow \{1, 2, \dots, m_c(V, R)\}$. For each $i = 1, \dots, m_c(V, R)$ denote $\{v | A'(v) = i\}$ by V_i . Define $A: V \rightarrow \{1, 2, \dots, \ell\}$ by $A(v) = 1 + (i - 1)M$ for each v an element of V_i (where $M = 1 + \max \{\max T(i) | i = 0, \dots, m\}$). It

is easy to show that A is an element of $F_0(V, R)$ and that $\max A(V) = M_0(V, R) \leq \ell$. Q.E.D.

Theorem 19: $F_0(V, R)$ is not empty.

H. A General Minimum-Order Assignment Problem With Unlimited Bandwidth (F*D-CAPO)

The integer $\min \{\max A(V) | A \text{ is an element of } F_0(V, R)\}$ is called the minimum span of a minimum-order feasible assignment for V and R and is denoted $m_0(V, R)$. If A is an element of $F_0(V, R)$ and $\max A(V) = m_0(V, R)$, then A is called a minimum-order assignment for V and R . The following results are immediate.

Theorem 20: $F_0(V, R, \ell)$ is not empty if and only if $\ell \geq m_0(V, R)$.

Theorem 21: $m_0(V, R) \leq M_0(V, R)$.

We are now ready to formulate a second minimum-order search problem called the F*D-constrained minimum-order assignment problem (with unlimited bandwidth).

F*D-CAPO

INSTANCE: V a finite subset of the plane, and R a set of F*D-constraints.

FIND: $A: V \rightarrow \{1, 2, \dots, m_0(V, R)\}$ a minimum-order assignment for V and R .

Theorem 22: If V is a finite subset of the plane, and R is a set of F*D rules, then there exists a minimum-order assignment for V and R .

Proof: By Theorem 18, if $\ell = M_0(V, R)$, then $F_0(V, R, \ell)$ is finite and not empty. Thus an exhaustive search will yield a minimum-order assignment for V and R . Q.E.D.

Theorem 23: F*D-CAPO is decidable.

Any algorithm which solves F*D-CAPO also solves F*D-CCAPO, F*D-ACAPO, and F*D-UHFO (where these subproblems of F*D-CAPO are obtained by restricting the form of R exactly as was done in Example Four).

Theorem 24: If A is an element of $F(V, R, \ell)$ and $\max A(V) = m_c(V, R)$, then $o(A) = m_c(V, R) = o(V, R, \ell) = m(V, R) = m_0(V, R, \ell) = m_0(V, R)$.

Proof: See Theorem 14.

Q.E.D.

We have the following two results as corollaries.

Theorem 25: If $m_c(V, R) = m(V, R)$ and $\ell \geq m(V, R)$, then $m_c(V, R) = o(V, R, \ell) = m(V, R) = m_0(V, R, \ell) = m_0(V, R)$.

Theorem 26: F*D-CCAPO is equivalent to F*D-CCAP.

F*D-ACAPO is not equivalent to F*D-ACAP by Example One.

Theorem 27: If $\ell \geq m(V, R)$, then $m_c(V, R) \leq m(V, R) \leq m_0(V, R, \ell)$.

Proof: By the definitions of $m_c(V, R)$, $m(V, R)$, $m_0(V, R, \ell)$ and the fact that $F(V, R, \ell) \subseteq F(V, R) \subseteq F(V, R_c)$. Q.E.D.

Theorem 28: If $\ell \geq m(V, R)$, then $m_c(V, R) \leq o(V, R, \ell) \leq m(V, R)$.

Proof: By definition $o(V, R, \ell) = \min \{o(A) | A \text{ is an element of } F(V, R, \ell)\}$. Therefore, $m_c(V, R) \leq o(V, R, \ell)$ by Theorem 16, and $o(V, R, \ell) \leq m(V, R)$ by Theorem 11. Q.E.D.

Theorem 29: If $\ell \geq m(V, R)$, then $m_c(V, R) \leq o(V, R, \ell) \leq m(V, R) \leq m_0(V, R, \ell) \leq m_0(V, R)$.

Proof: It remains to show that $m_0(V, R, \ell) \leq m_0(V, R)$. Suppose to the contrary that $m_0(V, R, \ell) > m_0(V, R)$. Let A

be an element of $F(V, R, \ell)$ such that $o(A) = o(V, R, \ell)$ and $\max A(V) = m_0(V, R, \ell)$. Now $m_0(V, R, \ell) > m_0(V, R)$ implies that if A' is an element of $F(V, R)$ such that $o(A') = m_c(V, R)$, then $\max A'(V) < m_0(V, R, \ell) = \max A(V)$. Thus it follows that $A'(V) \subseteq \{1, \dots, \max A(V)\} \subseteq \{1, \dots, \ell\}$ and A' is an element of $F(V, R, \ell)$. By definition of $o(V, R, \ell)$, we have, $o(V, R, \ell) \leq o(A') = m_c(V, R)$ and by Theorem 16, $o(V, R, \ell) = m_c(V, R)$. Now, by definition, $m_0(V, R, \ell) \leq \max A'(V)$ which contradicts the above result that $\max A'(V) < m_0(V, R, \ell)$. Q.E.D.

Example Two shows that each of the inequalities in Theorem 29 may be strict. That is, for $\ell = 6$, $m_c(V, R) < o(V, R, \ell)$ and $m_0(V, R, \ell) < m_0(V, R)$; and for $\ell = 7$, $o(V, R, \ell) < m(V, R)$ and $m(V, R) < m_0(V, R, \ell)$.

Theorem 30: If $\ell' \geq \ell \geq m(V, R)$ then $o(V, R, \ell') \leq o(V, R, \ell)$ and $m_0(V, R, \ell) \leq m_0(V, R, \ell')$.

Proof: $o(V, R, \ell') \leq o(V, R, \ell)$ by definition of $o(V, R, \ell)$ since $F(V, R, \ell) \subseteq F(V, R, \ell')$. $m_0(V, R, \ell) > m_0(V, R, \ell')$ leads to a contradiction by an argument identical to the one in the Proof of Theorem 29. Q.E.D.

Theorem 31: If, $\ell \geq m_0(V, R)$, then $m_c(V, R) = o(V, R, \ell)$ and $m_0(V, R, \ell) = m_0(V, R)$.

Proof: By Theorem 29, $m_c(V, R) \leq o(V, R, \ell)$. Suppose $m_c(V, R) < o(V, R, \ell)$, and let A be an element of $F(V, R, \ell)$ such that $o(A) = o(V, R, \ell)$ and $\max A(V) = M_0(V, R, \ell)$. Now, $o(V, R, \ell) > m_c(V, R)$ implies that if A' is an element of $F(V, R)$ such that $o(A') = m_c(V, R)$, then $m_c(V, R) = o(A') \leq \max A'(V) < m_0(V, R, \ell) = \max A(V)$. Thus A' is an element of $F(V, R, \ell)$ and $o(V, R, \ell) \leq o(A') = m_c(V, R)$, a contradiction. By Theorem 29, $m_0(V, R, \ell) \leq m_0(V, R)$. Now, let A be an element of $F(V, R, \ell)$ such that $o(A) = o(V, R, \ell)$. By what has already been shown, we have $o(V, R, \ell) = m_c(V, R)$. Therefore A is an element of $F(V, R, \ell) \subseteq F(V, R)$ and $o(A) = m_c(V, R)$. By definition, $m_0(V, R) \leq \max A(V) = m_0(V, R, \ell)$. Q.E.D.

I. A Summary of the Theory

At the beginning of this section, we promised to investigate the cochannel, minimum span, and minimum-order assignment problems, and to develop a theory which would illuminate the relationships among these problems. We have shown that the cochannel assignment problem plays a central role and serves to tie the other two problems together. In particular, we have demonstrated that: all of the search problems considered in this section (i.e., F*D-CAP, F*D-CAPOL, F*D-CAPO, and all subproblems of these) have algorithmic solutions (Theorems 2, 8, 10, and 23); if one is interested in merely minimizing the span of an assignment, then $m(V, R)$ channels will suffice and if any more are allocated they are wasted (Theorem 7); a minimum span assignment may tie up more channels than necessary (Examples One and Two); a minimum-order assignment (bandwidth limited or not) never ties up more channels than does a minimum span assignment and may tie up fewer channels (Theorem 28, Examples One and Two); a minimum-order assignment ties up at least $m_c(V, R)$ (the number of channels tied up by an optimal assignment for the cochannel subproblem) channels and possibly more (Theorem 16 and Example Two); as the number of channels available for assignment increases from $m(V, R)$ to $m_0(V, R)$ the number of channels tied up by a minimum-order assignment decreases from $m(V, R)$ to $m_c(V, R)$ (Theorem 30); if one is interested in minimizing the order of an assignment, then $m_0(V, R)$ channels will suffice and if any more are allocated they are wasted (Theorems 22 and 31); the minimum span and minimum-order

assignment problems intersect in the cochannel assignment problem (Theorems 15 and 26).

More concretely, if V is a set of locations of UHF-TV stations in the Eastern U.S., and R is the collection of UHF taboos (see Example Three) for this region, then a minimum span assignment for V and R requires exactly $m(V, R)$ channels. If the number of contiguous channels available for assignment is smaller than $m(V, R)$ then there is no assignment of channels to V that satisfies each of the UHF taboos. If R_c denotes R 's cochannel constraint (i.e., $R_c = \{\{0\}, 155\}$) then $m_c(V, R) = m(V, R_c)$ the span (and the order) of an optimal assignment for V and R_c is equal to or less than both the span and the order of any feasible assignment for V and R . If there are $m_0(V, R)$ contiguous channels available for assignment, then there is a feasible assignment for V and R which uses exactly $m_c(V, R)$ of the $m_0(V, R)$ contiguous channels. The span of such an assignment is exactly $m_0(V, R)$. If there are C contiguous channels available for assignment and $m(V, R) \leq C < m_0(V, R)$, then each feasible assignment for V and R in C has order greater than $m_c(V, R)$.

IV. FREQUENCY CONSTRAINED CHANNEL ASSIGNMENT PROBLEMS

The search problems discussed in Section III model existing and potential real world problems (e.g., the present UHF-TV problem and potential future variations upon this problem). These search problems are important but limited in scope. Important existing and potential problems do not use distance separation to mitigate interference. For example, fixed distance separation plays no role if the transmitters are mobile, if the transmitters are colocated, or if the distance between transmitters is insignificant. In this section, we develop an approach to channel assignment problems for this more complex situation. In particular, we model frequency constrained channel assignment problems (both minimum span and minimum order) as search problems; we show that these search problems extend the search problems of Section III to this more complex situation; and for these more general problems we indicate how to develop a theory that parallels the theory of Section III.

A. The Problems: F-CCAP, F-CAP, F-CAPOL, and F-CAPO

In each of the papers [8]–[10], [17] a frequency separation matrix serves as a set of interference limiting constraints. To illustrate, if $V = \{1, 2, \dots, n\}$ denotes a set of transmitters and $t(i, j)$ is the set of forbidden channel separations for transmitters i and j , then the $n \times n$ matrix $[t(i, j)]$ is a convenient way to display and/or store these forbidden channel separations (see Example Five below for concrete illustrations). A matrix such as $[t(i, j)]$ is a natural way to model interference limiting constraints which employ only frequency separation to mitigate potential interference (e.g., if the transmitters to which channels must be assigned are colocated, the distance separations are small enough to be insignificant or the transmitters are mobile). We now formalize such a matrix approach to frequency constrained channel assignment problems.

Let $P^*(Z_0^+) = \{S \subseteq Z_0^+ | S \text{ is empty or } S \text{ is finite and } 0 \text{ is an element of } S\}$, and let $V = \{1, 2, \dots, n\}$. If $t: V \times V \rightarrow P^*(Z_0^+)$ satisfies $t(i, j) = t(j, i)$ and $t(i, i) = \{ \}$ for all i and j in V , then t is called a *channel separation matrix* for V . If $A: V \rightarrow Z^+$ satisfies

$$|A(i) - A(j)| \text{ does not belong to } t(i, j), \quad \text{for all } i \text{ and } j \text{ in } V \quad (1)$$

then A is called a *feasible assignment* for V and t . The elements of V may be thought of as names for a set of n transmitters. Thus (1) requires that transmitters i and j not be assigned to channels with forbidden channel separations. If t is a channel separation matrix for V , then define $t_c: V \times V \rightarrow P^*(Z_0^+)$ by

$$t_c(i, j) = \begin{cases} \text{the empty set if } t(i, j) \text{ is empty} \\ \{0\} \text{ if } t(i, j) \text{ is not empty.} \end{cases}$$

Clearly, t_c is a channel separation matrix for V , and if t' is any channel separation matrix for V such that $t'(i, j) \subseteq t(i, j)$ for each i and j in V , then $t_c(i, j) \subseteq t'(i, j)$ for each i and j in V . Also, if A is a feasible assignment for V and t_c , then (1) requires that $A(i) \neq A(j)$ whenever $t_c(i, j) = \{0\}$. Therefore, t_c is called t 's *cochannel submatrix*.

If t is a channel separation matrix for V , then let $F(V, t)$ denote the set of all feasible assignments for V and t . Let $m(V, t)$ denote $\min \{\max A(V) | A \text{ is an element of } F(V, t)\}$. If A is an element of $F(V, t_c)$ and $\max A(V) = m(V, t_c)$, then A is called an *optimal assignment* for V and t_c . We now formulate the *frequency constrained cochannel assignment problem*.

F-CCAP

INSTANCE: t a channel separation matrix for $V = \{1, \dots, n\}$.

FIND: An optimal assignment for V and t_c .

If A is an element of $F(V, t)$ and $\max A(V) = m(V, t)$ then A is called a *minimum span assignment* for V and t . We now formulate the *frequency constrained minimum span assignment problem*.

F-CAP

INSTANCE: t a channel separation matrix for V .

FIND: A minimum span assignment for V and t .

If $\ell \geq m(V, t)$ then, let $F(V, t, \ell)$ denote $\{A | A \text{ is an element of } F(V, t) \text{ and } \max A(V) \leq \ell\}$; let $o(V, t, \ell)$ denote $\min \{o(A) | A \text{ is an element of } F(V, t, \ell)\}$; and let $m_0(V, t, \ell)$ denote $\min \{\max A(V) | A \text{ is an element of } F(V, t, \ell) \text{ and } o(A) = o(V, t, \ell)\}$. If A is an element of $F(V, t, \ell)$, $o(A) = o(V, t, \ell)$, $\max A(V) = m_0(V, t, \ell)$, and $L = \{1, 2, \dots, \ell\}$, then A is called a *minimum-order assignment* for V and t in L . We now formulate the *frequency constrained minimum-order assignment problem* (with limited bandwidth).

F-CAPOL

INSTANCE: t a channel separation matrix for V and $\ell \geq m(V, t)$.

FIND: A minimum-order assignment for V and t in $L = \{1, \dots, \ell\}$.

Let $m_c(V, t)$ denote $m(V, t_c)$. If A is an element of $F(V, t)$ and $o(A) = m_c(V, t)$ then A is called a *minimum-order assignment* for V and t . Let $F_0(V, t)$ denote the set of all such assignments. The integer $\min \{\max A(V) | A \text{ belongs to } F_0(V, t)\}$ is called the *minimum span of a minimum-order feasible assignment* for V and t and is denoted $m_0(V, t)$. If A is an element of $F_0(V, t)$ and $\max A(V) = m_0(V, t)$, then A is called a *minimum-order assignment* for V and t . We now formulate the *frequency constrained minimum-order assignment problem*.

F-CAPO

INSTANCE: t a channel separation matrix for V .

FIND: A minimum-order assignment for V and t .

B. Frequency Constrained Problems Generalize F*D Constrained Problems

The problems F-CCAP, F-CAP, F-CAPOL, and F-CAPO are called frequency constrained problems since superficially, at least, they employ only frequency separation to mitigate interference. We now show that any set of F*D constraints may be replaced by an equivalent channel separation matrix, and therefore the problems of this section contain the corresponding problems of Section III as subproblems.

Let $V = \{v_1, \dots, v_n\}$ be a subset of the plane and let $R = \{(T(i), d(i)) | i = 0, \dots, m\}$ be a set of F*D constraints. Let $V' = \{1, \dots, n\}$ and define $t': V' \times V' \rightarrow P^*(Z_0^+)$ as follows: if $i \neq j$ and k is the smallest integer for which $D(v_i, v_j) \leq d(k)$, then $t'(i, j) = T(k)$ and otherwise $t'(i, j)$ equals the empty set. If $A: V \rightarrow Z^+$, then define $A': V' \rightarrow Z^+$ by $A'(i) = A(v_i)$ for $i = 1, \dots, n$.

Theorem 32: A is feasible for V and R if and only if A' is feasible for V' and t' .

Proof: Suppose A is feasible for V and R . Case 1: if $v_i \neq v_j$ and k is the smallest integer for which $D(v_i, v_j) \leq d(k)$ then $|A'(i) - A'(j)| = |A(v_i) - A(v_j)|$ is not an element of $T(k) = t'(i, j)$. Case 2: otherwise $|A'(i) - A'(j)|$ is not an element of $\{ \} = t(i, j)$. Therefore A' is feasible for V' and t' . Conversely, suppose $|A'(i) - A'(j)|$ is not an element of $t'(i, j)$ for all i and j in V' . Also, suppose $v_i \neq v_j$ and $D(v_i, v_j) \leq d(\ell)$. Now $i \neq j$ and if k is the smallest integer for which $D(v_i, v_j) \leq d(k)$, then $t'(i, j) = T(k)$ and $|A(v_i) - A(v_j)| = |A'(i) - A'(j)|$ is not an element of $t'(i, j) = T(k) \subseteq T(\ell)$. Therefore, A is feasible for V and R . Q.E.D.

Example Five: F-ACAP, F-ACAPOL, and F-ACAPO and the subproblems of F-CAP, F-CAPOL and F-CAPO, respectively obtained by restricting $t(i, j)$ to be an element of $\{\{ \}, \{0\}, \{0, 1\}\}$. F-UHF, F-UHFOL, and F-UHFO are the subproblems of F-CAP, F-CAPOL, and F-CAPO, respectively obtained by restricting $t(i, j)$ to be an element of $\{\{ \}, \{0\}, \{0, 15\}, \{0, 7, 14, 15\}, \{0, 1, 7, 14, 15\}, \{0, 1, 2, 3, 4, 5, 7, 8, 14, 15\}\}$.

We have the following results as immediate corollaries of Theorem 32.

Theorem 33: F*D-CCAP, F*D-CAP, F*D-CAPOL, and F*D-CAPO are subproblems of F-CCAP, F-CAP, F-CAPOL, and F-CAPO, respectively.

Theorem 34: F*D-ACAP, F*D-ACAPOL, and F*D-ACAPO are subproblems of F-ACAP, F-ACAPOL and F-ACAPO, respectively.

Theorem 35: F*D-UHF, F*D-UHFOL, and F*D-UHFO are subproblems of F-UHF, F-UHFOL, and F-UHFO, respectively.

In Section VII, we will see that the converses of Theorems 33, 34, and 35 are not valid. Thus the frequency constrained matrix approach of this section is more general than the F*D approach of Section III. In addition, the matrix approach obscures the role played by distance separation and in this respect may hide (or encode) potentially useful information. In particular, efficient solutions for some important subproblems of F-CAP require that this encoded distance separation information be decoded. From this point of view F*D formulations of problems are more desirable. (This important point will be discussed at greater length in Section VII.)

The reader may easily verify that Theorems 1-31 of Section

III remain valid if F^*D and R are replaced in every occurrence by F and t , respectively. It may be beneficial to reread the summary at the end of Section III with this transformation in mind.

V. OTHER PROBLEMS

The main purpose of this paper is to provide a unifying theory which demonstrates that our formal modeling approach to assignment problems is a viable one that can handle the wide range of problems which arise (or may arise) in the real world. Up until now, we have restricted our attention to situations in which assignments are confined to discrete evenly spaced frequencies. As we shall see, our formal modeling approach is not limited to such problems.

Suppose there are two or more classes of transmitters C_i where all the transmitters in C_i have the same operating power P_i and the same operating bandwidth b_i but that $P_i \neq P_j$ and/or $b_i \neq b_j$ for $i \neq j$. In addition, suppose that ideally all the transmitters should be assigned to operating frequencies in the same region of the spectrum. Results of Section III (e.g., Examples One and Two, and Theorems 29, 30, and 31) suggest that spectrum may be conserved if these different classes were to share the same band in an interwoven fashion. In this section, we investigate F^*D and frequency constrained assignment problems that model this potentially useful interwoven approach to spectrum sharing. Two of these problems are not channel assignment problems, i.e., assignments are not restricted to discrete frequencies. We conclude this section with a discussion of other well-known assignment problems that are not channel or frequency assignment problems and note that some of these problems appear to be closely related to frequency assignment problems.

A. Interwoven Mixed Service with Variable Power Transmitters

For $i = 1, \dots, p$, let V_i denote the set of locations of all transmitters having power P_i and let d_i denote the cochannel separation distance for a pair of transmitters in V_i . The following search problem is a natural extension of F^*D -CCAP to this more complex variable power situation.

F^*D -CCAP(*)

INSTANCE: V a finite subset of the plane, $p \leq |V|$, $\{V_1, V_2, \dots, V_p\}$ a partition of V , and d_i an element of Q^+ for $i = 1, \dots, p$.

FIND: $A: V \rightarrow Z^+$ which satisfies the conditions:

$$\max A(V) \text{ is as small as possible} \quad (7)$$

and

$$|A(u) - A(v)| > 0 \text{ whenever } u \neq v, u \text{ is an element of } V_i, v \text{ is an element of } V_j \text{ and } D(u, v) \leq (d_i + d_j)/2. \quad (8)$$

More generally, if V_i and P_i are as above, let $R_j = \{(T_j(i), d_j(i)) | i = 0, \dots, m\}$ be a set of F^*D constraints for transmitters in V_j . Let $m = \max \{m_j | j = 1, \dots, p\}$ and for $j, k = 1, \dots, p$ defined T_{jk} and d_{jk} as follows:

$$T_{kk}(i) = \begin{cases} T_k(i), & \text{for } i = 0, \dots, m_k \\ T_k(m_k), & \text{for } i = m_k + 1, \dots, m \end{cases}$$

$$T_{jk}(i) = T_{jj}(i) \text{ union } T_{kk}(i), \quad \text{for } j, k = 1, \dots, p \text{ and } i = 0, \dots, m$$

$$d_{kk}(i) = \begin{cases} d_k(i), & \text{for } i = 0, \dots, m_k \\ 0, & \text{for } i = m_k + 1, \dots, m \end{cases}$$

$$d_{jk}(i) = (d_{jj}(i) + d_{kk}(i))/2, \quad \text{for } j, k = 1, \dots, p \text{ and } i = 0, \dots, m.$$

Clearly, $\{0\} = T_{jk}(0) \subseteq T_{jk}(1) \subseteq \dots \subseteq T_{jk}(m)$ and

$$d_{jk}(0) > d_{jk}(1) > \dots > d_{jk}(m) > 0.$$

Therefore, let $R = \{(T_{jk}(i), d_{jk}(i)) | j, k = 1, \dots, p \text{ and } i = 0, \dots, m\}$ be called a set of F^*D constraints for the mixed service $V = \{V_1, V_2, \dots, V_p\}$. The following search problem is a natural extension of F^*D -CAP to this more complex situation.

F^*D -CAP(*)

INSTANCE: V is a finite subset of the plane, $p \leq |V|$, and R a set of F^*D constraints for the mixed service $\{V_1, \dots, V_p\}$.

FIND: $A: V \rightarrow Z^+$ which satisfies (7) and $|A(u) - A(v)|$ is not an element of $T_{jk}(i)$ whenever $u \neq v$, u is an element of V_j , v is an element of V_k , and

$$D(u, v) \leq d_{jk}(i), \quad \text{for } j, k = 1, \dots, p \text{ and } i = 0, \dots, m. \quad (9)$$

An assignment $A: V \rightarrow Z^+$ which satisfies (7) and (9) is called a *minimum span assignment for V and R* . We must remark that the search problems F^*D -CAPOL(*) and F^*D -CAPO(*) in which we search for minimum-order assignments for V and R in L and minimum-order assignments for V and R (with obvious definitions), respectively, have the expected interrelationships with F^*D -CCAP(*) and F^*D -CAP(*). That is, Theorems 1-31, and analogs to Theorems 32, 33, and 34, and 35 remain valid for these problems. (Hint: if $i \neq j$, v_i is an element of V_k , v_j is an element of V_l and h is the smallest integer for which $D(v_i, v_j) \leq d_{kl}(h)$ then define $t'(i, j) = T_{kl}(h)$ and otherwise $t'(i, j) = \{\}$). In Section VII, we will see that the converses of Theorems 33, 34, and 35 are not valid for these problems.

B. Interwoven Mixed Service With Unevenly Spaced Discrete Frequencies

For $j = 1, \dots, p$, let V_j, P_j and R be as in the last paragraph, and let all the transmitters in V_j have operating bandwidth b_j belonging to Q^+ with $b_i \neq b_j$ when $i \neq j$. Let $B = \{b_1, \dots, b_p\}$. Now, in addition to allowing these different classes of transmitters to share the same band in an interwoven fashion also allow frequencies to be assigned to any element of $C'(B) = \{kb_i/2 | i = 1, \dots, p; k = 1, 3, 5, \dots\}$.

As motivation for this approach, consider that, in practice, many F^*D constraints result from the fact that assigning transmitters to discrete evenly spaced frequencies increases the potential for intolerable interference [82]. Intuition leads one to believe, therefore, that spectrum may be conserved by allowing transmitters to be assigned to unevenly spaced frequencies. In order, not to violate our convention that search problem assignments have the form $A: V \rightarrow Z^+$, let us rename the elements of $C'(B)$. That is, if $b_i = r_i/s_i$, then let 1cm be the least common multiple of $2, s_1, \dots, s_p$, and for $i = 1, \dots, p$

$$\text{let } r'_i = \begin{cases} 1\text{cm} \cdot r_i/s_i, & \text{if } s_1 \cdot s_2 \cdot \dots \cdot s_p \text{ is even} \\ 1\text{cm} \cdot r_i/2 \cdot s_i, & \text{otherwise.} \end{cases}$$

Now let $C(B) = \{1 + kr'_i | i = 1, \dots, p; k = 0, 1, 2, \dots\} \subseteq Z^+$. The following search problem is a natural extension of F*D-CAP(*) to this situation.

F*D-CAP(*; *)

INSTANCE: V a finite subset of the plane, $p \leq |V|$, R a set of F*D constraints for the mixed service $\{V_1, \dots, V_p\}$, and $B = \{b_1, \dots, b_p\} \subset Q^+$.

FIND: $A: V \rightarrow C(B)$ which satisfies (7) and $1/r'_Q \cdot |A(u) - A(v)|$ is not an element of $T_{jk}(i)$ whenever $u \neq v$, u is an element of V_j , v is an element of V_k , and $D(u, v) \leq d_{jk}(i)$ for $j, k, \ell = 1, \dots, p$ and $i = 0, \dots, m$. (10)

If $A: V \rightarrow C(B)$ satisfies (7) and (10) then A is called a *minimum span assignment* for V, R , and B . Condition (10) requires that u and v not be assigned to certain frequencies (namely those whose differences divided by r'_Q belongs to $T_{jk}(i)$) when u and v are separated by less than the minimum separation distance required by R . In particular, if R is restricted to have the form $\{(T_{jk}(0), d_{jk}(0)) | j, k = 1, \dots, p\}$, then the resulting subproblem is denoted F*D-CCAP(*; *), since in this case only cochannel assignments are constrained. The reader may define F*D-CAPO(*; *) and F*D-CAPO(*; *), and verify that propositions analogous to Theorems 1-35 remain valid for these problems.

C. Interwoven Mixed Service With No Restriction to Discrete Frequencies

Let V be a set of locations of transmitters. Let $|V| = n$, $p \leq n$, and $P = \{V_1, \dots, V_p\}$ be a partition of V . For $i = 1, \dots, p$ let P_i and b_i denote respectively the operating power and bandwidth of transmitters in V_i where $P_i \neq P_j$ and/or $b_i \neq b_j$ whenever $i \neq j$. If u is an element of V_j and v is an element of V_k , then let $S_{jk}(x)$ denote the minimum frequency separation required for assignments to u and v when $x = D(u, v)$; let $T_{jk}(x)$ denote the forbidden combinations of frequency assignments for u and v when $x = D(u, v)$; and let d_{jk} denote the cofrequency distance separation required of u and v . In practice, S_{jk} and T_{jk} may be functions of P_i, P_k, b_j, b_k , the rejection characteristics of receivers that tune to transmitters in V_j and V_k , etc. If m_{jk} and M_{jk} denote respectively the min and max of $\{D(u, v) | u \text{ is in } V_j \text{ and } v \text{ is in } V_k\}$, then $S_{jk}: [m_{jk}, M_{jk}]_Q \rightarrow [0, S_{jk}(m_{jk})]_Q$ and $T_{jk}: [m_{jk}, M_{jk}]_Q \rightarrow P^*(Z^+)$ where we, also, require that $D(u, v) = 0$ iff $u = v$; $S_{jk}(x) = 0$ and $T_{jk}(x) = \emptyset$ iff $d_{jk} < x \leq m_{jk}$ or $j = k$ and $x = 0$; and if $x > y$ then $S_{jk}(x) \leq S_{jk}(y)$ and $T_{jk}(x) \subseteq T_{jk}(y)$. Let $B = \{b_1, \dots, b_p\}$, $b = \min \{b_i/2 | i = 1, \dots, p\}$, $S = \{S_{jk} | j, k = 1, \dots, p\}$, $T = \{T_{jk} | j, k = 1, \dots, p\}$ and $I = (V, P, B, T, S)$.

If $A: V \rightarrow [b, \infty)$ satisfies: $A(v)$ is an element of Q for all v with $A(v) < \max A(V)$, $|A(u) - A(v)| \geq S_{jk}(D(u, v))$, and $\max \{A(u)/A(v), A(v)/A(u)\}$ is not an element of $T_{jk}(D(u, v))$ whenever $u \neq v$, u is in V_j and v is in V_k , then A is called a *feasible assignment* for I . Let $F(I)$ denote the set of all such assignments and for q an element of Q^+ let $F(I, q)$ denote $\{A | A \text{ is an element of } F(I) \text{ and } \max A(V) \leq q\}$. Let $v_1, \dots, v_n$ be a list of V such that v_1 is an element of V_i and $b = b_i/2$. If $A: V \rightarrow [b, \infty)$ is defined by $A(v_1) = b$ and for $i = 2, \dots, n$, $A(v_i) = (q_i + 1/n_i)A(v_{i-1})$ (where $q_i = A(v_{i-1}) + S_{jk}(D(v_{i-1}, v_i))$, and n_i is the smallest element of Z^+ such that $(q_i + 1/n_i)/A(v_{i-1})$ is not an element of $T_{jk}(D(v_{i-1}, v_i))$, v_{i-1} is an element of V_j , and v_i is an element of V_k), then A is an element of $F(I, q)$ when $q \geq A(v_n)$. Therefore, let $m(I)$ denote

$\inf \{\max A(V) | A \text{ is an element of } F(I)\}$. If A is an element of $F(I)$ and $\max A(V) = m(I)$ then A is called a *minimum span assignment* for I . The following optimization problem is called the *frequency-distance constrained frequency assignment problem*.

F*D-FAP

INSTANCE: $I = (V, P, B, T, S)$

FIND: A minimum span assignment for I .

We now formulate a frequency constrained generalization of F*D-FAP. Let $V = \{1, \dots, n\}$ be a set of transmitters, $[s(i, j)]$ be a symmetric $n \times n$ matrix where $s(i, j)$ is a nonnegative rational number that denotes the minimum frequency separation required of transmitters i and j , and let $[t(i, j)]$ be a symmetric $n \times n$ matrix where $t(i, j)$ (an element of $P^*(Z^+)$) represents the set of forbidden combinations of frequency assignments for i and j . In practice $s(i, j)$ and $t(i, j)$ may be functions of $D(i, j)$, the terrain surrounding i and j , the powers P_i and P_j of i and j , the bandwidths b_i and b_j of i and j , the rejection characteristics of receivers that tune to i and j , etc. We require that $s(i, i) = 0$ and that $t(i, j) = \emptyset$ iff $s(i, j) = 0$ for all i and j elements of V . Let $B = \{b_1, \dots, b_n\}$, $b = \min \{b_i/2 | i = 1, \dots, n\}$ and $I = (V, B, t, s)$.

If $A: V \rightarrow [b, \infty)$ satisfies: $A(v)$ is in Q for all v in V with $A(v) < \max A(V)$, $|A(i) - A(j)| \geq s(i, j)$ and $\max \{A(i)/A(j), A(j)/A(i)\}$ is not an element of $t(i, j)$ for all i and j in V , then A is called a *feasible assignment* for I . Let $F(I)$ denote the class of all such assignments and for q in Q^+ and let $F(I, q)$ denote $\{A | A \text{ is an element of } F(I) \text{ and } \max A(V) \leq q\}$. Now $F(I, q) \subset F(I)$ and if $A: V \rightarrow [b, \infty)$ is defined by $A(1) = b$ and for $i = 2, \dots, n$, $A(i) = (q_i + 1/n_i)A(i-1)$ (where $q_i = A(i-1) + s(i, i-1)$, and n_i is the smallest element of Z^+ such that $(q_i + 1/n_i)/A(i-1)$ is not an element of $t(i-1, i)$), then A is an element of $F(I, q)$ when $q \geq \max A(V)$. Therefore, let $m(I)$ denote $\inf \{\max A(V) | A \text{ is an element of } F(I)\}$. If A is an element of $F(I)$ and $\max A(V) = m(I)$, then A is called a *minimum span assignment* for I . The following optimization problem is called the *frequency constrained frequency assignment problem*.

F-FAP

INSTANCE: $I = (V, B, t, s)$

FIND: A minimum span assignment for I .

The reader may define $m_c(I)$, $o(I, q)$, $m_o(I, q)$, $m_o(I)$, F*D-CFAP, F*D-FAPOL, F*D-FAPO, F-CFAP, F-FAPOL, F-FAPO and verify that Theorems 1-35 (excepting 2, 8, 10, and 23) remain valid. The decidability of F*D-CFAP, F-CFAP, etc., are left as exercises for complexity theorists.

D. Other Combinatorial Optimization Problems

The assignment problems of this paper are special cases of a more general assignment problem. Given a collection of consumers who place demands upon a set of resources, find an assignment of consumers to resources that satisfies various constraints and that minimizes (or in some cases maximizes) a given objective function. The approach of this paper (i.e., the modeling of frequency assignment problems as search problems) has been effectively applied to other problems of the assignment type. To illustrate, in network routing problems, calls or packets are assigned to paths or links of the network in such a way that the number of simultaneous calls through the network is maximized or the average packet delay is mini-

mized; in school timetabling problems, instructional units are assigned to time periods, teachers, rooms, instructional equipment, or other resources in such a way that the consumed resource(s) is minimized; in computer job scheduling problems, jobs to be executed are assigned to starting times and processors in such a way that the earliest time at which all jobs are completed is minimized; and in the graph coloring problem, vertices are assigned colors in such a way that adjacent vertices are assigned different colors and the number of colors used is minimized.

We have not investigated frequency assignment problems in which the spectrum is time shared, but must remark that these problems appear to be closely related to the extensively studied computer job scheduling problems [83]–[88].

It is well known that the graph coloring problem is closely related to the cochannel assignment problem [5], [11], [12], [13] and to school timetabling problems [50], [51], [53]. In the next three sections, we extend and exploit the former relationship.

VI. GENERALIZED COLORING PROBLEMS

The papers [10], [12], [13] discuss the relationship of F*D-CCAP to the following search problem called the *coloring problem (CP)*.

CP

INSTANCE: $G = (V, E)$ a graph.

FIND: $A: V \rightarrow Z^+$ such that $\max A(V)$ is as small as possible and $A(u) \neq A(v)$ whenever uv is an element of E (such an assignment is called an *optimal coloring* for G , $\max A(V)$ is called the *chromatic number* of G and is denoted $X(G)$).

If $G = (V, E)$ is a graph and $t: E \rightarrow P(Z_0^+)$ then t is called an *edge constraint* for G and $G_t = (G, t)$ is called an *edge constrained graph*. If $A: V \rightarrow Z^+$ satisfies $|A(u) - A(v)|$ is not an element of $t(uv)$ whenever uv is an element of E , then A is called a *feasible coloring* for G and t . Let $F(G, t)$ denote the class of all such colorings, and let $X_1(G, t)$ denote $\min \{\max A(V) | A \text{ is an element of } F(G, t)\}$. If A is an element of $F(G, t)$ and $\max A(V) = X_1(G, t)$, then A is called a *minimum span coloring* for G and t . The integer $X_1(G, t)$ is called the *minimum span chromatic number* for G and t .

The following search problem extends CP to edge constrained graphs and is called the *generalized coloring problem*.

GCP

INSTANCE: $G = (V, E)$, and an edge constraint for G .

FIND: A minimum span coloring for G and t .

If A is an element of $F(G, t)$, then $|A(V)|$ is called the *order* of A and is denoted $o(A)$. If ℓ is an element of Z^+ , and $\ell \geq X_1(G, t)$, then let $F(G, t, \ell)$ denote $\{A | A \text{ is an element of } F(G, t) \text{ and } \max A(V) \leq \ell\}$, let $o(G, t, \ell)$ denote $\min \{o(A) | A \text{ is an element of } (G, t, \ell)\}$, and let $X_2(G, t, \ell)$ denote $\min \{\max A(V) | A \text{ is in } F(G, t, \ell) \text{ and } o(A) = o(G, t, \ell)\}$. If $L = \{1, \dots, \ell\}$, then $X_2(G, t, \ell)$ is called the *minimum-order chromatic number* for G and t in L . If A is an element of $F(G, t, \ell)$, $o(A) = o(G, t, \ell)$ and $\max A(V) = X_2(G, t, \ell)$, then A is called a *minimum-order coloring* for G and t in L . The following search problem extends the notion of bandwidth limited minimum-order assignment to graph coloring.

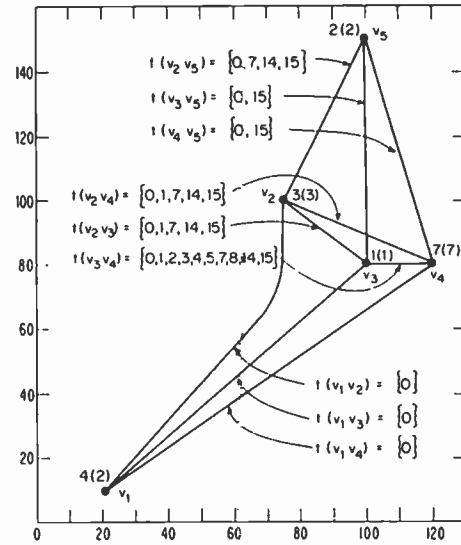


Fig. 3. Graphical depiction of the set of transmitter locations, the taboo combinations of channel assignments, the minimum span assignment A and the minimum-order assignment B of Example Three.

GCPOL

INSTANCE: $G = (V, E)$, t an edge constraint for G , and $L = \{1, \dots, \ell\}$ where $X_1(G, t) \leq \ell$.

FIND: A minimum-order coloring for G and t in L .

Let $G = (V, E)$ and define $c: E \rightarrow P(Z_0^+)$ by $c(uv) = \{0\}$ for all uv in E . Clearly, c is an edge constraint for G and if t is any edge constraint for G then $c(uv) \subseteq t(uv)$ for all uv in E . Therefore, c is called the *minimal edge constraint* for G , and by definition $X_1(G, c) = X(G)$. Also, as in Section III Theorem 16, $X(G) \leq o(A)$ for any A in $F(G, t)$. Thus $\min \{\max A(V) | A \text{ is an element of } F(G, t) \text{ and } o(A) = X(G)\}$ is denoted $X_2(G, t)$ and is called the *minimum order chromatic number* for G and t . If A is an element of $F(G, t)$, $o(A) = X(G)$ and $\max A(V) = X_2(G, t)$ then A is called a *minimum-order coloring* for G and t . The following search problem extends the notion of minimum order assignment (with unlimited bandwidth) to graph coloring.

GCPO

INSTANCE: $G = (V, E)$ and t an edge constraint for G .

FIND: A minimum-order coloring for G and t .

Example Six: Fig. 3 of Section III depicts an edge constrained graph generated by the UHF taboos and the set of transmitter locations V of Example Three. The $t(v_i, v_j)$'s in Fig. 3 are the values of the edge constraint imposed by the UHF taboos. Similarly, Figs. 1 and 2 depict edge constrained graphs generated by instances of F*D-ACAP. In addition, the minimum span (minimum-order) assignments illustrated in these figures are minimum span (minimum-order) colorings for the corresponding edge constrained graphs.

By the definitions, if $\ell \geq X(G)$, then $X(G) = o(G, c, \ell) = X_1(G, c) = X_2(G, c, \ell) = X_2(G, c)$ and the reader may verify that Theorems 1–31 and their proofs remain valid if V, R, m_c, m, m_0 , F*D-CCAP, F*D-CAP, F*D-CAPOL, and F*D-CAPOL are replaced in every instance by G, t, X, X_1, X_2 , CP, GCP, GCPOL, and GCPO, respectively.

Let G and t be as above and let $C \subseteq Z^+$. If $A: V \rightarrow C$ satisfies $|A(u) - A(v)|$ is not an element $t(uv)$ for all uv in E then A is called a *feasible coloring* for G , t , and C . Let $F(G, t, C)$ denote the class of all such colorings, and let $X_1(G, t, C)$ denote $\min \{\max A(V) | A \text{ is an element } F(G, t, C)\}$. If A is an element of $F(G, t, C)$ and $\max A(V) = X_1(G, t, C)$, then A is called a *minimum span coloring* for G , T and C . The following search problem extends GCP to the situation of unevenly spaced colors.

GCP(*)

INSTANCE: $G = (V, E)$, t an edge constraint for G , and $C \subseteq Z^+$.

FIND: A minimum span coloring for G , t , and C .

If $t: E \rightarrow P(Z_0^+)$ is an edge constraint for $G = (V, E)$, and $s: E \rightarrow Q^+$, then (V, E, t, s) is denoted G_{ts} and is called a *doubly edge constrained graph*. If $A: V \rightarrow R^+$ satisfies: $A(v)$ is an element of Q^+ for all v in V such that $A(v) < \max A(V)$, $|A(u) - A(v)| \geq s(uv)$ and $\max \{A(u)/A(v), A(v)/A(u)\}$ is not an element of $t(uv)$ for all uv in E , then A is called a *feasible coloring* for G , t and s . Let $F(G, t, s)$ denote the class of all such colorings and $X_1(G, t, s)$ denote $\inf \{\max A(V) | A \text{ is an element of } F(G, t, s)\}$. If A is an element of $F(G, t, s)$ and $\max A(V) = X_1(G, t, s)$, then A is called a *minimum span coloring* for G , t and s . The following optimization problem extends GCP to the situation in which there is a nondiscrete set of allowable colors.

GCP(*, *)

INSTANCE: $G = (V, E)$, $t: E \rightarrow P(Z_0^+)$, and $s: E \rightarrow Q^+$

FIND: A minimum span coloring for G , t and s .

The reader may define $CP(*)$, $GCPOL(*)$ and verify that theorems analogous to Theorems 1-31 remain valid for these problems. Similarly, analogs to Theorems 1-31 (excepting the proofs for 2, 8, 10, and 23) remain valid for the problems $C(*, *)$, $GCP(*, *)$, $GCPOL(*, *)$ and $GCPO(*, *)$.

VII. ASSIGNMENT PROBLEMS AS GENERALIZED COLORING PROBLEMS

An important element of the scientific approach to problem solving consists of attempting to show that the problem under study is closely related to a known, well-studied problem. In this section, we show that each of the frequency constrained problems of Sections IV and V is equivalent to a generalized graph coloring problem and that each of the F*D constrained problems of Sections III and V is equivalent to a generalized coloring problem restricted to a narrow subclass of the class of all graphs. From these results, it follows that the frequency constrained approach is more general than the frequency-distance constrained approach to assignment problems.

Recent developments in the theory of computational complexity allow for the classification of optimization problems according to the "execution time efficiency" of algorithms that may be devised for their solution. Informally, if an optimization problem is *NP-hard*, then it is very unlikely that a polynomial time solution will ever be devised. (The reader who is unfamiliar with the concept of NP-hardness and who would like more information on what is meant by "very unlikely" is referred to [23] for both a low-level introductory

and a rigorous treatment of these matters. In addition, the paper [24] presents an expository discussion of these matters.) Using recent results on the computational complexity of graph coloring together with the equivalences between frequency assignment problems and generalized graph coloring problems, we show that each of the assignment problems of Sections III, IV, and V is NP-hard, but that some important subproblems of these problems have efficient solutions.

A. Frequency Constrained Problems and Their Complexity

It is well known that CP is NP-hard [20] and that F-CCAP is related to CP [10]. In this paragraph, we show that F-CCAP, F-CAP, F-CAPOL, F-CAPO, F-CCAP(*, *), F-CAP(*, *), F-CAPOL(*, *), F-CAPO(*, *), F-CFAP, F-FAP, F-FAPOL and F-FAPO are equivalent to CP, GCP, GCPOL, GCPO, CP(*, *), GCP(*, *), GCPOL(*, *), GCPO(*, *), CP(*, *), GCP(*, *), GCPOL(*, *), and GCPO(*, *), respectively. From these equivalences and the NP-hardness of CP it follows that each of the twelve frequency constrained problems listed above is NP-hard.

Theorem 36: F-CCAP is equivalent to CP.

Proof: If $V = \{1, \dots, n\}$ and t_c is an instance of F-CCAP then let $E = \{ij | t_c(i, j) \neq \emptyset\}$. Now $G = (V, E)$ is an instance of CP and $A: V \rightarrow \{1, \dots, X(G)\}$ an optimal coloring for G is also an optimal assignment for V and t_c with $m(V, t_c) = X(G)$. Conversely, if $G = (V, E)$ is an instance of CP where $V = \{v_1, \dots, v_n\}$ then let $V' = \{1, \dots, n\}$ and define

$$t_c(i, j) = \begin{cases} \{0\} & \text{if } v_i v_j \text{ is in } E \\ \{\} & \text{otherwise.} \end{cases}$$

Now V' and t_c is an instance of F-CCAP and if $A': V' \rightarrow \{1, \dots, m(V', t_c)\}$ is an optimal assignment for V' and t_c , then $A: V \rightarrow Z^+$ defined $A(v_i) = A'(i)$ for all $i = 1, \dots, n$ is an optimal coloring for G and $X(G) = m(V, t_c)$. Q.E.D.

Theorem 37: F-CAP, F-CAPOL, and F-CAPO are equivalent to GCP, GCPOL, and GCPO, respectively.

Proof: If $V = \{1, \dots, n\}$, t and l is an instance of F-CAPOL, then let $E = \{ij | t(i, j) \neq \emptyset\}$ and continue as in the proof of Theorem 36. Q.E.D.

Theorem 38: F-CCAP(*, *) is equivalent to CP(*, *).

Proof: If $V = \{1, \dots, n\}$, t_c , and $C \subseteq Z^+$ is an instance of F-CCAP(*, *), then let $E = \{ij | t_c(i, j) \neq \emptyset\}$. Now $G = (V, E)$ and C is an instance of CP(*, *). Continue as in the proof of Theorem 36. Q.E.D.

Theorem 39: F-CAP(*, *), F-CAPOL(*, *), and F-CAPO(*, *) are equivalent to GCP(*, *), GCPOL(*, *) and GCPO(*, *), respectively.

Proof: If $V = \{1, \dots, n\}$, t and $C \subseteq Z^+$ is an instance of F-CAP(*, *), then let $E = \{ij | t(i, j) \neq \emptyset\}$ and define $t': E \rightarrow P(Z_0^+)$ by $t'(ij) = t(i, j)$ for all ij in E . Now $G = (V, E)$, t' and C is an instance of GCP(*, *), etc. Q.E.D.

Theorem 40: F-CFAP is equivalent to CP(*, *).

Proof: If $V = \{1, \dots, n\}$, t_c , and S_c is an instance of F-CFAP, then let $E = \{ij | t_c(i, j) \neq \emptyset\}$ and define $t': E \rightarrow P(Z_0^+)$, $s': E \rightarrow Q^+$ by $t'(ij) = t_c(i, j) = \{1\}$, $s'(ij) = S_c(i, j)$ for ij in E . Now $G = (V, E)$, t' and s' is an instance of CP(*, *), etc. Q.E.D.

Theorem 41: F-FAP, F-FAPOL, and F-FAPO are equivalent to GCP(*, *), GCPOL(*, *) and GCPO(*, *), respectively.

Proof: If $V = \{1, \dots, n\}$, t , and s is an instance of F-FAP, then let $E = \{ij | t(i, j) \neq \emptyset\}$ and define $t': E \rightarrow$

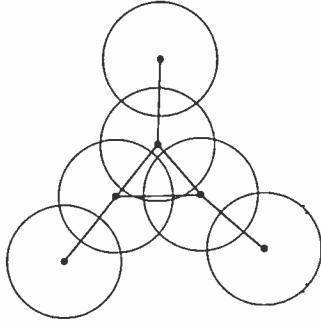
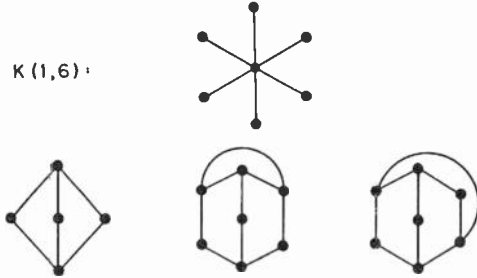


Fig. 4. A unit disk graph together with one of its intersection models.


 Fig. 5. The six pointed star $K(1,6)$ and other graphs that are not unit disk graphs.

$P(Z_0^+)$, $s': E \rightarrow Q^+$ by $t'(ij) = t(i, j)$, $s'(ij) = s(i, j)$ for all ij in E . Now $G = (V, E)$, t' , s' is an instance of $GCP(*; *)$, etc.

Q.E.D.

Theorem 42: F-CCAP, F-CAP, F-CAPOL, F-CAPO, F-CCAP(*; *), F-CAP(*; *), F-CAPOL(*; *), F-CAPO(*; *), F-CFAP, F-FAP, F-FAPOL, and F-FAPO are NP-hard.

Proof: It is well known that CP is NP-hard and the theorem follows since F-CCAP is a subproblem of each of the others.

Q.E.D.

B. Frequency-Distance Constrained Problems and Their Complexity

It is known that F*D-CCAP is related to CP [5], [12], [13], and that other F*D constrained problems are equivalent to generalized coloring problems [89]. In this paragraph, we show that F*D-CCAP is equivalent to CP restricted to a narrow class of graphs called unit disk graphs. Similarly, we show that each of the F*D constrained problems of Sections III and IV is equivalent to a generalized coloring problem restricted to a narrow class of edge constrained graphs called disk graphs. From these equivalences and the recent discovery that CP restricted to unit disk graphs is NP-hard it follows that the F*D constrained problems of Sections III and IV are each NP-hard. Thus open questions concerning the complexity of F*D constrained problems [89] are resolved. Finally, the frequency-constrained approach is more general than the F*D approach since $K(1,6)$ the six-pointed star (and many other graphs) is not a unit disk graph [90] (see Figs. 4 and 5).

Theorem 43: F*D-CAP(*; *) is equivalent to a subproblem of $GCP(*)$.

Proof: If $V, P = \{V_1, \dots, V_p\}$, $R = \{(T_{jk}(i), d_{jk}(i)) | i = 0, \dots, m; j, k = 1, \dots, p\}$ and $B = \{b_1, \dots, b_p\} \subset Q^+$ is an instance of F*D-CAP(*; *) and $r'_\ell, \ell = 1, \dots, p$ and $C(B)$ are

as in Section V-B, then let $E = \{uv | u \neq v, u \text{ is an element of } V_j, v \text{ is an element of } V_k \text{ and } D(u, v) \leq d_{jk}(0), j, k = 1, \dots, p\}$ and define $t: E \rightarrow P(Z_0^+)$ by $t(uv) = \{hr'_\ell | \ell = 1, \dots, p; h \text{ is in } T_{jk}(i) \text{ where } u \text{ is in } V_j, v \text{ is in } V_k \text{ and } i \text{ is the largest integer for which } D(u, v) \leq d_{jk}(i)\}$. Now $G = (V, E)$, t and $C(B)$ is an instance of GCP and $A: V \rightarrow C(B)$ a minimum span coloring for G, t and $C(B)$ is also a minimum span assignment for V, P, R , and B .

Q.E.D.

For future reference, the edge constrained graph $G_t = (V, E, t)$ in the proof above is denoted $G_t[I]$ and is called the *edge constrained graph generated by $I = (V, P, R, B)$* . Let $G_t[*; *]$ denote the class of all such graphs, let $G_t[*]$ denote the subclass that results when $b_i = b$ for $i = 1, \dots, p$. (Note: in this case, $r'_\ell = 1$ for $\ell = 1, \dots, p$ and $C(B) = Z^+$ so $G_t[*]$ is the class of edge constrained graphs generated by instances of F*D-CAP(*)), let $G_t[p; p]$ and $G_t[p]$ denote the subclasses that result when p is fixed. (Note: $G_t[1]$ is the class of edge constrained graphs generated by instances of F*D-CAP.)

Theorem 44: F*D-FAP is equivalent to a subproblem of $GCP(*; *)$.

Proof: If $I = (V, P, B, T, s, d)$ is an instance of F*D-FAP, then let $E = \{uv | u \neq v, u \text{ is in } V_j, v \text{ is in } V_k, D(u, v) \leq d_{jk}, j, k = 1, \dots, p\}$. Define $t: E \rightarrow P(Z_0^+)$ and $s': E \rightarrow Q^+$ by $t(uv) = T_{jk}(D(u, v))$ and $s'(uv) = s_{jk}(D(u, v))$ when u is in V_j, v is in V_k , and $j, k = 1, \dots, p$. Now $G = (V, E)$, t and s' is an instance of $GCP(*; *)$ and if $A: V \rightarrow R^+$ is a minimum span coloring for G, t and s' , $\min A(V) = q'$ (an element of Q^+) and $q = b/q'$ then $A: V \rightarrow [b, \infty)$ defined $A'(v) = qA(v)$ for all v in V is a minimum span assignment for I . Suppose, to the contrary, that B is an element of $F(I)$ and $\max B(V) < \max A(V)$. Let $e = \max A'(V) - \max B(V)$ and let q'' belong to $(0, e)_Q$ such that $q'' < 1/q$. Now $A'': V \rightarrow R^+$ defined $A''(v) = q''A'(v)$ is a feasible coloring for G, t and s' such that $\max A''(V) < \max A(V)$ which is impossible.

Q.E.D.

For future reference, the doubly edge constrained graph $\{V, E, t, s'\}$ in the proof above is denoted $G_{ts}[I]$ and is called the *doubly edge constrained graph generated by I* . Let $G_{ts}[*; *]$ denote the class of all such graphs. (Note: $G_t[*; *]$ is a proper subclass of $G_{ts}[*; *]$). In order to classify the F*D constrained problems as to their complexity, it is convenient to first characterize the edge constrained graphs generated by these problems. A closed disk in the plane is called a *unit disk* if it has diameter one, and $G = (V, E)$ is called a *unit disk graph* if it has an intersection model $\{D_v | v \text{ is in } V\}$ consisting of unit disks in the plane (e.g., see Fig. 4). Let $B_1(2)$ denote the class of all unit disk graphs. If $G = (V, E)$ belongs to $B_1(2)$, $\{D_v | v \text{ is in } V\}$ is an intersection model for G , and $R = \{(T(i), d(i)) | i = 0, \dots, m\}$ is a set of F*D constraints, then let $d'(i) = d(i)/d(0)$ for $i = 0, \dots, m$ and let v' denote the center of D_v for each v in V . Define $t: E \rightarrow P(Z_0^+)$ by $t(uv) = T(i)$ where i is the largest integer for which $D(u', v') \leq d'(i)$. Now $G_t = (V, E, t)$ is an edge constrained $B_1(2)$ graph generated by R . Let $B_1^*(2)$ denote the class of all edge constrained $B_1(2)$ graphs obtained in this way.

Theorem 45: $G_t[1] = B_1^*(2)$.

Proof: $G_t[1] \subseteq B_1^*(2)$: Let $G_t = (V, E, t) = G_t[V, R]$ belong to $G_t[1]$ where $R = \{(T(i), d(i)) | i = 0, \dots, m\}$. For each v in V , let D_v be the unit disk centered at $v' = v/d(0)$. Now uv is an element of E if and only if $u \neq v$ and $D(u, v) \leq d(0)$ if and only if $u \neq v$ and $D(u', v') \leq 1$ if and only if $u \neq v$ and D_u and D_v have nonempty intersection. Therefore, $\{D_v | v \text{ is in } V\}$ is an intersection model for $G = (V, E)$ and G belongs

to $B_1(2)$. By definition, t is an edge constraint generated by R and therefore G_t belongs to $B_1^*(2)$. $B_1^*(2) \subset G_t[1]$: Let $G_t = \{V, E, t\}$ belong to $B_1^*(2)$. By definition $G = (V, E)$ has an intersection model $\{D_v | v \text{ is in } V\}$ and if v' is the center of D_v , then $V' = \{v' | v \text{ is in } V\}$ is a subset of the plane. Also by definition of $B_1^*(2)$, t is generated by $R = \{(T(i), d(i)) | i = 0, \dots, m\}$ a set of F*D constraints and G_t is an edge constrained graph generated by V' and $R' = \{(T(i), d'(i)) | i = 0, \dots, m\}$ where $d'(i) = d(i)/d(0)$ for $i = 0, \dots, m$. Q.E.D.

We have the following results as corollaries to Theorem 45.

Theorem 46: F*D-CCAP is equivalent to CP restricted to $B_1(2)$.

Theorem 47: F*D-CAP is equivalent to GCP restricted to $B_1^*(2)$.

Theorem 48: F*D-CAPOL is equivalent to GCPOL restricted to $B_1^*(2)$.

Theorem 49: F*D-CAPO is equivalent to GCPO restricted to $B_1^*(2)$.

A graph $G = (V, E)$ is called a *disk graph* if it has an intersection model $\{D_v | v \text{ is in } V\}$ consisting of closed disks in the plane each of which has rational diameter ≤ 1 (e.g., see Fig. 4). Let $B(2)$ denote the class of all disk graphs. If $G = (V, E)$ belongs to $B(2)$ and $\{D_v | v \text{ is in } V\}$ is an intersection model for G , then let $P = \{q | \text{the diameter of } D_v = q \text{ for some } v \text{ in } V\} \subset Q^+$, let $|P| = p$, let $q_1, \dots, q_p$ be a list of P , let $V_i = \{v | v \text{ is in } V \text{ and the diameter of } D_v = q_i\}$ for $i = 1, \dots, p$, let $R = \{(T_{jk}(i), d_{jk}(k)) | i = 0, \dots, m; j, k = 1, \dots, p\}$ be a set of F*D constraints for the mixed service $\{V_1, \dots, V_p\}$ and let $B = \{b_1, \dots, b_p\} \subset Q^+$. Let $d'_{jk}(i) = d_{jk}(i)/d_{jk}(0)$ for $i = 0, \dots, m; j, k = 1, \dots, p$, let v' denote the center of D_v for each v in V , and let $r'_k, k = 1, \dots, p$ be as in Section V-B. Define $t: E \rightarrow P(Z_0^+)$ by $t(uv) = \{hr'_k | k = 1, \dots, p, h \text{ is in } T_{jk}(i) \text{ where } u \text{ is in } V_j, v \text{ is in } V_k \text{ and } i \text{ is the largest integer for which } D(u', v') \leq d_{ij}(k)\}$. Now $G_t = (V, E, t)$ is an edge constrained $B(2)$ graph generated by R and B . Let $B^*(2)$ denote the class of all edge constrained $B(2)$ graphs obtained in this way, and let $B_b^*(2)$ denote the subclass of $B^*(2)$ that results when $b_i = b$ for $i = 1, \dots, p$. Note that $B_1^*(2)$ is the subclass that results when $p = 1$.

Theorem 50: $B_b^*(2) = G_t[*]$ and $B^*(2) = G_t[*; *]$

Proof: The proof is very similar to the proof of Theorem 45. Q.E.D.

We have the following results as corollaries.

Theorem 51: F*D-CCAP(*) and F*D-CCAP(*; *) are equivalent to CP restricted to $B(2)$ and CP(*) restricted to $B(2)$, respectively.

Theorem 52: F*D-CAP(*), F*D-CAPOL(*), and F*D-CAPO(*) are equivalent, respectively, to GCP, GCPOL, and GCPO restricted to $B_b^*(2)$.

Theorem 53: F*D-CAP(*; *), F*D-CAPOL(*; *), and F*D-CAPO(*; *) are equivalent, respectively, to GCP(*), GCPOL(*), and GCPO(*) restricted to $B^*(2)$.

Let $G = (V, E)$ belong to $B(2)$, let $\{D_v | v \text{ is in } V\}$, $P = \{q_1, \dots, q_p\}$, $\{V_1, \dots, V_p\}$, and B be as above. Let $s = \{s_{jk} | j, k = 1, \dots, p\}$, $d = \{d_{jk} | j, k = 1, \dots, p\}$, and $T = \{T_{jk} | j, k = 1, \dots, p\}$ be as in Section V-C. Define $t: E \rightarrow P(Z_0^+)$ and $s: E \rightarrow Q^+$ by $t(uv) = T_{jk}(d_{jk}D(u', v'))$ and $s(uv) = s'_{jk}(d_{jk}D(u', v'))$ when u is in V_j , v is in V_k , and $j, k = 1, \dots, p$. Now, $G_t = (V, E, t, s)$ is a doubly edge constrained $B(2)$ graph generated by T , s , and d . Let $B^{**}(2)$ denote the class of all doubly edge constrained $B(2)$ graphs obtained in this way.

Theorem 54: $G_t[*; *] = B^{**}(2)$.

Proof: The proof is very similar to the proof of Theorem 45.

The following results are immediate corollaries. Q.E.D.

Theorem 55: F*D-CFAP is equivalent to CP(*; *) restricted to $B(2)$.

Theorem 56: F*D-FAP, F*D-FAPOL and F*D-FAPO are equivalent, respectively, to GCP(*; *), GCPOL(*; *), and GCPO(*; *) restricted to $B^{**}(2)$.

Theorem 57: F*D-CCAP, F*D-CAP, F*D-CAPOL, F*D-CAPO, F*D-CCAP(*), F*D-CAP(*), F*D-CAPOL(*; *), F*D-CAPO(*), F*D-CCAP(*; *), F*D-CAP(*; *), F*D-CAPOL(*; *), F*D-CAPO(*; *), F*D-CFAP, F*D-FAP, F*D-FAPOL, and F*D-FAPO are NP-hard.

Proof: In April of 1980, J. B. Orlin demonstrated that CP restricted to $B_1(2)$ is NP-hard. The result follows from the fact that F*D-CCAP is a subproblem of each of the others.

Q.E.D.

C. Polynomial Time Subproblems

We now exploit the equivalence between frequency assignment problems and graph coloring to obtain efficient solutions for some important real world problems. For instance, if the transmitters and receivers that tune to them are restricted to lie on a straight line (as along a highway, a pipe line, etc.) then the subproblem of F*D-CCAP(*) corresponding to this situation is equivalent to a subproblem of CP restricted to interval graphs and the algorithm [30] is an efficient solution for this problem. Also, an obvious modification of this algorithm yields an efficient solution for the analogous subproblem of F*D-CCAP(*; *). Indeed the transmitters need not be omnidirectional and the highway need not be straight; it is sufficient to require that the highway intersect the coverage area of each transmitter in a simple arc. More generally, if the locations of transmitters are restricted in such a way that the resulting generated subclass of $B(2)$ is made up of perfect graphs then L. Lovasz has found, using L. G. Khachian's ellipsoid method, an efficient solution for this subproblem of F*D-CCAP(*) (soon to be published).

If the transmitters are restricted to lie on the circumference of a circle (as in a ring network) then the subproblem of F*D-CCAP corresponding to this situation is equivalent to a subproblem of CP restricted to proper circular-arc graphs and the algorithm [49] is an efficient solution for this problem. More generally, if the transmitters are restricted to lie on the circumferences of concentric circles, then the corresponding subproblem of F*D-CCAP(*) (where if v is an element of V_i , then v lies upon the circle centered at $(0, 0)$ with radius $\sqrt{1 + (d_i/2)^2}$) is equivalent to CP restricted to circular-arc graphs in which arcs are restricted to be on the unit circle and to have arc length no longer than pi. (To see this, if D_i is a disk with radius r_i centered at polar coordinates (R_i, a_i) where $R_i = \sqrt{1 + r_i^2}$, then let a'_i be the circular arc with midpoint at $(1, a_i)$ and radian measure $2 \cdot \arctan r_i$. Clearly, a'_i and a'_j are disjoint iff D_i and D_j are disjoint.) Therefore, if the number of channels (or colors) available is fixed at $k \leq |V|$ (as is usually the case in practical problems), then there is a polynomial time algorithm which produces a minimum span assignment using k or fewer channels, if such an assignment exists [48].

In Section III, we remarked that potentially useful information may be encoded when F*D constrained problems are modeled as frequency constrained problems, and we indicated that the frequency constrained approach should only be used for problems in which distance separation plays no role. In

support of this view, if the preceding problem is modeled as a frequency constrained problem, then the circular-arc nature of the problem may be encoded. Although there is a polynomial time algorithm which decodes this information [91] this algorithm, its proof, and its efficient implementation are all non-trivial. A quick reading of [91] should convince the reader that one should model any problem in which distance separation plays a role as an F*D constrained problem.

VIII. CONCLUDING REMARKS

In this paper, we have introduced the minimum-order approach to frequency assignment and have developed a theory which relates this potentially useful approach to the traditional minimum span approach. We have modeled existing (e.g., co-channel, adjacent channel, UHF-TV) and potential (e.g., mixed service with interwoven spectrum sharing) real world assignment problems as both F*D constrained and frequency constrained optimization problems. We have demonstrated that the frequency constrained approach is more general than the frequency-distance approach and should be avoided if distance separation is employed to mitigate interference. We have shown that a restricted class of graphs, called disc graphs, plays a central role in F*D constrained problems. We have introduced two generalized chromatic numbers and have shown that each of the frequency assignment problems studied in this paper is equivalent to a generalized graph coloring problem. Using these equivalences and recent results concerning the complexity of graph coloring, we have shown that each of the general assignment problems studied in this paper is NP-hard, but that several important subproblems have polynomial time solutions. We have noted that the theory relating the minimum span and the minimum order approaches, as developed for the F*D constrained problems, remains valid for the frequency constrained and the generalized graph coloring problems.

What is the significance of all of this? First of all, there are the standard benefits of knowing the complexity classifications of problems. That is, employers may choose not to spend money for the development of polynomial time solutions for the assignment problems now known to be NP-hard. They may instead invest in the development of polynomial time solutions for subproblems of NP-hard problems, nonpolynomial time solutions for the NP-hard problems, which are almost always fast for practical problems, and/or heuristics for the NP-hard problems, which almost always perform well for practical problems, etc. In addition, there are several ways to exploit the close connection between frequency assignment and graph coloring. The many existing solutions [26]–[37], [39], [40], [42], [45]–[47] (heuristics [50]–[68]) for the graph coloring problem may be applied directly (without modification) to cochannel assignment problems. If it can be demonstrated that one of these almost always runs sufficiently fast (produces sufficiently good approximate solutions), then it may be modified to handle more general assignment problems. If none of the existing solutions (heuristics) shows promise even for co-channel problems, then a solution (heuristic) which exploits the special structure of disk graphs may be devised for the F*D constrained cochannel assignment problem and subsequently extended to more general problems.

More generally, using the approach of this paper, one may evaluate various proposed conventions, policies, and procedures which are to govern a new or existing communications service. For example, suppose that improvements in UHF-TV receivers allow for the relaxations of some of the distance separation

requirements. One can use our approach to determine which taboo(s) to modify for the maximum gain in spectrum efficiency [92]. As another example, consider the FM-broadcast service. One may use our approach to evaluate the effectiveness of assigning frequencies to the different classes of FM transmitters in an interwoven fashion or of allowing frequencies to be assigned to unevenly spaced discrete frequencies, etc. Finally, one may use our approach to accurately determine the amount of spectrum to allocate for a proposed new service (given a projected saturated environment).

What remains to be done? As indicated in our discussion of exploiting the graph coloring connection: We need to devise good algorithms and/or heuristics for assignment problems. The smallest last [58], largest first [51] and saturation degree [47] graph coloring heuristics have been generalized to handle minimum span assignment problems [10], [92] and the minimum residual difficulty heuristic has recently appeared [18], but very little else has been done.

What about performance guarantees [63]–[65] for these heuristics restricted to F*D constrained problems (i.e., to disk graphs)? None of the exact graph coloring algorithms has been applied to the cochannel assignment problem. How fast do these algorithms run when restricted to disk (or to unit disk) graphs? There is no graph coloring algorithm or heuristic which exploits the special structure of unit disk or disk graphs. There is no known intrinsic characterization of unit disk graphs (a reasonable forbidden subgraph characterization seems out of the question, as a large list of infinite families of forbidden subgraphs continues to grow). Such a characterization would be helpful in other applications involving unit disk graphs [93]–[98]. What is the complexity of the clique problem [23] for unit disk graphs? Exhaustive search algorithms are the only known exact solutions to nontrivial (i.e., problems involving constraints other than cochannel) minimum span and minimum-order assignment problems; and although minimum span algorithms may be readily obtained from graph coloring algorithms, it is not obvious that trivial modifications of these or other known algorithms will work for minimum order problems. There is no known polynomial time heuristic for nontrivial minimum order assignment problems. Except for what we have presented in this paper, there is no chromatic graph theory for edge constrained graphs. For example, there are no nontrivial upper or lower bounds on $X_1(G, T)$, $X_2(G, T, \ell)$, and $X_2(G, t)$ either for edge constrained graphs restricted to $B^*(2)$ or for the general case (one expects many of the results found in [69]–[81] to have analogs here).

In a 1964 U.S. Government report (see [2]), the annual economic value of the electromagnetic spectrum was estimated to be \$17 billion. Every facet of personal, commercial, and governmental life in the developed world relies heavily upon successful use of the spectrum. It is widely acknowledged that successful communication contributes to world health, safety, understanding, and peace. Clearly, it is important that we address the unsolved problems discussed above.

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REFERENCES

- [1] D. M. Jansky, *Spectrum Management Techniques*, Germantown, MD: Don White Consultants, 1977.
- [2] JTAC, "Spectrum engineering—The key to progress," New York: IEEE, 1968.
- [3] H. Eden, H. W. Fastert, and K. H. Kaltbeitzler, "More recent methods of television network planning and the results obtained," *E.B.U. Rev.*, no. 60-A, pp. 54-59, Apr. 1960.
- [4] H. W. Fastert, "The mathematical theory underlying the planning of transmitter networks," *E.B.U. Rev.*, no. 60-A, pp. 60-69, Apr. 1960.
- [5] B. H. Metzger, "Spectrum management technique," presented at 38th Nat. ORSA Meet. (Detroit, MI), Fall 1970.
- [6] J. J. Pawelec, "An algorithm for assignment of optimum frequencies to homogeneous VHF radio networks," *Telecommun. J.*, vol. 40, pp. 21-27, 1973.
- [7] J. Arthur Zoellner, "Frequency assignment games and strategies," *IEEE Trans. on Electromagn. Compat.*, vol. EMC-15, pp. 191-196, Nov. 1973.
- [8] C. E. Dadson, J. Durkin, and R. E. Martin, "Computer prediction of field strength in the planning of radio systems," *IEEE Trans. Veh. Technol.*, vol. VT-24, pp. 1-8, Feb. 1975.
- [9] R. A. Frazier, "Compatibility and the frequency selection problem," *IEEE Trans. Electromagn. Compat.*, vol. EMC-17, pp. 248-254, Nov. 1975.
- [10] S. H. Cameron, "Sequential insertion: An algorithm for conserving spectrum in the assignment of operating frequencies to operating systems," Annapolis, MD: ECAC, Sept. 1975, (ECAC-TN-75-0023).
- [11] T. Sakaki, K. Nakashima, and Y. Hattori, "Algorithms for finding in the lump both bounds of the chromatic number of a graph," *Comput. J.*, vol. 19, no. 4, pp. 329-332, Nov. 1976.
- [12] R. J. Pennotti and R. R. Boorstyn, "Channel assignments for cellular mobile telecommunications systems," in *Proc. IEEE Nat. Telecommunications Conf.* (Dallas, TX), pp. 16.5-1-16.5-5, Nov. 1976.
- [13] J. A. Zoellner and C. L. Beall, "A breakthrough in spectrum conserving frequency assignment technology," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, pp. 313-319, Aug. 1977.
- [14] C. L. Beall, and M. J. Dash, "An automated frequency assignment system for air voice communication circuits in the frequency band from 225 MHz to 400 MHz," in *Proc. IEEE Int. Symp. Electromagnetic Compatibility* (Seattle, WA), pp. 302-304, Aug. 1977.
- [15] P. A. Major, "A parameter-sensitive frequency-assignment method (PSFAM)," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, pp. 330-332, Aug. 1977.
- [16] M. J. Dash and S. R. Green, "Parameter sensitivity analysis: An approach used in the investigation of frequency assignment problems," in *Proc. Conf. Electromagnetic Compatibility* (Guildford, England), pp. 55-64, Apr. 1978.
- [17] F. Box, "A heuristic technique for assigning frequencies to mobile radio nets," *IEEE Trans. Veh. Technol.*, vol. VT-27, pp. 57-74, May 1978.
- [18] S. Cameron, and Y. Wu, "A frequency assignment algorithm based on a minimum residual difficulty heuristic," in *Proc. IEEE Int. Symp. EMC '79* (CH 13839 EMC), pp. 350-354, Oct. 1979.
- [19] S. A. Cook, "The complexity of theorem-proving procedures," *Proc. 3rd ACM Symp. Theory of Computing*, pp. 151-158, 1971.
- [20] R. M. Karp, "Reducibility among combinatorial problems," in *Complexity of Computer Computations*, R. E. Miller and J. W. Thatcher, Eds. New York: Plenum Press, pp. 85-104, 1972.
- [21] M. R. Garey, D. S. Johnson, and L. Stockmeyer, "Some simplified NP-complete problems," in *Proc. 6th ACM Annu. Symp. Theory and Computing*, pp. 237-267, 1974.
- [22] M. R. Garey and D. S. Johnson, "The complexity of near-optimal graph coloring," *J. ACM*, vol. 23, no. 1, pp. 43-49, Jan. 1976.
- [23] —, *Computers and Intractability: A Guide to the Theory of NP-Completeness*. San Francisco, CA: Freeman, 1979.
- [24] H. R. Lewis and C. H. Papadimitriou, "The efficiency of algorithms," *Scientific Amer.*, pp. 96-109, Jan. 1978.
- [25] R. L. Brooks, "On colouring the nodes of a network," in *Proc. Cambridge Philosophy Society*, vol. 37, pp. 194-197, 1941.
- [26] A. A. Zykov, "On some properties of linear complexes," *Mat. Sbornik*, vol. 24/26, p. 163 (in Russian) (Amer. Math. Soc. Translation, No. 79, 1952.)
- [27] C. Berge, *Theory of Graphs and its Applications*. Paris, France: Dunod, 1958.
- [28] F. Harary, *Graph Theory*. Reading, Ma: Addison-Wesley, 1969.
- [29] N. Christofides, "An algorithm for the chromatic number of a graph," *Comput. J.*, vol. 14, no. 1, pp. 38-39, Feb. 1971.
- [30] F. Gavril, "Algorithms for minimum colouring, maximum clique, minimum covering, by cliques and maximum independent set of a chordal graph," *SIAM J. Comput.*, vol. 1, no. 2, pp. 180-187, 1972.
- [31] S. Even and A. Pnueli, "Permutation graphs and transitive graphs," *J. ACM*, vol. 19, no. 3, pp. 400-410, July 1972.
- [32] A. A. Borovikov and V. A. Gorbakov, "A criterion for coloring of the vertices of a graph," *Eng. Cybernetics*, vol. 10, no. 4, pp. 683-686, 1972.
- [33] J. Randall-Brown, "Chromatic scheduling and the chromatic number problems," *Management Sci.*, vol. 19.4, Part I, pp. 456-463, Dec. 1972.
- [34] A. C. Tucker, "Perfect graphs and an application to optimizing municipal services," *SIAM Rev.*, vol. 15, pp. 585-590, 1973.
- [35] S. I. Roschke and A. L. Furtado, "An algorithm for obtaining the chromatic number and an optimal coloring of a graph," *Inf. Process. Lett.* (The Netherlands), vol. 2, no. 2, pp. 34-38, June 1973.
- [36] D. G. Corneil and B. Graham, "An algorithm for determining the chromatic number of a graph," *SIAM J. Comput.*, vol. 2, no. 4, pp. 311-318, Dec. 1973.
- [37] C. C. Wang, "An algorithm for the chromatic number of a graph," *J. ACM*, vol. 21, no. 3, pp. 385-391, July 1974.
- [38] A. Tucker, "Coloring a family of circular arcs," *SIAM J. Appl. Math.*, vol. 29, pp. 493-502, 1975.
- [39] N. Christofides, *Graph Theory: An Algorithmic Approach*, New York: Academic Press, pp. 58-78, 1975.
- [40] E. L. Lawler, "A note on the complexity of the chromatic number problem," *Inf. Process. Lett.*, (The Netherlands), no. 3, pp. 66-67, Aug. 1976.
- [41] M. C. Golumbic, "The complexity of comparability graph recognition and coloring," *Computing* (Austria), vol. 18, no. 3, pp. 199-208, 1977.
- [42] S. H. Cameron, "The solution of the graph-coloring problem as a set-covering problem," *IEEE Trans. Electromagn. Compat.*, vol. ECM-19, no. 3, Pt. 2, pp. 320-322, Aug. 1977.
- [43] A. M. Walsh and W. A. Burkhard, "Efficient algorithms for (3, 1) graphs," *Inform. Sci.*, vol. 3, no. 1, pp. 1-10, 1977.
- [44] P. K. Srimani, B. P. Sinha, and A. K. Choudhury, "A new method to find out the chromatic partition of a symmetric graph," *Int. J. Syst. Sci.*, vol. 9, no. 12, pp. 1425-1437, Dec. 1978.
- [45] S. M. Korman, "The graph-colouring problem," in *Combinatorial Optimization*, N. Christofides, A. Mingozzi, P. Toth, and C. Sandi, Eds. Chichester, England: Wiley, pp. 211-235, 1979.
- [46] C. McDiarmid, "Determining the chromatic number of a graph," *SIAM J. Comput.*, vol. 8, no. 1, pp. 1-14, Feb. 1979.
- [47] D. Brelaz, "New methods to color the vertices of a graph," *Commun. ACM*, vol. 22, no. 4, pp. 251-256, Apr. 1979.
- [48] M. R. Garey, D. S. Johnson, G. L. Miller, and C. H. Papadimitriou, "The complexity of coloring circular arcs and chords," *SIAM J. Discrete Algebraic Methods*, to be published.
- [49] J. B. Orlin, M. Bonucelli, and D. P. Bovet, "An $O(n^2)$ algorithm for coloring proper circular arc graphs," *SIAM J. Discrete Algebraic Methods*, to be published.
- [50] J. E. L. Peck and M. R. Williams, "Examination scheduling, algorithm 286," *Commun. ACM*, vol. 9, no. 6, pp. 433-434, 1966.
- [51] D. J. A. Welsh and M. B. Powell, "An upper bound for the chromatic number of a graph and its application to timetabling problems," *Computer J.*, vol. 10, pp. 85-86, 1967.
- [52] I. Tomescu, "An algorithm for determining the chromatic number of a finite graph," *Econ. Comput. Cybern. Stud. Res.* (Rumania), no. 1, pp. 69-81, 1969.
- [53] D. C. Wood, "A technique for colouring a graph applicable to large scale timetabling problems," *Comput. J.*, vol. 12, pp. 317-319, 1968.
- [54] M. R. Williams, "The colouring of very large graphs," in *Combinatorial Structures and Their Applications*, R. K. Guy, H. Hanani, N. Sauer, and J. Schonheim, Eds. New York: Gordon and Breach, 1970, pp. 477-478.
- [55] R. S. Wilkov and W. H. Kim, "A practical approach to the chromatic partition problem," *J. Franklin Inst.*, vol. 289, no. 5, pp. 333-349, May 1970.
- [56] R. A. Draper, "A graph coloring algorithm and a scheduling problem," M.S. thesis, Naval Postgraduate School Monterey, CA, 1971.
- [57] A. A. Kalnin'sh, "The coloring of graphs in a linear number of steps," *Cybern.*, vol. 7, no. 4, pp. 691-700, July-Aug. 1971.
- [58] D. W. Matula, W. G. Marble and J. D. Isaacson, "Graph coloring algorithms," in *Graph Theory and Computing*, R. C. Read, Ed. New York: Academic Press, 1972, pp. 109-122.
- [59] D. W. Matula, "Bounded color functions on graphs," *Networks*,

- vol. 2, pp. 29-44, 1972.
- [60] M. R. Williams, "Heuristic procedures (if they work leave them alone)," *Software Practice and Experience*, vol. 4, no. 3, pp. 237-240, July-Sept. 1974.
- [61] F. Dunstan, "Greedy algorithms for optimization problems," presented at Euro I meeting, (Brussels, Belgium) Jan. 1975.
- [62] A. Tehrani, "Un algorithme de coloration," *Cahiers du centre d'Etudes de Recherche Operationnelle*, vol. 17, no. 2-4, pp. 395-398, 1975.
- [63] D. S. Johnson, "Worst case behavior of graph coloring algorithms," in *Proc. 5th Southeastern Conf. Combinatorics, Graph Theory Computing* pp. 513-528, 1974. (Winnepeg, Canada: Utilitas Mathematica Publishing.)
- [64] D. S. Johnson, "Approximation algorithms for combinatorial problems," *J. Comput. Syst. Sci.*, vol. 9, no. 3, pp. 256-278, 1974.
- [65] R. Karp and D. W. Matula, "Probabilistic behaviour of a naive coloring algorithm on random graphs," *Bull. Oper. Res. Soc. Amer.*, vol. 23, suppl. 2, p. 264, Fall 1975.
- [66] J. Mitchem, "On various algorithms for estimating the chromatic number of a graph," *Comput. J.*, vol. 19, no. 2, pp. 182-183, May 1976.
- [67] M. Kubale, and J. Dabrowski, "Empirical comparison of efficiency of some graph colouring algorithms," *Arch. Autom. Telemech.* (Poland), vol. 23, no. 1-2, pp. 129-139, 1978.
- [68] N. K. Mehta, "Performance of selected graph coloring algorithms-empirical results," presented at the 1980 TMS/ORSA Conf. (Washington, DC), May 4-7, 1980.
- [69] A. P. Ershov and G. I. Kozhukhin, "Estimates of the chromatic number of connected graphs," *Dokl. Akad. Nauk*, vol. 142, pp. 270-273; and *Trans. Soviet Math.*, vol. 3, pp. 50-53, 1962.
- [70] H. S. Wilf, "The eigenvalues of a graph and its chromatic number," *J. London Math. Soc.*, vol. 42, pp. 330-332, 1967.
- [71] G. Szekeres and H. S. Wilf, "An inequality for the chromatic number of a graph," *J. Comb. Theory*, vol. 4, pp. 1-3, 1968.
- [72] J. H. Folkman, "An upper bound on the chromatic number of a graph," Rand Corp., California, Rep. RM-5808-PR, NTIS no. AD-684 527, Febr. 1969.
- [73] P. Holgate, "Majorants of the chromatic number of a random graph," *J. Roy. Statistics Soc. Ser. B*, vol. 31, pp. 303-309, 1969.
- [74] A. J. Hoffman, "On eigenvalues and colorings of graphs," in *Graph Theory and Its Applications*, B. Harris, Ed. New York: Academic Press, pp. 79-91, 1970.
- [75] B. Andrásfai, P. Erdos, and V. T. Sos, "On the connection between chromatic number, maximal clique and minimal degree of a graph," *Discrete Math.* (The Netherlands), vol. 8, no. 3, pp. 205-218, May 1974.
- [76] J. Lawrence, "Covering the vertex set of a graph with subgraphs of smaller degree," *Discrete Math.* (The Netherlands), vol. 21, no. 1, pp. 61-68, Jan. 1978.
- [77] P. A. Catlin, "A bound on the chromatic number of a graph," *Discrete Math.* (The Netherlands), vol. 22, no. 1, pp. 81-83, Apr. 1977.
- [78] —, "Another bound on the chromatic number of a graph," *Discrete Math.* (The Netherlands), vol. 24, no. 1, pp. 1-6, Oct. 1978.
- [79] E. Nordhaus, E. and J. Gaddum, "On complementary graphs coloring," *Amer. Math. Monthly*, vol. 63, pp. 175-177, 1956.
- [80] J. A. Bondy, "Bounds for the chromatic number of a graph," *J. Combin. Theory*, vol. 7, pp. 96-98, 1969.
- [81] B. R. Myers, and R. Liu, "A lower bound on the chromatic number of a graph," *Networks*, vol. 1, no. 3, pp. 273-277, 1972.
- [82] L. C. Middlekamp, "UHF taboos—History and development," *IEEE Trans. Consumer Electron.*, vol. CE-24, pp. 514-519, Nov. 1978.
- [83] K. Baker, *Introduction to Sequencing and Scheduling*, New York: Wiley, 1974.
- [84] E. G. Coffman, Jr., *Computer and Job Shop Scheduling Theory*, New York: Wiley, 1976.
- [85] R. W. Conway, W. L. Maxwell, and L. W. Miller, *Theory of Scheduling*. Reading, MA: Addison-Wesley, 1967.
- [86] S. Elmaghraby Ed., *Symposium on the Theory of Scheduling*. Berlin, Germany: Springer-Verlag, 1973.
- [87] J. L. Lenstra, *Sequencing of Enumerative Methods*. Amsterdam, The Netherlands: Mathematisch Centrum, 1976.
- [88] A. H. G. Rinnooy Kan, *Machine Scheduling Problems: Classification, Complexity and Computations*. The Hague, The Netherlands: Nijhoff, 1976.
- [89] W. K. Hale, "Optimal channel assignment and chromatic graph theory," presented at MAA/AMS/ASL Nat. Meet., Boulder, CO, Mar. 1980.
- [90] A. M. Odlyzko and N. J. A. Sloane, "New bounds on the number of unit spheres that can touch a unit sphere in n dimensions," *J. Combin. Theory Ser. B* (USA), vol. 26, no. 3, pp. 276-294, Mar. 1979.
- [91] A. Tucker, "An efficient test for circular-arc graphs," *SIAM J. Comput.*, vol. 9, pp. 1-24, Feb. 1980.
- [92] W. K. Hale, "Spectrum efficiency as a function of frequency distance rules," presented at ORSA/TMS Nat. Meet. (Colorado Springs, CO), Nov. 10-12, 1980.
- [93] P. Armitage, "An overlap problem arising in particle counting," *Biometrika*, vol. 36, pp. 257-266, 1949.
- [94] C. Mack, "The expected number of clumps when convex laminae are placed at random and with random orientation on a plane area," in *Proc. Cambridge Philosophy Society*, vol. 50, pp. 581-585, 1954.
- [95] E. Gilbert, "Random plane networks," *J. Soc. Indust. Appl. Math.*, vol. 9, no. 4, pp. 533-543, Dec. 1961.
- [96] —, "The probability of covering a sphere with N circular caps," *Biometrika*, vol. 52, nos. 3 and 4, pp. 323-330, 1965.
- [97] H. DeWitt and M. Krieger, "An efficient algorithm for computing the minimal spanning tree of a graph in a Euclidean-like space," in *Proc. 8th Hawaii Int. Conf. System Sciences*, pp. 253-255, 1975.
- [98] —, "Expected structure of Euclidean graphs," presented at the 1976 Symp. New Directions and Recent Results in Algorithms and Complexity, Carnegie-Mellon Univ., Pittsburgh, PA, Apr. 7-9, 1976.

Frequency Assignment Games and Strategies

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Abstract—The way the spectrum is committed through the processes of allocation and assignment has a definite bearing on spectrum utilization. Both processes are stochastic in nature and nearly irreversible. Decisions are made with respect to each applicant as time progresses without knowing the requirements of future applicants, and it is difficult, if not impossible, to revoke or change an assignment once given. This paper examines the frequency assignment game to determine the effect of assignment strategy on spectrum utilization, and to define the principle underlying the development of optimum strategies. The results of this investigation show that there is an effect of strategy, that the effect bears on spectrum utilization, that there is an optimum strategy, and that there are some very useful near-optimum ones as well. Finally, there is evidence that we may not be doing things quite the right way, and some recommendations are offered.

INTRODUCTION

More than ever, the electromagnetic spectrum is recognized as one of man's most important resources by all developed nations. Stepped up concern in this country brought about Executive Order 11556 in 1970, which established the Office of Telecommunications Policy. The intent was to obtain a firmer grip on the problem of securing the greatest possible benefit from the use of the spectrum. This was followed by the creation of the Office of Telecommunications within the Department of Commerce to provide the necessary scientific and technical support. In 1960 the Department of Defense established the Electromagnetic Compatibility Analysis Center (ECAC) in recognition of the same need. Of the many factors that affect spectrum utilization, the process by which the spectrum is committed to use is one of the more significant.

The first step in committing the spectrum is allocation: land mobile radio services go here, satellite communications go there, etc. The present allocation scheme evolved out of a complex socio-politico-technological process that began at the turn of the century. The spectrum was committed to those already there. As technology opened up the usable part of the spectrum to higher and higher frequencies, more commitments swiftly followed. The second step in committing spectrum resources is frequency assignment. This process, like allocation, is stochastic in nature and is nearly irreversible. Once a user has obtained a license to operate on a particular frequency, it is difficult to revoke his license or move him to another frequency.

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It was easy as long as the useful part of the spectrum could be expanded. But expansion in this respect has virtually ground to a standstill with greater attention now being devoted to the prospect of reallocating and reassigning portions of the spectrum to obtain greater benefits from its use. In short, matters have reached a desperate state.

The stochastic process of committing the spectrum is taken as the game where we have applicants on the one side and frequency assigners on the other. We put aside, for the time being, those games where there is an examiner rather than an assigner. Applicants propose frequencies to examiners. In the game taken here, the assigner both selects and assigns a frequency to each applicant, not knowing about future applicants.

Can the assigner do anything to secure the greatest possible use of the spectrum for us? What could be meant by the term "greatest possible use"? These are the questions that matter, and they matter more every day. Are we doing something wrong about our way of committing the spectrum or are we doing it right? If we are doing it wrong, what way should we do it? The answers have far-reaching ramifications. They affect the small businessman who wants to operate a mobile radio system; the company wanting to establish a communications satellite service; or the military planner who wants a frequency plan for a tactical exercise or a contingency plan.

The objective of this paper is to examine the stochastic game of committing the spectrum from the point of view of game theory to find out first, if there is an effect of strategy on the outcome of the game; and, second, if there is, to identify the principle on which optimum strategies can be constructed. The approach taken is to represent the game of committing resources in some more or less abstract manner so as to more clearly identify its elements and possibly discover what can be done to achieve improved use of the spectrum.

GAME SIMULATION

The stochastic frequency assignment game is taken to be a game with two opponents for purposes of simulation. One opponent can be used to represent the sequence of applicants; the other can be used to represent the assigner. By limiting the simulation to games with assigners rather than examiners, the flow of applications can be represented by sequences of uniformly random locations where radio service is desired. Only one location is presented to the assigner at a time. Each location could, for example, represent the location of a mobile radio base station. The assigner attempts to find a channel that can be used at each location, without information about locations that will be presented later on. In a real situation, the distribution of geographic locations requested may tend to cluster just as population density varies throughout an area. The choice of uniformly random geographic locations merely

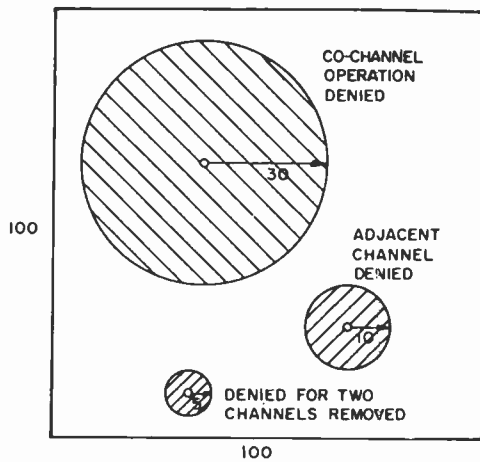


Fig. 1. Operational restrictions assumed.

simplifies the job of simulation; it does not impair the value of the simulation in this investigation. The geographic area in the game is taken to be a one-hundred unit square.

Rules that concern frequency allocation instruments, treaties, or other political agreements can be called regulations. Rules pertaining to technical reasons why a license should not be granted can be referred to as operational restrictions. An operational restriction, for example, states that a channel assignment cannot be made to two users unless they are separated by a specified distance. The rule may be predicated on theoretical grounds, may be based upon experience, or on some combination of both.

The intent here is to study strategy, not to solve any particular frequency assignment problem; neither is it the intent to determine the effects of regulations or operational restrictions, or, even to examine how matters might be improved by taking advantage, say, of using cross-polarization techniques to obtain increased use of the spectrum. All that is needed for this study is a representative set of assignment restrictions. No regulations are assumed, and the only operational restrictions used in the simulation consist of the channel separation versus base station distance separation requirements illustrated in Fig. 1. These require a minimum separation of thirty units for co-channel operation, ten units for adjacent channel operation, and five units if two channels removed. There are no restrictions if more than two channels apart. Twenty channels are assumed to be available.

Any results obtained investigating this stochastic frequency assignment game also have a direct bearing on the static frequency assignment game, where the locations of all radio service requirements are known beforehand. Such a game is played, for example, in drawing up a frequency plan for a military exercise or in coming up with a new air traffic control communication frequency plan. It always turns out that the optimum assignment cannot be found in this type of game by enumerating all possible assignments. The work of exhaustive enumeration simply cannot be accomplished within practical amounts of time and money. Consequently, such games are attacked with sequential strategies such as illustrated in Fig. 2. The technique makes use of two algorithms. One is used to compute the sequence of assigning resources, and the other

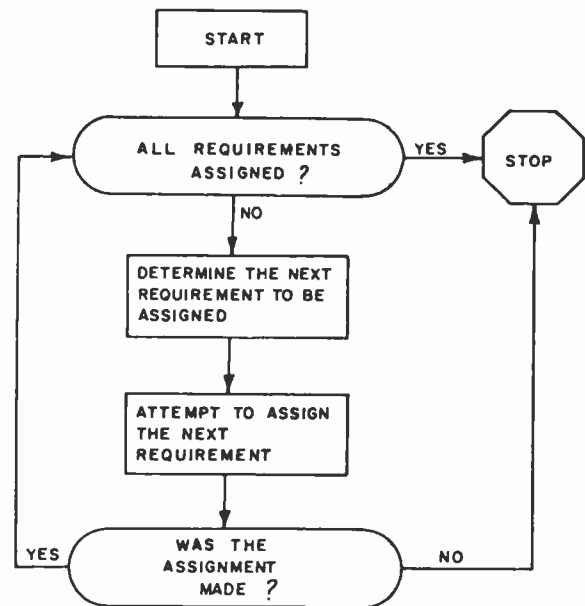


Fig. 2. Sequential assignment technique.

performs the assignment function. The sequence may be determined at the outset, or it may be determined one step at a time following each assignment. In any case, the assignment algorithm is sequentially applied, turning a static game into a stochastic one.

SELECTION OF STRATEGY CONCEPTS FOR TEST

The first concept selected for evaluation is termed the Random concept. It is a kind of baseline strategy. When the applicant presents a request for service, the assigner picks a channel at random, checks to see if the channel selected for use at the place designated by the applicant violates any of the rules. If no rules are violated, the assigner commits the channel in question. If rules are violated, the assigner picks another channel at random and tries again. This trial and error procedure ends in a denial of the application if no channel can be assigned.

A concept with a little more purpose and one that has some intuitive appeal is to make each successive assignment in a way that maximizes the electromagnetic isolation between the applicant and the users already there. In terms of isolation, a decrease in distance between two users can be offset by an increase in channel separation, and vice-versa. Therefore one measure of isolation is the product of these two quantities. This concept can be extended to express the separation between a given user and all other users in the environment by summing these products over all users. In situating an applicant as "far away as possible" from users already there, an assigner would choose the channel for which the sum of these products is largest. There exists a whole family of possible separation measures given by

$$Q = \sum_i [(C - C_i)^\alpha \cdot (D_i)^\beta]^\gamma$$

where α , β , and γ are real positive numbers, C represents a candidate channel assignment, C_i represents the channel



Fig. 3. Average number of assignments by time of 100 denials in a row.

number assigned to requirement i , and D_i represents the distance between the candidate and the i th previously assigned requirement.

There is no need, however, to investigate every possible choice of α , β , and γ in order to determine whether the idea of maximum isolation has any merit. If the concept has any value, then it must have merit to some extent in all cases. Hence, it is only necessary to select one measure out of the family for evaluation. And for this purpose, the criteria based on $\alpha = \beta = \gamma = 1$ will suffice. This concept is referred to as the Max-F*D strategy.

Two other concepts are identified for test. One is called the Levelizer concept. At any assignment stage in the game, the attempt is made to assign the channel previously assigned the least number of times. If it cannot be assigned, then an attempt is made to assign the next least assigned channel, and so forth. The other concept is called the Sequential concept. In using it, an attempt is made to first assign channel 1. If that is impossible, an attempt is made to assign channel 2, and so forth.

EVALUATION

The evaluation of each concept was carried out by presenting each one with sixty different sequences representing the flow of applications. Each sequence was generated by a pseudo-random process in the computer. The results of applying the four designated concepts to these sixty sequences are shown in Fig. 3 in terms of the number of assignments made by the time 100 applications in a row were denied. The games were ended at this point because it represented a saturation condition for all practical purposes. The results presented in Fig. 3 show that all strategy concepts tested have the same performance characteristics when it comes to the question of how many applicants can be accommodated by the time saturation is reached. However, they differ in a number of other significant ways; they affect the number of applications processed by the time saturation is reached (Fig. 4); and they affect the number of assignments made by the first time an application is denied (Fig. 5). More significantly, they affect the number of times they win over or tie each other in terms of numbers of assignments made by the first denial

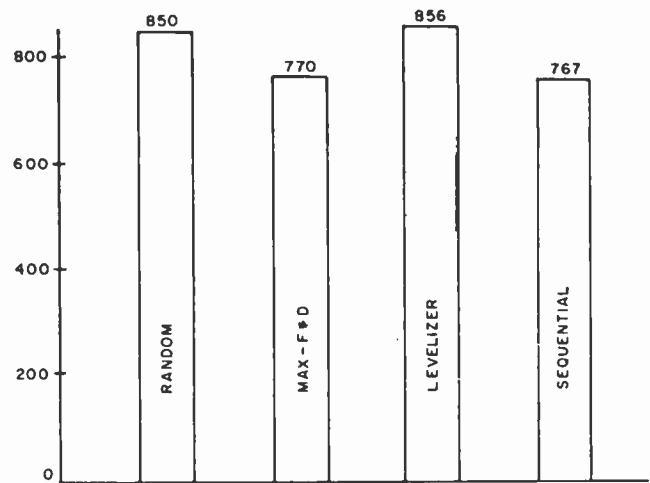


Fig. 4. Average number of applicants processed by time of 100 denials in a row.

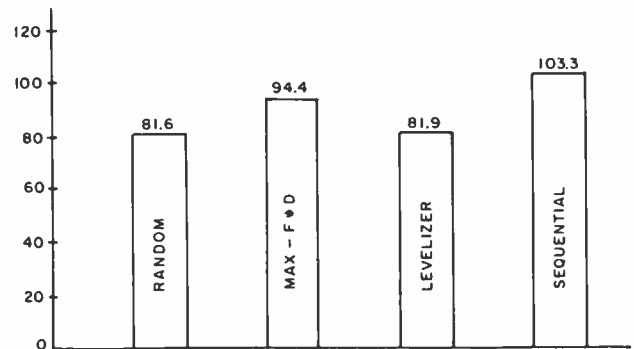


Fig. 5. Average number of assignments by time of first denial.

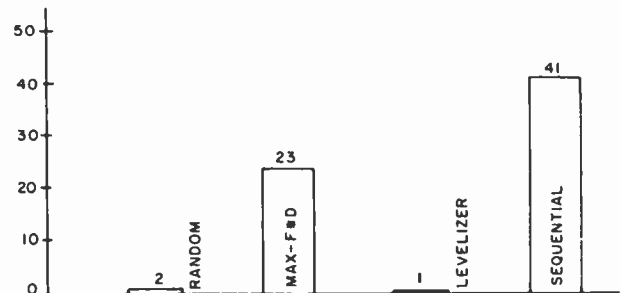


Fig. 6. Number of games out of sixty won or tied.

(Fig. 6). The Sequential concept did as well as or better than any other concept tested in nearly 70 percent of all games!

The stochastic game can be characterized as a game having two epochs. The first can be called the acceptance epoch and the second called the saturation epoch. The length of the acceptance epoch equals the number of applicants assigned by the time the first applicant is denied. The length of the saturation epoch is the number of applications processed between the time that the first applicant is denied spectrum support and the time that spectrum saturation is reached and the game ends.

The way that strategy affects the game is illustrated in Fig. 7. The average lengths of the acceptance and saturation

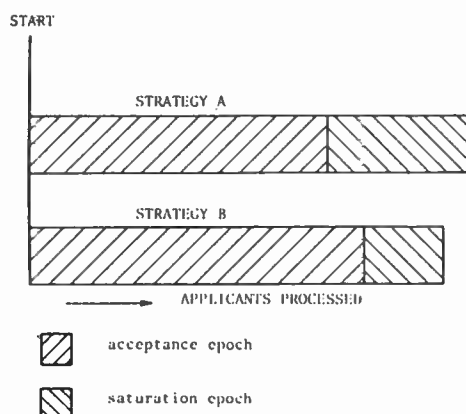


Fig. 7. Game characteristics.

epochs for two strategies, A and B, are shown in the figure. It is apparent from the results of the simulation test that strategies that generate longer acceptance epochs produce shorter saturation epochs and shorter overall game lengths. Therefore from the standpoint of minimizing the cost and frustration of futile application preparation, strategy B is obviously preferred over strategy A.

CONCEPT DEVELOPMENT

The encouraging results of the Sequential concept led to a search for an optimum concept. In doing so, the idea of a channel map was needed; Fig. 8 presents two examples. The shaded areas are regions where reassignment of the channel is denied because of previous assignments. The large circles are due to co-channel assignments; the small ones are due to adjacent channel assignments. Assume that an assignment game is in process and that the condition of the channel maps for channels 3 and 8 are as shown in Fig. 8. Furthermore, suppose the next applicant has a request for service at the location marked by the "x" in the figure. In this case either channel 3 or channel 8 could be assigned. Assigning channel 3 will result in the least additional loss of spectrum space. It follows, in general, that assigning the channel whose map contains the largest denied reassignment area will result, on the average, in the least additional loss in spectrum space. The Sequential concept has a tendency to do this because it generally gives the most assigned channels the greatest opportunity to be reassigned. As a consequence, the losses in spectrum space are conserved to some extent.

The next step in concept development would be to deliberately conserve the spectrum by always striving to reassign the most assigned channel. This is called the Max-select concept. With it an attempt is made to reassign the most assigned channel first; if that cannot be done, an attempt is made to reassign the next most assigned channel; etc.

The logical follow-on to the Max-Select concept is one that selects channels for assignment on the basis of the actual amount of denied area in each channel map rather than on the basis of simply the number of assignments made of each channel. This is called the Max-area concept.

The Max-area concept suggests yet an even better one. At any stage in the game, choose for assignment among the

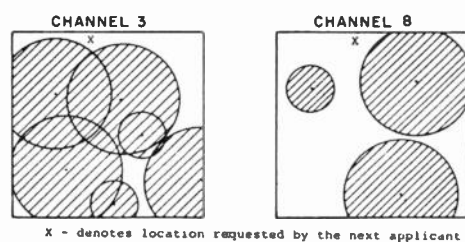


Fig. 8. Channel maps.

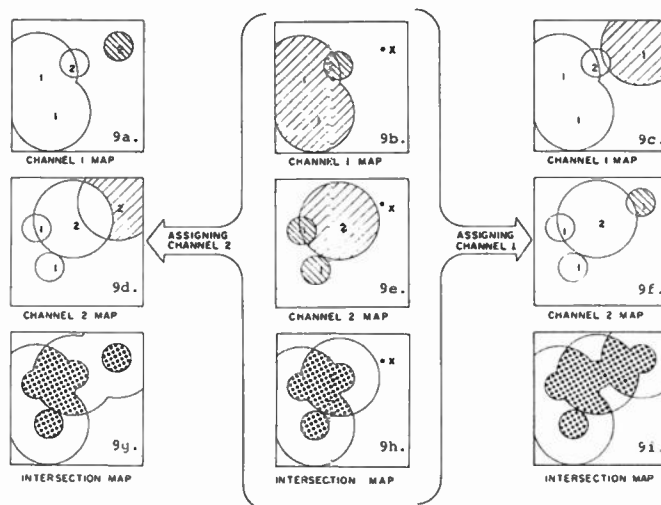


Fig. 9. Strategy development—example 1.

channels that can be assigned the one that adds least to the total spectrum spaces committed. Such a procedure would be even more deliberate than the Max-area concept in conserving spectrum space at each step in the assignment. This is called the Minadd concept.

The promising performance expected of all of these concepts is based upon their spectrum conservation properties. Any concept that conserves spectrum space increases the chance that the game will continue. And there is the key! The optimum strategy is the one that maximizes the chance that the game will proceed one more step.

The first step required in formulating the optimum concept for strategy development is being able to determine the chance the game will continue one more step. The center column in Fig. 9 represents the situation in a hypothetical two-channel game at the point where channel 1 has been assigned twice and channel 2 assigned once. The shaded area shown in Fig. 9(h) represents the logical intersection of the corresponding shaded areas in the channel 1 and channel 2 maps. The intersection represents the area where the occurrence of a requirement will result in a denial. Under conditions where the chance occurrence of the next requirement is governed by a uniform probability distribution law, as the case in this simulation, the chance the game will continue one more step is measured by the proportion of the area that is unshaded. Consequently, the optimum concept calls for assigning channels at each stage that minimize the intersection of all channel maps. There is one complication, however, that occurs when there are uncommitted channels still in the game.

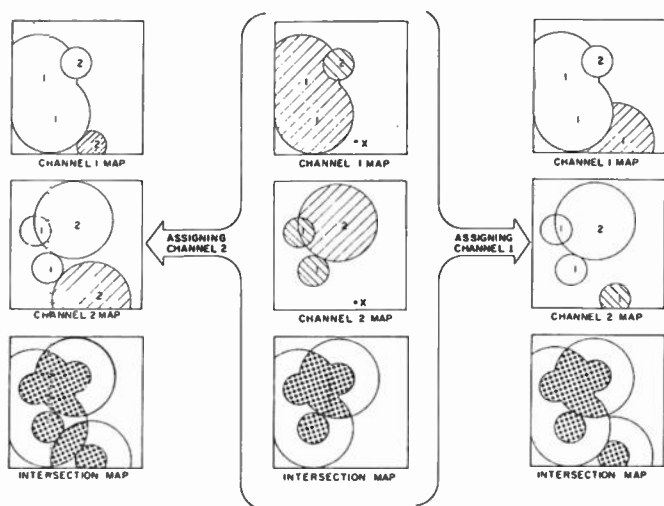


Fig. 10. Strategy development—example 2.

A channel is defined to be committed whenever its corresponding channel map contains a denied region for reassignment. When all channels are committed, the procedure is to choose the channel that minimizes the probability measure of the intersection map. Prior to that point, the procedure would be to determine the subset of channels that can be assigned without committing any additional channels. If such a subset exists, choose the channel that minimizes the probability measure of the intersection map over all committed channels. If the set is empty, choose the channel requiring the least increase in the number of committed channels. In case of ties, choose that channel minimizing the probability of measure of the intersection map. This concept is called the Minimum Intersection concept.

The contrast between these last three strategies is further illustrated in, Fig. 9. Assume that a new applicant requests radio service at the cross-marked location. Under the conditions present, either channel 1 or channel 2 could be assigned to the applicant. The Max-area concept could dictate the assignment of channel 1 to the applicant. This choice results in the channel maps shown in Fig. 9(c) and 9(f), where the shaded area represents the additional spectrum space denied for further reassignment consideration. Adopting the Minadd concept, on the other hand, would result in assigning channel 2 to the applicant, since it can be seen from the channel maps in Fig. 9(a) and 9(b) that the total amount of spectrum space removed from both channel maps would be less than if channel 1 were assigned. From the intersection maps in Fig. 9 it is seen that assigning the applicant channel 2 maximizes the chance that the next assignment also will be made. Consequently, application of the Minimum Intersection concept would lead to selecting channel 2. A second example contrasting the three concepts is shown in Fig. 10. In this case, the application of each concept results in the same choice of channel for the applicant.

EVALUATION

The least difficult of the developmental concepts to implement is the Max-select concept. The complexity of the com-

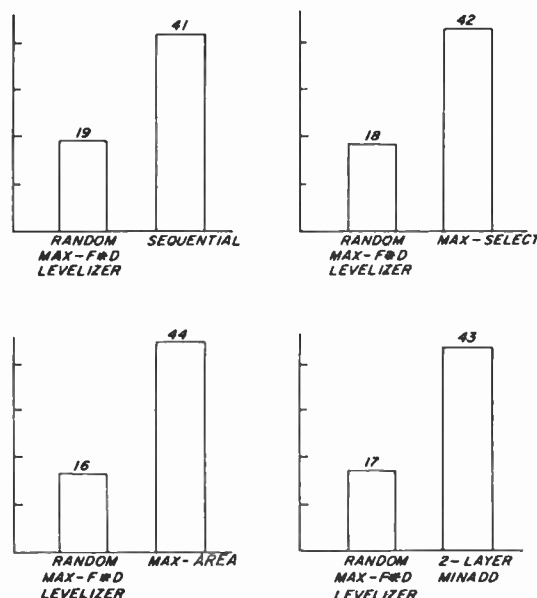


Fig. 11. Comparison of development strategy—games won or tied out of sixty.

puter program required to put the Max-area concept into operation is an order of magnitude larger. As a matter of fact, it was found necessary to convert from floating point to fixed point arithmetic to reduce running time to a practical level. Fortunately, it was possible to make recursive use of the computer program for the Max-use concept in implementing the Minadd concept.

The Minimum Intersection concept was not implemented. Writing a computer program to calculate the intersection area was discovered to be a very formidable task. As matters turned out, implementation of the concept was not essential to the main objective of the investigation. It is logically the optimum concept for the particular game under study and therefore no necessity exists to provide proof by demonstration. Furthermore, considering the structure of all these concepts, the relationship between the Minimum Intersection concept and the other developmental concepts will be very close in terms of channel selection behavior. Only small variations in results are to be expected. This was found to be the case.

Initial computer simulation results showed that the Minadd concept was taking nearly ten times as much computing time as the Max-area concept. Since the Minadd concept computer program made recursive use of the Max-area computer program, it was possible to determine how deep the recursive use of the Max-area concept need be taken to simulate the Minadd concept for all practical purposes. The Minadd selected channel was found to agree with the Max-area selected channel in 90 percent of the cases. With only few exceptions, the rest of the time the Minadd channel turned out to be the "next most used" channel according to the Max-area concept. Therefore, in order to conserve computing resources as much as possible, it was decided to back off and evaluate a 2-layer version of the Minadd concept, i.e., to only go as far as choosing between the first two opportunities for assignment.

Test performance results of the Max-select, Max-area and 2-layer Minadd concepts are shown in Figs. 11 and 12. Fig. 11

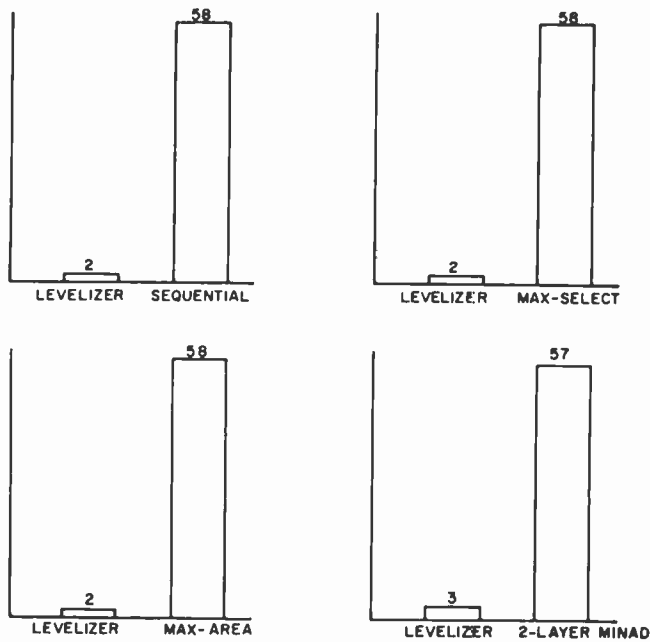


Fig. 12. Comparison of developmental strategies with Levelizer strategy.

contrasts the performance of these strategy concepts as opposed to the combined competition of the Random, Levelizer, and Max-F*D techniques. The relative performance of the Sequential concept is also shown for reference. A similar evaluation is given in Fig. 12 where competition was restricted to the Levelizer concept. The Levelizer concept won out in less than 5 percent of the games. The results show a tendency toward improvement as the complexity of strategy concept increases. The trend however, is small, and the decision against implementation of the Minimum Intersection concept was definitely justified in this case.

CONCLUSIONS

Stochastic frequency assignment games cover two epochs. The first is initiated by the entry of the first applicant and ends the first time an applicant is denied spectrum support. This epoch is called the acceptance epoch. Its length is measured by the number of applications accepted by the first time an application is denied.

The spectrum saturation epoch begins with the first denial and ends when spectrum saturation occurs. In stochastic frequency assignment games, spectrum saturation is defined to occur the first time a specified number of applications are denied access in a row to the spectrum. The length of the spectrum saturation epoch is measured by the difference between the number of applications processed by the time satura-

tion occurs and the number of assignments made by the time the first application is denied.

The strategy selected by the assigner determines the average lengths of both epochs. Strategies leading to relatively longer acceptance epochs also lead to shorter saturation epochs and to shorter overall games from beginning to end. For both economical and psychological reasons the optimum strategy is the one that maximizes the average length of the acceptance epoch. The basis of optimum strategy development for the stochastic frequency assignment game has been determined to be the Minimum Intersection concept. The application of the Minimum Intersection concept essentially means that in securing the greatest possible spectrum support for future requirements each new assignment should be made in such a way that the increase in the total spectrum space committed is as small as possible. This dictates a policy of always trying to assign the most heavily committed channel before resorting to those less heavily committed. The number of assignments recorded for a given channel can be taken as a fairly accurate measure of commitment in some applications. More complex measures of spectrum commitment may be required in other cases in order to carry out the intent of the concept.

Our national policies in regard to obtaining frequency assignments do not guarantee the best procedure. The *Manual of Regulations and Procedures for Radio Frequency Management* published by the Office of Telecommunications Policy (Ch. 8, p. 1) states that "Each government agency . . . selects possible frequencies . . . coordinates the selection with other agencies . . . and files application with the Executive Secretary of the Interdepartment Radio Advisory Committee." Similarly, the *Federal Communications Commission Rules and Regulations*, vol. 1, paragraph 1.511, pp. 99, states that "each individual request . . . shall contain . . . the frequency assignment . . . desired." These statements suggest a practice whereby the applicant specifies the channel desired. Left to himself, he will tend to select the least used channel. When this happens, it is the same as playing the stochastic assignment game using the Levelizer strategy, a strategy that can be beaten almost all of the time.

There has been, however, a trend in recent years not to let the applicant specify the channel. Working groups, for example, such as the Aeronautical Assignment Group of the Interdepartment Radio Advisory Committee have been organized within the government to perform the function of assignment. In some cases, the practice of trying to reassign the most assigned channel is followed, although it is not a written procedure. A formalization of assignment policy along the lines suggested in this paper could help to assure that the practices followed in the assignment process are the best possible.

Optimum frequency planning: a new concept

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SUMMARY

The problem of optimum frequency and power assignment in a transmitter network is formulated in this paper, and an appropriate solution method is outlined.

The paper describes an heuristic technique capable of solving a class of frequency planning problems involving: co-channel, adjacent-channel, spurious, and intermodulation interferences; fixed pre-existing frequency assignments and frequency-separation requirements; non-repetitive zone structures and frequency resource lists that contain gaps and vary from zone to zone; natural or political boundaries; specific terrain topography and irregular transmitter locations; signal and noise environment, transmitter powers, and directive antenna patterns that vary from transmitter to transmitter. The method is based on normalization, decomposition, and reduction techniques and on graph-colouring procedures. It assures that all relevant constraints and requirements are fulfilled and the total power radiated by all transmitters is minimum.

The paper is addressed to persons involved in preparation, revision, or approval of frequency plans: to spectrum planners, spectrum managers, frequency assigners, electromagnetic compatibility analysts and all those responsible for efficient radio spectrum utilization.

1. Introduction

General

As evidenced by the recent World and Regional Administrative Radio Conferences, there have been growing demands for spectrum sharing by many users (see, e.g. Kirby and Rutkowski [9]). Unfortunately, radio transmission systems may not employ the same area without interfering with one another. Thus a fundamental problem in sharing the spectrum is the elimination of harmful interferences that limit the effectiveness of radio services. Hence, use of the spectrum resource involves careful co-ordination of several factors by which one radio com-

munication may be distinguished from another, and interference between them avoided. In addition to precluding interferences, the rational use of the spectrum should assure accommodation for as many users as possible with the limited frequency resource available. The most efficient way to achieve these goals consists in a preventive activity: that is, in a minimization of possible conflicts and spectrum wastage before their occurrence.

Both national and international wireless communications would dissolve into chaos without a system for allocating proper places in the radio spectrum among the claimant transmitters. As the number of transmitters is use grows,

more requirements concerning electromagnetic compatibility must be given due consideration, and the problem becomes more and more complex. Since the earliest days of radio, this problem has been of great international interest. Initially, the rule "the higher power radiated the better" was the only guide in planning transmitter networks, and it was not so long ago that it became evident that this approach leads to pitfalls: to raising of interference background level; to power racing; to natural environment degradation; to capital investment losses.

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Relatively soon it became clear that the effective use of the radio spectrum depends on both the operational characteristics of systems and frequency planning techniques. This has been confirmed recently by the CCIR which endorses special studies on optimum network planning and frequency assignment techniques that could be recommended for use on world, regional, or national, scales (CCIR [1]).

A frequency plan is a function that assigns appropriate operational characteristics to each of the claimant transmitters. Generally, this may be one, a few, or all, of the factors by which radiocommunications can be distinguished from one another: operating frequency (frequency discrimination); power radiated (power level discrimination); antenna location, height, and radiation pattern (direction discrimination); polarization (polarization discrimination); time-structure of the signal (signal structure discrimination); operating time. Initially, only the frequency was assigned, and this explains the expression "frequency planning".

Although there are numerous publications on frequency planning (see e.g. Hale's bibliography [6] and special issues of the Institute of Electrical and Electronics Engineers (IEEE) and European Broadcasting Union (EBU) journals [5, 7, 8]) the general problems of optimum frequency planning with all the above-mentioned factors taken into account have not yet been solved, and are among the main topics of CCIR activity [2]. The reason is that mathematical models accounting for numerous factors and complex interactions, as well as a great amount of required input data, create severe problems in attempts to apply rigorous formal methods to real-life situations.

Paper organization

The chief aim of this paper is to introduce a new formulation of the problem of optimum frequency and power assignment in a transmitter network and to outline its possible solution.

The remaining part of the paper is organized as follows:

In section 2 we formulate the problem. We formulate it as an optimization issue. It is worth noting here that, generally, optimization is the determination of the value of design parameters subject to specific constraints that yield the best result. The following elements of any optimization problem are implicit:

- there are variables subject to control;

- the result to be optimized is described in mathematical terms of controllable parameters;
- a measure, or criterion, of system performance which should be optimized is selected;
- all requirements and assumptions, jointly named constraints, are stated explicitly.

We base our approach on mathematical models in which variables describing relevant components, states and performances of a system are described, and relationships between them represented through mathematical expressions. Many factors of a physical, technical, economic and even social and political nature, must be given due consideration when planning transmitter networks. There is no realistic way to include all of them into a mathematical model explicitly, and their effect is evaluated by handling them as constraints.

In section 3 we outline the proposed solution method, and main difficulties encountered. The usual question in any optimization problem is how much work or how much time is required to find the solution. In our approach we apply the decomposition principle. The original problem is decomposed into several sub-problems of a lower dimensionality, and each of them is solved separately. Their order is determined so that results of preceding sub-problems are used in subsequent ones. Normalization, reduction, and graph-colouring procedure are the key elements of the solution method proposed.

Section 4 introduces important definitions of two graphs: the signal graph and the bond graph, on which our solution method is based. Two algorithms for construction of these graphs are also offered here.

Sections 5 and 6 present two key sub-problems concerning the transmitter ordering and frequency channel ordering. Appropriate algorithms are also proposed.

In section 7, guided by our efforts in sections 4, 5, and 6, we present an outline of the proposed solution method to the problem, along with a relevant algorithm. In this paper, a frequency plan is a function which assigns to each of the claimant transmitters a pair: an operating frequency (from a set of available frequencies, called the frequency catalogue), and an operating power (from a set of available powers, called the power catalogue). This contrasts with the traditional

methods, which are still widely used, and which account for only one of them: frequency or power (see, e.g. Strużak [12]). There are three main reasons for proposing the new concept. Firstly, the frequency and power are both the crucial factors that control the interference and coverage zones in any transmitter network. Secondly, they are operational parameters that can be modified easily during the planning process. Finally, it is natural to expect that an optimum sought over the plane frequency-power should be closer to the "ideal" than an optimum sought with the single variable: power or frequency only.

In section 8 we conclude with a summary of our findings. Main concepts of this paper are developed from the ideas presented at the Seminar on optimization methods, Institute of Computer Science, Mathematics Department, University of Wrocław, and the lectures given by the author in January 1980, and partially published (Strużak [11, 12]).

2. Problem formulation

This paper deals with the following problem: given a collection of test points and a collection of radio transmitters to be assigned frequencies and powers, find an optimum assignment that satisfies specific constraints and that minimizes the total power radiated by all transmitters. The constraints are of three types:

- 1) catalogue constraints (powers and frequencies must be selected from the specified catalogues);
- 2) environmental constraints (EM compatibility with a specified environment signal must be assured at the test points);
- 3) quality constraints (reception quality must be guaranteed at the test points).

It is assumed that complete information is available.

It is assumed also that a specified test receiver with a test antenna is situated at each test point.

Locations, heights, directive radiation patterns, orientations, polarizations and other relevant parameters of both transmitters and test receivers are optional, however, their choice is beyond the scope of this paper. They should be established before the frequency and power assignment.

Any number of transmitters, test points, and constraints is acceptable; the total number of transmitters, test points, fre-

quencies, powers, environmental signals and other constraints that determine the problem's dimension, is, however, finite.

It is assumed moreover that a list of environment signals is attributed to each test point. The list contains data on signal power at the receiver input (or power-flux density, polarization and azimuth of signal arrival).

Several real-life situations can be reduced to the form presented above. The test points, for example, can represent the units of area. Then, with a large number of them and their regular distribution, continuous coverage area problems can be approximated. The test points can also represent cities or other concentrations of people. In that case, population coverage problems are manageable. Singular transmitter test point locations can simulate point-to-point radiocommunications. Very specific distributions may be required to fit the coverage area to natural or political boundaries or to fill in gaps in the coverage by other networks.

techniques (Arnaud in [8]). As is known, these techniques are based on the following assumptions:

- a) all transmitters are identical; their powers and antenna heights are the same;
- b) all antennae are omnidirectional;
- c) terrain effects are ignored; the Earth is supposed to be flat and propagation is isotropic;
- d) no natural or political boundaries; each transmitter is located at a node of a boundless, regular lattice (no other locations allowed);
- e) all lattice nodes are occupied by transmitters (no free nodes or coverage gaps);
- f) interference environment is the same for each transmitter;
- g) one set of channels is regularly re-used throughout the whole boundless plane (other frequency allocations ignored).

These assumptions make it impossible to take into account optional locations and antenna patterns, non-continuous cover-

age area, effects of other radio services sharing the same area, etc.

Discontinuity

The discontinuous nature of the problem excludes differential calculus, Lagrangian multipliers and, generally, all continuous-type techniques, including linear programming. Integer and non-linear programming general techniques are not directly applicable either.

Problem dimension

One of the distinct characteristics of our problem is the large number of possible cases that must be taken into account. Even with a moderate number of frequencies, powers, transmitters and test points, the number of computations required for exhaustive inspection of all possible combinations is enormous. If the catalogues contain N_f frequencies and N_p powers are available, then there are $N_f \times N_p$ pairs of frequency power. With N_T claimant transmitters, this makes N different frequency plans possible

$$N = (N_f \times N_p)^{N_T} \quad (1)$$

3. Solution outline

Geometric interpretation

Figure 1 shows a general interpretation of our problem. Three abstract spaces are distinguished: the "transmitter", the "signal" and the "receiver performance" spaces. Each of the transmitters considered is represented by a point in the "transmitter" space, and each of the test receiver input signals is represented by a point in the "signal" space; the same is true of the test "receiver performance" space. Relations between these spaces are also shown: each point from the "transmitter" space is mapped in the "signal" space, and points from this space are mapped in the "receiver performance" space. These relations are dependent on many factors, some of them uncontrollable (noise, propagation effects). This introduces some uncertainty in the mapping process. Generally, the problem constraints cut out allowable regions in each of the spaces separately. The problem consists, firstly, of transforming the allowable regions from the "receiver performance" and "signal" spaces into the "transmitter" space and, secondly, of finding the optimum allocation of points within the resultant allowable region there.

Irregularity

Due to irregular structures allowed, the problem is insoluble by the classic lattice

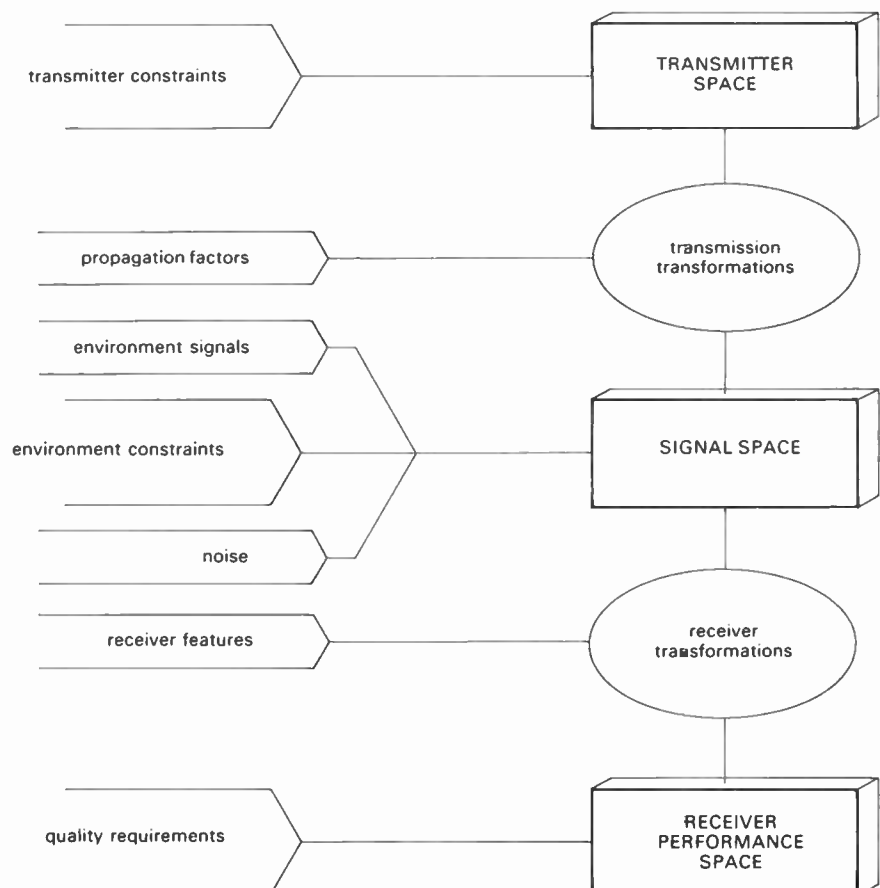


Figure 1—"Transmitter", "signal", and "receiver" performance, spaces and relations between them. The problem constraints and influencing factors are also shown.

(all possible permutations with repetitions allowed). **

If there are N_c test points, then each of these plans should be checked N_c times for compatibility and quality constraints. For $N_F = 20$ frequencies, $N_p = 5$ powers, $N_T = 10$ transmitters and $N_c = 100$ test points, the total number of tests is $100 \times 100^{10} = 100^{11} = 10^{22}$. Even if each test takes only 1 millisecond of computer time, the job would not be finished in 3×10^{11} years! Note, for comparison, that the estimated age of the Earth is 5×10^9 years or so.

For this reason no solution method based on such an exhaustive inspection is acceptable. The author conducted a search of the literature but found no other formal solution to the problem.

Proposed solution method

It is well known from practice that the signal environment usually varies from one test point to another and that the degree of difficulty in finding a proper frequency also varies from transmitter to transmitter. We make use of these inequalities by applying the "worst-case" rule. Thus, we identify the "most difficult" transmitter and the "most critical" test point and we do an assignment that optimally "fits in" this particular transmitter to its environment at this particular test point. After assigning a frequency and power to the first transmitter, all signals of this transmitter are considered as new environmental signals, and the next "most difficult" transmitter is fitted in to them at its "worst" test point. The first transmitter is matched to the original environment, whereas the last is fitted in to the environment modified by all previous

assignments. This method equalizes chances of the claimant transmitters by offering more freedom to the transmitters which are initially in a more difficult situation. It reduces the number of different frequency plans and the number of verifications required to check whether all constraints are fulfilled or not. The number of possible plans is:

$$N = N_F \times N_p \times N_T \quad (2)$$

With, as previously, $N_F = 20$ frequencies, $N_p = 5$ powers, $N_T = 10$ claimant transmitters, $N = 1000$.

Decomposition

In order to apply this method, the original problem is decomposed into sub-problems of lower complexity. These sub-problems are ordered and solved separately, in a determined sequence, so that results of preceding stages are used in the subsequent ones. Specific constraints are imposed on each sub-problem, so that their sum can be equivalent to the original problem.

In the first sub-problem, a transmitter priority list is arranged. All transmitters are intercompared, and the transmitter with maximum interference potential is selected and placed at the top of the list. The assignment begins with this transmitter. In the second sub-problem, a channel priority list is prepared for a given transmitter. Here all relevant environmental signals are intercompared channel by channel, and the channel that assures minimal radiated power in the worst case is placed at the top of the list, and is the first assigned. The last sub-problem consists of tests and an assignment of optimum frequency and power. Here the solutions of the previous sub-problems are used, and specific test procedures are applied. This is a systematic transmitter-by-transmitter and channel-by-channel procedure that stops when an optimum combination is found. More "prominent" transmitters have more freedom here and others are automatically adjusted to them, because each new assignment takes into account all assignments made previously. After a limited number of computation, ordering, and testing steps, the final solution is found or any inconsistency in the problem conditions is stated.

4. Graphs

In our attempt some graph-theory concepts are applied. A graph is a set of vertices partially or completely intercon-

nected by lines (see Christofides [4]). We introduce here graphs of two different kinds: signal graph G, and bond graph H.

Signal graph G

Imagine a map with all claimant transmitters and test points marked. Mark also sources of all environment signals at convenient places on the map and all the vertices of graph G will be displayed. In this graph the vertices represent signal sources (transmitters, environment) and signal sinks (test points) whereas the lines represent the power flow. If the signal from a transmitter reaches a test point with a significant power, there is an oriented line (arrow) from the transmitter to the test point. Lines outgoing from test points or ingoing to signal sources are forbidden in graph G, so that there are no lines interconnecting the sources or interconnecting the sinks. There are no isolated (unconnected) sources or sinks. An example is shown in figure 2.

The graph may also be memorized within a computer, without delineating it on paper. All elements of such a graph are labelled so that full information concerning the transmitting stations and their signal environment is contained in the graph (see table 1). At the beginning, the information about the operating frequencies and powers is not available, and graph G is constructed according to the following algorithm:

Algorithm: signal graph G construction

Step 0

Start with the list of test points (TEP), list of claimant transmitters (TRA) and list of environment signals (ESI), assuming tentatively that all transmitters radiate the same unit power and all transmitters and test receivers use the same frequency. Introduce all transmitters and test points as the vertices of the graph.

Step 1

Stop if there are no points on list TEP, otherwise select a test point from the top of this list.

Step 2

Go to step 7 if there are no transmitters on list TRA, otherwise select a transmitter from the top of this list and determine its distance d from the test point. If the transmitter is desired at the test point and $d > A$ go to step 5, if it is undesired and $d > B$ go to step 6.

Step 3

Determine the signal power p at the input of the test receiver accounting for propagation losses and directive anten-

** Note: Formula (1) results from the following considerations:

A frequency plan is a list of transmitters, each with a specific frequency and power assigned. When two such plans are intercompared, they are considered identical if they contain the same transmitters and each transmitter has the same frequency and power in both plans. With a single transmitter, a single power and N_F different frequencies, N_F different plans are possible, because each of the frequencies can be assigned to the transmitter. If N_p different values of the power are available instead of a single value, the number of different plans is $(N_F \times N_p)$, because for each of the N_p powers each of the frequencies can be assigned to the transmitter. Let $N(i)$ be the number of different frequency plans for i transmitters, with N_F frequencies and N_p powers available, with an extra transmitter added $(N_F \times N_p)$ different assignments are possible for this transmitter, and each of them can be combined with each of $N(i)$ former plans. Therefore the resultant number of different plans with this extra transmitter added is $(N_F \times N_p) \times N(i)$. For $i = 1, 2, 3, \dots, N_T$, there is $N = (N_F \times N_p)^2, (N_F \times N_p)^3, \dots, (N_F \times N_p)^{N_T}$.

na patterns. If the transmitter is desired and $p < C$ go to step 5, if it is undesired and $p < D$ go to step 6.

Step 4

Insert a line from the transmitter to the test point, note the signal at the re-

ceiver input, remove the transmitter from list TRA and return to step 2.

Step 5

Stop: problem inconsistency (quality constraints not fulfilled). Revise the problem and return to step 0.

Step 6

Signal path irrelevant: remove the transmitter from list TRA and return to step 2.

Step 7

Select and note all relevant environment signals, insert corresponding lines in the graph, remove the test point from list TEP, and return to step 1.

The limiting values A-D are determined according to the problem constraints and nominal usable field strength.

Transmitters from the outside of the circle with radius A are unable to produce any signal that could be usable, and transmitters from the outside of the circle with radius B are unable to produce any signal that could be usable or interfering at the test point considered, even in the most favourable conditions (maximum allowable power radiated, minimum propagation losses, maximum antenna directive gains).

There is no restriction concerning the propagation model used in signal power density computations (see CCIR [3]), but models that are based on detailed terrain data analyses are the most appropriate. An example for UHF/VHF can be found in Sgga *et al.* [10] A discussion of this question is, however, beyond the scope of this paper.

The number of distance determinations N_d , required in step 2, equals

$$N_d = N_t \times N_i \quad (3)$$

The number of necessary power calculations N_p (step 3), is much lower: its lower bound is

$$N_p \geq \max [N_t, N_i] \quad (4)$$

and the upper bound is given by (3).

Graph G consists, therefore, of $(N_t + N_i)$ vertices and a number of oriented lines for which the lower and upper bounds are (3) and $\max [N_t, N_i]$. N_t is the number of the signal sources. Note that graph G is a sparse one and contains only a small percentage of the lines of the complete graph with the same vertices, which is

$$\frac{1}{2} (N_t + N_i) \times (N_t + N_i - 1) \quad (5)$$

because in the complete graph all nodes are mutually interconnected.

For example, if—as previously— $N_t = N_i = 10$ transmitters, and $N_i = 100$ test points, graph G consists of 110 vertices and less than 1000 lines, which is only 17% of the total 5995 lines of the complete graph. The algorithm requires 1000 calculations of the distance and from 100

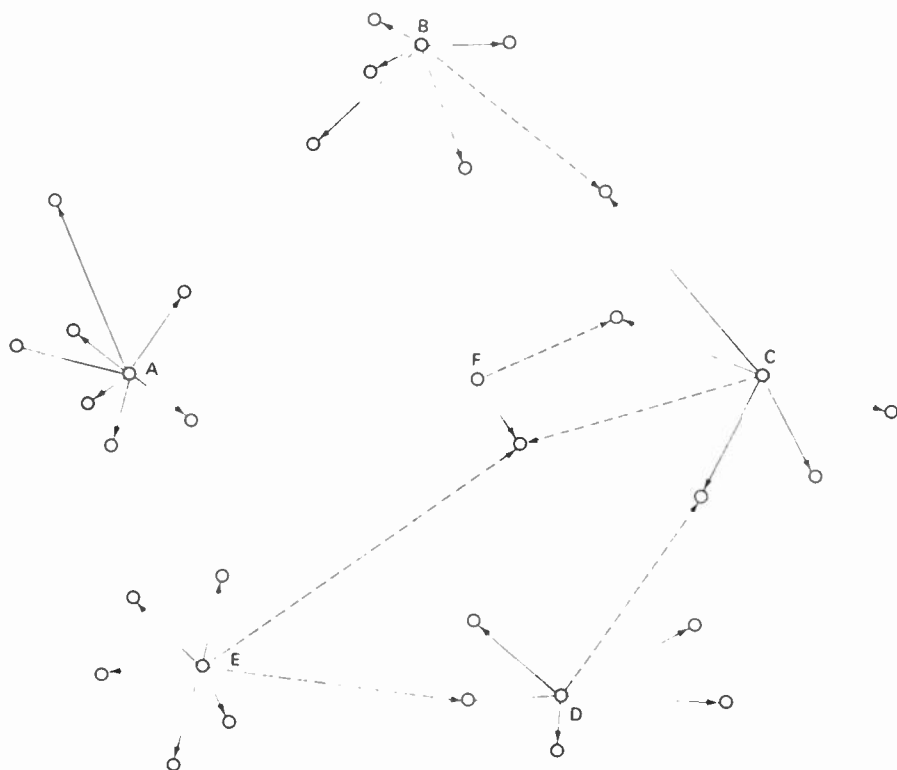


Figure 2—Signal graph G. It represents 5 transmitting stations (A-E), 1 environment signal (F), 28 test points (not labelled), and 34 signal paths: 28 desired (continuous arrows) and 6 undesired (dotted arrows)

Table 1

Information contained in signal graph G

No	graph element	information carried
1	claimant transmitter vertex	— geographical location, — antenna* — frequency and power of each signal radiated
2	test point vertex	— geographical location, — antenna* — test receiver nominal and spurious response (or signal-to-interference ratios) — environment signal lists
3	environment signal vertex	— no specific information
4	oriented line	— frequency, power, and desirability index of each signal at the test receiver input

* Height, polarization, orientation, radiation pattern.

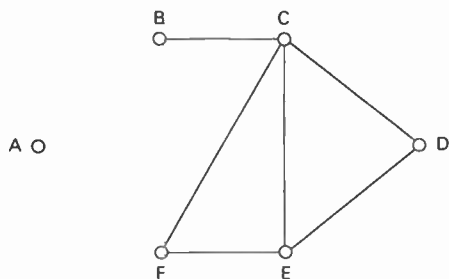


Figure 3—Bond graph H corresponding to figure 2. Its 6 vertices (A-F) represent signal sources and its 6 lines represent potential transmitter influences

to 1000 power evaluations. With 1 ms of distance calculation time and 100 ms of power calculation, the job would take 10 to 100 seconds of computer time.

The information contained in graph G is modified during the planning process. At the beginning, all transmitters have the same frequency.

After the assignment of an actual frequency-power pair to the i -th transmitter, this power and frequency along with all signals generated by the transmitter, modify the existing data in graph G.

Finally, all its vertices and lines are labelled by proper data, as listed in table 1.

We define the transmitter zone as the set of all test points at which its signal is relevant. In graph G this zone is the set of all test-point vertices incident to the vertex representing this transmitter (signal source).

Bond graph H

Bond graph H is generated from the signal graph G according to the following algorithm:

Algorithm: bond graph H construction

Step 0

Start with graph G, test point list TEP, transmitter list TRA and signal list ESI.

Step 1

Go to step 3 if there are no points on list TEP; otherwise select a test point from the top of the list, identify all source vertices in graph G that are connected with the test point and insert them as vertices in graph H (without duplication).

Step 2

If there is only one transmitter or signal source connected, remove the test point from the list TEP and return to step 1. In the opposite case, insert lines non-oriented in graph H between each pair of transmitters or signal sources

connected, remove the test point from list TEP and return to step 1.

Step 3

If there are parallel lines in graph H, replace them by single lines and stop.

As it follows from this algorithm, graph H is of a lower dimension than graph G because it contains only signal sources as vertices. A line exists between two vertices in graph H if these vertices are connected with a common test point in graph G. The number of vertices in graph H is therefore N_s and the lower and upper bounds for the number of lines are zero and $\frac{1}{2}N_s \times (N_s - 1)$ (the latter is valid if the graph is complete). For $N_s = 10$ signal sources, graph H consists of 10 vertices and less than 45 lines. An example is shown in figure 3.

As shown, isolated vertices are allowed in graph H. The structure of graph H indicates how many frequencies are required. If all its vertices are isolated, that is, there are no influences between the signal sources, all transmitters can use the same frequency, and a single frequency channel is sufficient for the whole network.

In the opposite case, when graph H is complete and each one of its vertices is connected with its $(N_s - 1)$ neighbours, all transmitters are mutually related, and N_s frequency channels are required.

5. Transmitter ordering

This sub-problem consists in ordering of all transmitters waiting for the frequency and power assignment in such a way that the "most difficult" or the "most prominent" one is in the top position. The criterion is the number of potential conflicts, i.e. the number of frequency channels that must be co-ordinated with the neighbouring transmitters and environment signals. We call this number the "interference potential".

The interference potential of a transmitter can be evaluated using bond graph H, and we apply the known colouring procedure in order to establish proper transmitter order. In colouring the graph, interconnected vertices may not receive the same colour. The objective of the classical colouring problem is to find the minimum number of colours required to colour all vertices. Here we are interested in ordering the vertices to be coloured. We base our approach on the known heuristic procedure described elsewhere (e.g. Christofides [4], Zoellner [7]), according to the following reduction algorithm. The

degree of a vertex equals the number of lines incident to it. The procedure consists of the consecutive exclusion of the least degree vertex from the graph.

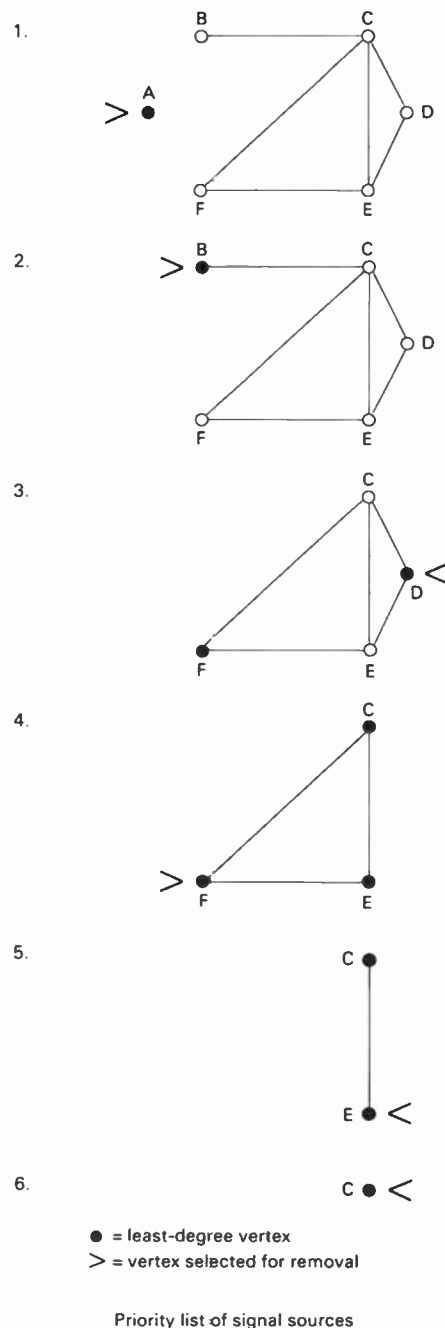


Figure 4—Example of transmitter ordering by graph reduction. Graph H shown in upper left part of the figure corresponds to figures 2 and 3

Algorithm: transmitter ordering

Step 0

Start with graph H.

Step 1

Remove a signal-source vertex of the least degree from the graph along with lines connected to it, and place it at the last position on the signal-source list.

Step 2

Repeat step 1 with the reduced graph, place the removed vertex at the last as yet unoccupied position on the list, until the last vertex is removed from the graph.

Step 3

Remove vertices representing environment signals from the list and stop.

An example is shown in figure 4. As can be seen, this sub-problem is of lower complexity than the original problem because all test points and original constraints are not involved directly. The number of steps in this algorithm equals the number of the signal sources.

6. Frequency channel ordering

Frequency channel ordering concerns the selection of the best operating frequencies for a given transmitter. As follows from the original problem formulation, there are several test points, each with a specific signal environment. With signal sources active, all these signals can be observed on the screen of a spectrum analyser connected to the test antenna. The quantitative characterization of these signals may derive from direct measurement or from solution of prediction equations. The signal environment, or spectrum occupancy, may be different at each of the test points. Due to their geographical dispersion it is difficult to intercompare the reception conditions over the transmitter zone.

In order to omit this difficulty we normalize all environment signals. The normalization consists in compensation for transmission losses which each signal suffers on its path from the transmitter to the test point. In other words, the normalized environment signal power is the power that should be radiated by the transmitter in order to equalize the environment signal at a given test point. The idea is illustrated by figure 5. With all signals normalized, the intercomparison of signal reception over the whole transmitter zone is easy, independently on direction and distance from the trans-

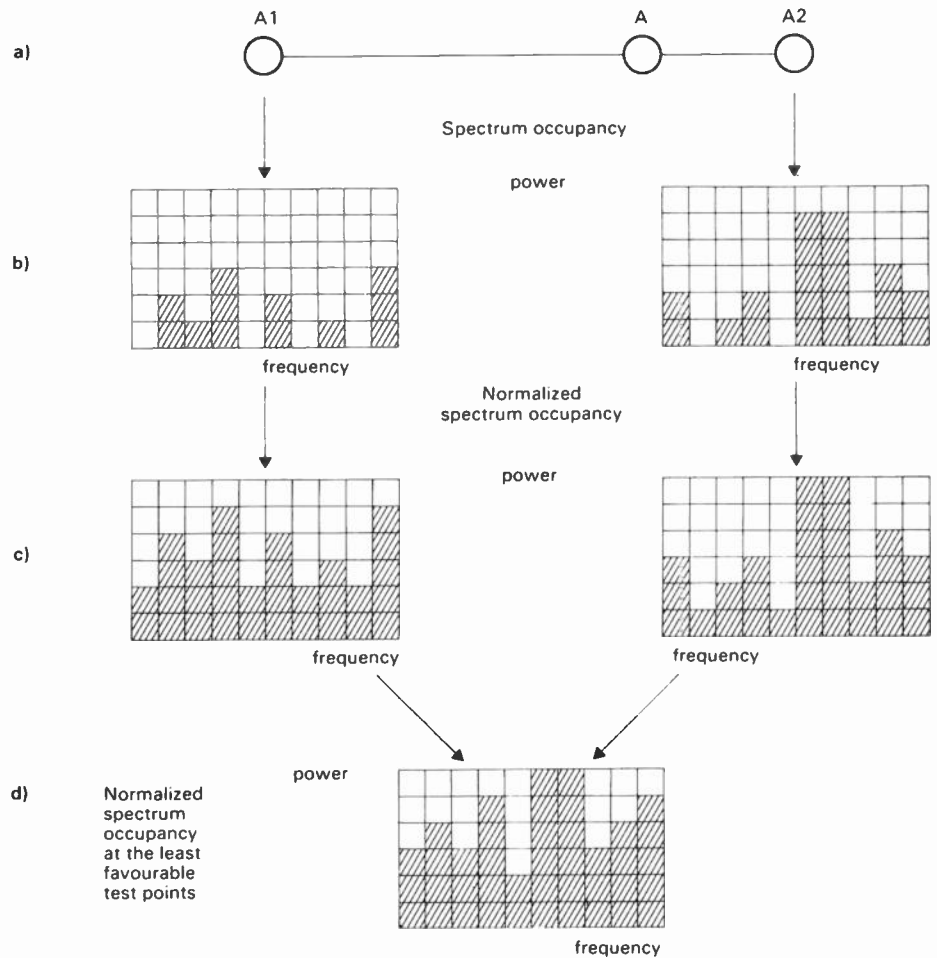


Figure 5—Idea of environment signals normalization and selection of the best frequency channel

- a) geographical location of transmitter A and its zone consisting of test points A1 and A2
- b) spectrum occupancy at A1 and A2
- c) normalized spectrum occupancy at A1 and A2
- d) envelope of normalized spectrum occupancy at A1 and A2 = spectrum occupancy over the transmitter zone. See text for explanation

mitter. Thus it now becomes possible to select the critical test point at each frequency channel and find that channel which contains the minimum of signal power at the least favourable test point. We use the following algorithm:

Algorithm: frequency channel ordering

Step 0

Given a transmitter, start with its zone in graph G.

Step 1

For each test point and each environment signal (ES) divide the ES power by the test receiver input power due to the unit power transmitter, accounting for frequency difference—if necessary.

Step 2

For each frequency channel select the test point at which the normalized sig-

nal power found in step 1 is the highest (critical test points selection).

Step 3

Order the channels according to non-decreasing normalized signal power at critical test points.

Note that all required data are already contained in graph G. This sub-problem is generated sequentially, once per transmitter. As a result, a channel priority list is obtained in which the frequency channel that assures a minimum transmitter power in the worst case is in the top position.

The dimension of this sub-problem is lower than the original problem because a single transmitter and relevant signals are considered simultaneously. The number of comparisons equals the number of test points multiplied by the number of relevant environment signals.

7. Optimum frequency and power assignment

Here, the results of earlier sub-problems are used, according to the following algorithm:

Algorithm: optimum frequency and power assignment

Step 0

Start with the transmitter priority list (A) and frequency priority list (B).

Step 1

Stop if there are no transmitters on list A; otherwise select a transmitter from the top of the list.

Step 2

Go to step 6 if there are no channels on list B; otherwise select a channel from the top of the list and assign it tentatively to the transmitter.

Step 3

Determine the power required for reception quality at the least favourable test point and select the nearest higher power from the catalogue. If there is no such allowable power go to step 6.

Step 4

Check if constraints are fulfilled in the critical test points. If they are not, go to step 7.

Step 5

Assign power and frequency channel tested, include all signals generated by this assignment to the environment, remove the transmitter from list A, and return to step 1.

Step 6

The constraints cannot be fulfilled (problem inconsistency). Verify the problem data and return to step 0.

Step 7

Remove the channel from list B and return to step 2.

This is a systematic reduction method which stops after a limited number of steps: when the job is done, i.e. when the transmitter list is exhausted, or when a problem inconsistency is discovered. This sub-problem is of lower dimensionality than the original problem because only a single transmitter is considered at each step. The possible number of tests are N_T for the most favourable case (final solution found at first attempt) and $N_T N_F$ for the least favourable one, where N_T and N_F are the numbers of transmitters and frequency channels, respectively.

If an assignment is made, then the transmitter is best fitted into its environment, all constraints are fulfilled, and transmitter power is minimum. If problem data are inconsistent it is automatically indicated where and why the assignment cannot be made.

The methods of verification where the compatibility and quality requirements are fulfilled or not are described elsewhere (see e.g. White [13]) and are not repeated here.

8. Conclusions

In this paper we have generalized the classical frequency planning problem. Instead of the traditional assignment of an operating frequency only, we have considered the assignment of a pair: an operating frequency and power to the transmitter. We have formulated this issue as a constrained optimization problem. As shown, several real-life situations can be reduced to the form presented. An heuristic method for solving this problem has been proposed, based on decomposition, reduction, and normalization principles.

New concepts have been introduced, the most significant being the signal and bond graphs; the critical points of the trans-

mitter zone; the transmitter and frequency channel priority lists. We have proposed several algorithms for constructing these graphs and lists. In one of them we use the known graph-colouring procedure. The systematic solution method proposed offers a solution that fulfills all problem constraints and ensures the best fit-in of each transmitter to its local environment in the sense of minimum power radiated. If there is any inconsistency in the input data, such that all constraints cannot be fulfilled everywhere, the method offers indications of where, why, and which of them cannot be fulfilled. This makes it possible to modify the data and repeat the solution with corrected data.

Owing to the breaking up of the original problem into sub-problems of lower complexity and solving them separately one after the other, economy in memory size and number of computations required can be achieved in comparison with the exhaustive search methods. Similar to other heuristic procedures, our method does not guarantee any unique, ideally optimum solution but offers a sub-optimum or near-to-optimum one. We believe that our approach and ideas presented here can serve as an efficient tool to cope with new tasks facing radio-communications, and open new vistas in theory and practice of frequency planning.

Acknowledgement

Valuable comments were received from Dr. Jerzy Kucharczyk of the Institute of Computer Science, Mathematics Department, University of Wrocław, and from Mr. Jerzy Rutkowski, Senior Counsellor of the CCIR. It is the pleasant duty of the author to express his gratitude to them.

(Original language: English)

References

- [1] CCIR: "Optimum network planning and frequency assignment techniques"—Study Programme AL/1 (draft) Doc. 1/122 (30 July 1980)
- [2] CCIR: *Recommendations and Reports of the CCIR, 1978, Vol. I: Spectrum utilization and monitoring*. ITU (Geneva, 1978)
- [3] id., Vol. V: *Propagation in non-ionized media*; Vol. VI: *Propagation in ionized media*
- [4] Christofides N.: *Graph theory. An algorithmic approach*. New York, Academic Press (1975)
- [5] EBU Review, No. 60A (*Special issue on transmitter network planning*) (April 1960)
- [6] Hale W. K.: "Frequency assignment methodology: an annotated bibliography". NTIA-SP-80-10, US Department of Commerce (1980)
- [7] *IEEE Transactions on Electromagnetic Compatibility*, Vol. EMC-19, No. 3, Part II (*Special issue on spectrum management*) (August 1977)
- [8] IEEE: *Proceedings of the IEEE*, Vol. 68, No. 12 (December 1980)
- [9] Kirby R. C. and Rutkowski J.: "Electromagnetic compatibility guidelines for the next 20 years—Impact of the WARC-79"—*Proceedings of the Vth International Symposium on Electromagnetic Compatibility* (Wrocław, 17-19 September 1980) pages 13-24
- [10] Sęga W., Strużak R. G. and Waszkis W.: "Computer prediction of VHF/UHF transmitting station coverage area"—op. cit., pages 497-506
- [11] Strużak R. G.: "On optimum frequency and power assignment in transmitter networks"—*Proceedings of the 111rd National Symposium on Radio Science URSI (Wrocław, 12-14 February 1981)* (in Polish), see also *Proceedings of the IVth International Symposium on Electromagnetic Compatibility* (Zurich, 10-12 March 1981), pages 89-94
- [12] Strużak R. G.: "Comments on a frequency assignment problem"—*Proceedings of the IEEE*, Vol. 69, No. 10 (October 1981)
- [13] White D. R. J.: "A handbook series on electromagnetic interference and compatibility". Don White Consultants Inc., Germantown, United States (1971)

FAA REMOTE TERMINAL SYSTEM
FREQUENCY ASSIGNMENT MODEL

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Abstract

A system of interactive analysis models was developed for the Federal Aviation Administration (FAA) to provide automated, quick-response capabilities for use by FAA frequency managers in solving frequency management problems.

This paper describes the frequency assignment model that was developed as part of the FAA's interactive system. The model is used to make VHF (118-136 MHz) Air Traffic Control (ATC) frequency assignments. The criteria used by the model, the operation of the model, and examples of the model's use are discussed in this paper.

Background

Direct voice communication between pilots and air traffic controllers is a vital link in the operation of the National Airspace System (NAS) by the Federal Aviation Administration (FAA). To provide air traffic control (ATC) communications, the FAA makes use of approximately 12.5 MHz of spectrum in the 118-136 MHz frequency (VHF) band to control civil aircraft, and approximately 40 MHz in the 225-400 MHz (UHF) band to control military aircraft. With these frequency resources, the FAA must accommodate the need for approximately 3000 discrete communication channels. One channel usually consists of one VHF frequency and one UHF frequency, in order to provide control to both types of aircraft at once. The need for a communication channel is defined as a requirement, and the fulfillment of that need with a frequency is an assignment. The demand for ATC channels is increasing as air traffic continues to grow. The result is that a shortage of interference-free air/ground assignments exists particularly in areas of high traffic density such as New York, Chicago, Los Angeles, and Atlanta.

The FAA has in the past assigned channels at 50-kHz tuning intervals in the VHF band; i.e., 118.050, 118.100, etc. To help satisfy the demand for ATC channels, the FAA has implemented a change to 25-kHz channel spacing; i.e., 118.050, 118.075, 118.100, etc. Because of the high capital investment by the civil aviation community in airborne equipment designed to operate with 50-kHz channel spacing, assignments of the odd 25-kHz channels have been made very selectively. This situation has created a mixed (interleaved) environment of 25-kHz and 50-kHz equipment. The combined effects of limited spectrum, the mixture of 25-kHz and 50-kHz equipment in the environment, the need to consider interference interactions caused by collocating many facilities, and the presence of FM and TV transmissions in adjacent bands have made the manual assignment of ATC frequencies more difficult and time consuming than in the past.

Difficulty in accommodating new requirements using methods current at the time, was first noticed around 1970. An extensive manual study performed by the FAA and computer-assisted studies performed by the Electromagnetic Compatibility Analysis Center (ECAC), indicated that, without major changes in the way the ATC bands were utilized, the FAA would be unable to satisfy all of the anticipated future requirements. Changes considered included a redeployment of all existing assignments and channel splitting. Based on these studies, the FAA also determined that automated frequency assignment methods would be required to derive maximum benefit from any large-scale changes in the use of the VHF/UHF bands. In 1971, ECAC was contracted to develop an assignment model for the FAA that would incorporate the established FAA assignment criteria, include cosite interference calculations as well as high-power TV and FM considerations, and handle the mixed 25/50-kHz equipment environment.

As the development of this model progressed, the need for a second model was identified. The initial, more comprehensive, model was employed to explore methods of improving spectrum use. The purpose of the second model was to make available to frequency managers automated frequency assignment methods to more efficiently utilize the spectrum when making case-by-case frequency assignments. The initial model was first used in 1973. At that time, frequency-redeployment and channel-splitting proposals were investigated using the model. Major redeployment of frequencies proved to be impractical; however, the change to 25-kHz channel spacing was endorsed. The model was then used extensively to plan the first phase of the change to 25-kHz channel spacing. A UHF version of this model has also been developed for planning future FAA use of the ATC portion of the UHF band.

The second model, identified as the operational VHF model, was ready for use in 1977. This VHF model resides at ECAC and is available for use by FAA frequency managers. The frequency manager provides the name, location, and service volume of the requirement. This information is entered into the model, which produces a list of candidate frequencies for the frequency manager. The development of a comparable UHF operational model is possible, but at present has been delayed because of questions concerning the classified data files required for comprehensive cosite analyses. The VHF assignment model will reside at ECAC for at least another year in order to refine and evaluate the performance of the system. The FAA will then decide if this system should be implemented in their Regional Offices, either via commercial computer time-sharing or via a remotely

located minicomputer, thus eliminating the present verbal interface with ECAC. This operational VHF assignment model is the subject of this paper.

Assignment Criteria

The term criteria applies to the standard values of parameters such as desired-to-undesired (D/U) signal ratio, geographic separations, and frequency separations, used in the frequency assignment evaluation procedure. In most cases, the assignment criteria used by ECAC in the models are those specified in the FAA UHF/VHF Frequency Assignment Handbook.¹ This handbook was derived from international standards and practices,² FAA research and development, and actual experience in frequency assignment. Some situations, such as 25/50-kHz interleaving, required that new criteria be developed. The intent of this section of the paper is to describe the most critical interference interaction analyzed by the VHF model, introduce the standard FAA criteria, and discuss those situations for which new criteria were required.

Of the potential cochannel interference interaction analyzed by the model only the most critical interaction is discussed in this paper. This case is shown graphically in Figure 1. To provide adequate performance, the desired signal (D) at the victim aircraft in service volume 1 must be at least 14 dB greater than the undesired signal (U) from an interfering aircraft in service volume 2. The 14 dB D/U signal ratio must also be realized when the roles of the victim aircraft and interfering aircraft are reversed and for every combination of assignments served by the same frequency.

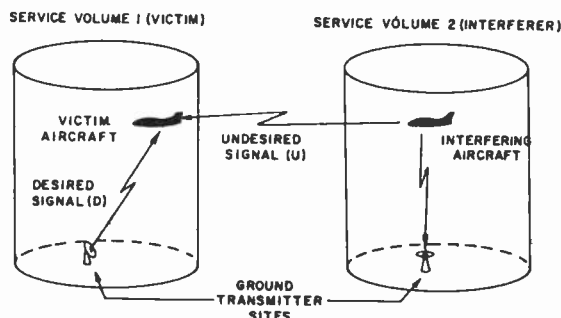


Figure 1. Geometry of airborne transmitter in service volume 2 interfering with airborne receiver in service volume 1.

An assignment must perform as well in the presence of an adjacent-channel signal as it does in the presence of a cochannel signal. The IF selectivity of an airborne receiver designed for 50-kHz operation is assumed to provide at least 60 dB of attenuation to a signal offset by 50 kHz. An airborne receiver designed for 25-kHz operation is assumed to provide at least 60 dB of attenuation to a signal offset by 25 kHz. With this amount of rejection by the receiver of the interfering adjacent signal, a -46 dB (14 dB-60 dB) D/U signal ratio will achieve performance equivalent to the 14 dB D/U signal ratio specified for cochannel assignments. This would allow adjacent-channel assignments in adjoining service volumes. Even though the desired-to-undesired signal protection is achieved, the level of the undesired signal can exceed the muting threshold of the victim receiver if the aircraft in the adjacent-channel service volume is near the victim. This could cause an undesirable on and off action of the squelch

and possibly desensitize the victim receiver. To avoid this, the FAA separates adjacent-channel volumes by 2 nautical miles (4 kilometers).

The same level of performance must also be achieved when an odd 25-kHz (e.g., 118.075) channel is interleaved between 50-kHz channels (e.g. 118.050-118.100). The IF selectivity of a 50-kHz receiver will only provide 6 dB of rejection to a signal offset 25 kHz (See Figure 2). This value was obtained assuming that both the victim receiver and interfering transmitter are at their maximum allowable frequency drifts; ie. 0.003% for airborne equipment³. Thus, for the worst case situation, to provide the required 14 dB D/U of interference protection, 8 dB (14 dB-6 dB) must be obtained as a result of geographic separation.

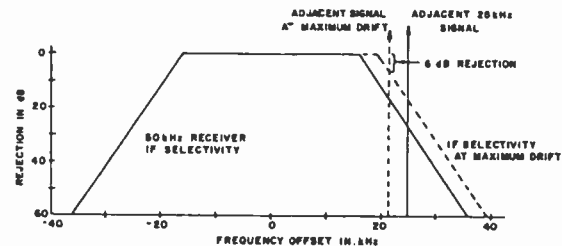


Figure 2. Rejection of a 25-kHz adjacent channel by the IF selectivity of a 50-kHz receiver

To calculate the D/U signal ratios in the cochannel and 25/50-kHz interleaving cases, two assumptions are made. First, that the effective isotropic radiated power (EIRP) of the desired signal is equal to the EIRP of the undesired signal. Second, that the propagation of the signals can be approximated by free-space loss within line-of-sight and by infinite loss beyond the radio horizon. The power budget shown in TABLE 1 reflects typical ground and airborne system parameters and illustrates the first assumption.

TABLE 1
POWER BUDGET

Parameter	Desired Signal (Ground)		Undesired Signal (Aircraft)	
Transmitter Output Power	10 watts	40.0 dBm	25 watts	44.0 dBm
Line Loss	- 1.5 dB		- 3.0 dB	
Antenna Gain	+ 2.2 dBi		+ 0.0 dBi	
EIRP	40.7 dBm		41.0 dBm	

The D/U ratio is calculated as follows:

$$D/U = EIRP_1 - L_1 - EIRP_2 + L_2 \quad (1)$$

where:

D/U = the desired-to-undesired signal ratio, in dB

EIRP₁ = EIRP of the desired signal, in dBm

EIRP₂ = EIRP of the undesired signal, in dBm

L₁ = the transmission loss from the desired ground facility to the victim aircraft, in dB

L₂ = the transmission loss from the interfering aircraft to the victim aircraft, in dB.

Since $EIRP_1$ is approximately equal to $EIRP_2$, equation (1) reduces to:

$$D/U = L_2 - L_1 \quad (2)$$

Since it is assumed that L_1 and L_2 can be approximated by free-space loss, equation (2) becomes:

$$D/U = 37.8 + 20 \log d_U + 20 \log f - 37.8 - 20 \log d_D - 20 \log f \quad (3)$$

where:

d_U = the distance between the victim and interfering aircraft, in nmi

d_D = the distance from the desired ground facility to the victim aircraft, in nmi

f = the frequency, in MHz.

Equation (3) reduces to:

$$D/U = 20 \log (d_U/d_D) \quad (4)$$

Equation (4) is used in the assignment model to determine D/U signal ratios. For a 14 dB D/U ratio, d_U must be approximately five times greater than d_D . This method of calculating D/U signal ratios closely approximates results obtained using median propagation curves for most cases of interest.

One of the more difficult compatibility problems involves the collocation of equipment. To assist with the solution to this problem, adjacent-signal frequency separations and intermodulation and harmonic protection calculations have been incorporated in the models. The standard FAA adjacent-signal separation for collocated facilities is 500 kHz. A 0.2 nmi (0.4 km) radius for the site allows for variations in the reported and recorded geographic coordinates of facilities actually at the same location. The intermodulation products considered in this model are two- and three-signal, third-order combinations of FM and TV broadcasting signals in the 54-108 MHz band and/or other aeronautical facilities in the 108-136 MHz band. These products are considered by the FAA to be the most harmful sources of interference to ATC ground facilities. Because of their high EIRP's, broadcasting stations as far away as 15 nmi (28 km) from the site can produce harmful intermodulation and harmonic products. Since aeronautical stations operate at much lower power levels, only those frequencies assigned to aeronautical stations located within 2 nmi (4 km) of the site are considered in the analyses. These distances were judged to be large enough to include in the analyses the most likely potential sources of interference in the area without overly restricting the number of possible assignments. The model will not assign frequencies that would result in adjacent-signal, intermodulation, or harmonic interactions. Frequencies that would produce harmonic products in FAA UHF receivers in the area are also avoided. The 0.2, 2 and 15 nautical mile (0.4, 4, and 28 kilometer) criteria used for searching the data base were developed specifically for use in the assignment models.

Model Description

The objective was to develop a Remote Terminal Assignment Model that would utilize the FAA assignment criteria and perform the task in a timely manner. A responsive assignment model requires a data base that

is structured to ensure fast access and efficient computational methods. Therefore, the model development was divided into two major tasks: 1) structure a data base and develop the necessary data management system to make the FAA-supplied data easily accessible to the model; and 2) develop an assignment capability that is consistent with the FAA-supplied criteria.

Data Base Design

Two types of data are required for the FAA assignment model: data for the intersite analysis (requirement file), and data for the cosite analysis (background file).

The requirements file contains existing VHF assignments in the continental U.S., Canada, Mexico, and portions of the Caribbean. Each record contains the frequency, site name, site location, service-volume data (radius, altitude, service-volume center) and the unique requirement identification (ID) in the Government Master File (GMF). If the frequency serves an en-route function (low-altitude or high-altitude), the latitude and longitude points that describe its multi-point service volume are also included in the record.

The second data file, the background file, contains those frequencies in the U.S. that are most likely to cause cosite problems for VHF assignments. Sources for this file are:

GMF: 108-136 MHz and 225-400 MHz bands

FCC: 54-108 MHz band

APRINC: 118-136 MHz band.

The background file is ordered by longitude, to permit rapid access to records for a specific geographic area. Each record in the background file contains the site latitude and longitude and the associated assigned frequency.

Assignment-Model Development

The assignment model must be able to perform data-base modifications and make the necessary cosite and intersite calculations. The initial assumption for any execution of the model is that all existing ATC requirements are currently satisfied. Any assignments to be made will result from new ATC requirements that must be added to the file, or from modifications to existing requirements that need a frequency change. The model is divided into two sections: assignment problem definition, and assignment problem solution.

Assignment Problem Definition - The model provides the user with the ability to change the file to reflect the operating environment that will require new frequencies and/or frequency changes. Changes to the file are made by entering the unique GMF ID number, which enables the model to access the requirement that is to be modified or deleted. New requirements are entered by specifying the site name and location and all pertinent service volume information. The assignment process begins after all file changes have been entered.

Assignment Problem Solution - The process is initiated by the user by specifying the cosite and intersite assignment criteria. The standard FAA criteria, discussed earlier, are preset in the model; however, the frequency manager has the flexibility to modify these criteria to account for unusual circumstances. Next, the user determines the frequency resources by specifying the channel spacing and frequency range or designating specific frequencies. Finally, the user

specifies the requirement to be satisfied.

After all input data are specified, the model proceeds to the cosite and intersite analyses. To initiate the cosite analysis, frequencies are selected from the background file within a specified radius of the site where the frequency is to be assigned. The standard radius values are used; i.e. the 0.2; 2; and 15-nmi radii mentioned earlier. The model prohibits assignments that might contribute to such cosite interference phenomena as adjacent-signal, intermodulation, and harmonic interactions. The cosite analysis provides a list of all denied frequencies and the reason(s) for their denial. The intersite analysis begins by sequentially considering those candidate frequencies that have met the cosite criteria. These cosite-acceptable frequencies are tested to determine if they meet the cochannel and adjacent-channel criteria. Frequencies that meet the intersite criteria are shown to the user. The user may select the displayed frequency for assignment or continue to search for alternate acceptable frequencies. When a frequency is selected by the user, the model is instructed to record the assignment on a temporary basis and the user then designates the next requirement to be assigned a frequency. All frequencies assigned in a given execution of the model meet the FAA criteria and are compatible with the environment and other selections made during that execution. The data base reverts to its original configuration upon completion of the problem.

Sometimes, no frequency exists that meets all of the specified criteria. In this case, the user can return to the problem definition portion of the model to "free-up" a frequency. Frequencies can sometimes be made available to satisfy the new requirement by shifting the frequencies associated with one or two existing assignments. The file can handle 10 changes for any execution; therefore, the number of frequency shifts is limited. Frequencies for existing assignments so affected must be reassigned. Presently, the candidates for shifting are usually restricted to high-enroute frequencies that can be reassigned on 25-kHz channels. (Only the high-enroute requirements utilize 25-kHz channels at present.) All other requirements are satisfied with 50-kHz channels.

Typical Examples

The FAA frequency managers have been using this model for over one year. In that time, over 100 operational frequency selections have been made with the model. In making these selections, the model has performed well and the results have been favorably received by the FAA Regional Frequency Managers.

The two examples below are typical of assignment problems that were solved by the model. The first example illustrates a problem in which an existing assignment had to be changed and the second example illustrates how an assignment for a new ATC requirement is determined.

Example 1 - A low-enroute assignment at Dayton, Ohio, presently using 134.450 MHz, was interfering with a high-enroute assignment at Brunswick, Georgia. The calculated D/U signal ratio was 10.1 dB. There was also an intermodulation problem on 134.450 MHz. No

violation-free 50-kHz channels were available, so the frequency of an existing assignment had to be changed to accommodate Dayton. One of the best candidate frequencies for Dayton was 127.850 MHz; because only one existing assignment (Portsmouth, Ohio) would need to be changed to permit Dayton to use 127.850 MHz. The assignment at Portsmouth was a high-enroute frequency that could be switched to a 25-kHz channel. Therefore, Portsmouth was changed to 135.175 MHz and Dayton was assigned on 127.850 MHz.

Example 2 - A local control frequency assignment at Boise, Idaho was needed to serve general aviation aircraft, many of which have vintage radios that tune only to channels spaced at 100-kHz intervals in the 118.0 - 126.9 MHz band. Initially, only two-signal third-order intermodulation protection was specified and three frequencies, 120.6, 120.7 and 125.9 MHz, passed all the criteria. It was later learned that three-signal intermodulation protection was required which resulted in only 120.6 MHz meeting the criteria. Therefore, 120.6 MHz was proposed for assignment at Boise.

Summary

A frequency assignment model has been designed to help the FAA frequency manager make assignments that meet all of their prescribed assignment criteria. The model provides the user with a variety of capabilities not generally found in a single model, and offers a substantial savings in time, effort, and regional resources. Cosite calculations for any site in an urban area would normally take an engineer many hours to complete. The model performs the cosite analysis, including a search for the frequencies to be considered, in a matter of seconds. The model also gives the frequency manager the flexibility to define each assignment problem to reflect conditions of which only he might be aware, and this knowledge is often a very important ingredient in a go/no-go assignment situation.

Acknowledgement

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References

1. Federal Aviation Agency, Washington, D.C., VHF-UHF Air/Ground Communications Frequency Engineering Handbook, June 1965.
2. International Civil Aviation Organization, International Standards and Recommended Practices, Aeronautical Telecommunications, Annex 10 to the Convention on International Civil Aviation, Volume 1, July 1972.
3. Department of Transportation, Federal Aviation Administration, Washington, D.C., U.S. National Aviation Standard for the VHF Air-Ground Communication System, November 1977.

Frequency Planning for Broadcast Services in Europe

JEAN-FRANÇOIS ARNAUD

Abstract—The regular lattice theory is a powerful tool to achieve an efficient use of the frequency spectrum when assigning frequencies or channels to broadcast transmitters. In this paper the basis of the theory is explained, and it is shown how it can be implemented in planning broadcasting transmitter networks for AM or FM sound and television. Physical laws and local considerations will, of course, influence the design of networks and some practical examples are given to make clear how they have been taken into account. The theory will be useful not only in building or remodeling actual transmitter networks, but also with the aim of optimizing technical parameters such as channel spacing, transmitter characteristics, etc. In this later case computerized method will be efficient. Regular lattices have been of some help in former ITU planning conferences, and will certainly be of assistance to experts in charge of achieving good plans in the future conferences of the years to come.

I. GENERAL

FREQUENCY planning is more popular in Europe and Africa than in America, and it may be interesting to state why it is so before trying to describe the planning methods which have been implemented so far.

In America there is some fear that planning in advance might lead to an inefficient use of the frequency spectrum as technology will hopefully improve and allow for more clever assignments in the future. But in Europe and Africa, administrations believe that assignments on a first-come first-served basis would deprive less developed countries of their rights to secure the frequencies they will need within a few decades. Moreover, a long-term plan has only a few operating transmitters to take into account and may be made according to sophisticated methods, the result of them being the availability of more transmitters to serve each zone. In order to support the Eurafri-can point of view, a satisfactory method of frequency planning was necessary, and it is not surprising that the first attempts had been made when preparing for the 1961 VHF/UHF broadcasting conference (Stockholm) for the European Broadcasting Area, where all the prerequisites were found [1], [2].

II. REQUIREMENTS FOR PLANNING

A theoretical planning method can be developed where at least the following conditions are met.

1) There shall be some uniformity of standards. It was not the case for VHF television in Europe where the number of lines per picture were not even the same everywhere.

2) The frequency band to be planned shall be free, as a "new frontier" of the spectrum. Actually, the 1961 Stockholm plan for VHF television broadcasting only acknowledged the status of the networks as they were operated in some countries. Planning from scratch was impossible because it would have

been unpractical to change all frequencies, as such a change would have involved modifications in the transmitters as well as for the viewers.

Nevertheless, a rearrangement was possible for VHF sound broadcasting, because of the relative narrowness of the band and the easy retuning of transmitters, receivers, and antenna. UHF bands were still empty and were planned according to theory.

Since 1961 many plans have been agreed upon in the frame of many ITU Conferences, some of them based on the theoretical methods that are described hereafter [3], [4].

III. BACKGROUND

The theory of uniform transmitter networks has been imagined in the Institut für Rundfunktechnik (Hamburg, Germany) before the 1961 Stockholm planning Conference. Fastert *et al.* have written a monograph which has been published by the European Broadcasting Union (EBU) [5]. The practical aim of the method was then to achieve the best use of channels 21–68 in bands IV and V.¹ The number of channels (48) was too high for a good plan to be reached by means of purely empirical methods. Since then the Fastert's theory has been used to build, in 1963, VHF sound and television plans for the African Broadcasting Area [3] and helped in preliminary studies for the LF/MF broadcasting conference [4] in 1974/1975. This latter application is an interesting example because, although the theoretical method has not been actually used for planning, as there were already a high number of operational transmitters, nevertheless experts have been able to identify the best attainable coverage and an optimal channel spacing as results of theoretical studies based upon that method.

IV. THE THEORY OF REGULAR NETWORKS

It should be noted that the networks which will be studied here, in the first paragraph, are purely theoretical in the following sense:

- 1) all the transmitters are identical: their power and antenna height are the same;
- 2) they are equipped with nondirectional antennas;
- 3) propagation is isotropic and does not vary with the frequency, at least within the band to be planned.

The earth is supposed to be flat from a geometrical point of view (not propagation), and the population evenly spread on it; there are neither political nor natural boundaries.

In these conditions, and provided interferences are negligible, the service area, i.e., the region where a good reception is

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¹ In this paper, all the examples refer to European channeling: channel 21 ranges from 470 MHz to 478 MHz, channel 22 from 478 MHz to 486 MHz, etc.

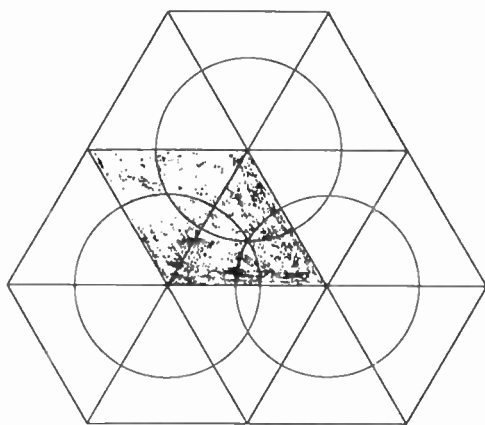


Fig. 1. Location and service zone of identical broadcasting transmitters in a regular network.

achievable with a normal domestic receiver, is limited by a curve within which the electromagnetic field strength is greater or equal to the value necessary to get a signal-to-noise ratio conventionally chosen. In the ideal situation described above, this curve is a circle whose radius depends on the type of service and the propagation laws valid for the considered frequency range. If it is desired to tile the plan with such service areas, it is quite obvious that the number of transmitters per unit surface will be minimized if they are situated at the intersections of straight lines forming a regular lattice of equilateral triangles (Fig. 1). It is not true to say that there is one transmitter per triangle, but rather one transmitter for each pair of triangles forming a rhombus (shaded area on Fig. 1). This remark is of importance when computing the network efficiency.

With this configuration, every location on the earth is served by at least one transmitter and overlapping is minimized. In what follows, we will take as a unit of length the side of the elementary equilateral triangle. The transmitter surface density is then one for each elementary rhombus whose area is $\sqrt{3}/2$. The network efficiency can be expressed by the ratio: total area where the service is good/sum of the (overlapping) coverages. A regular lattice of triangles gives the optimum value, i.e., 0.83. The ideal value would obviously be one, but it is not attainable as it is impossible to tile the plan with circles. A regular lattice of squares only achieves a ratio of 0.64 (the service area of each transmitter has an area of $\pi/3$ and a radius of $\sqrt{3}/3$).

V. AN EXAMPLE OF THEORETICAL NETWORK

It is supposed that the available frequency band has been suitably channelized; that means it has been divided in equal frequency slots, each of them occupied by a sound or television program (9 kHz for AM sound broadcasting; 100 or 200 kHz for FM sound; 6 or 8 MHz for television). It is then easy to derive the number of channels that can be used when planning. As this number is obviously finite, sooner or later, at some distance from the starting point which has been taken as the origin of the planning process, the channel assigned to the starting point has to be reused. The smaller the distance D , between two transmitters operating on the same channel, the lower the number of channels to cover the whole earth. But it is necessary that D is long enough for the two cochannel transmitters not to interfere with each other.

Finding out the value of D is an easy task. With the help of suitable propagation curves, field strengths of the wanted trans-

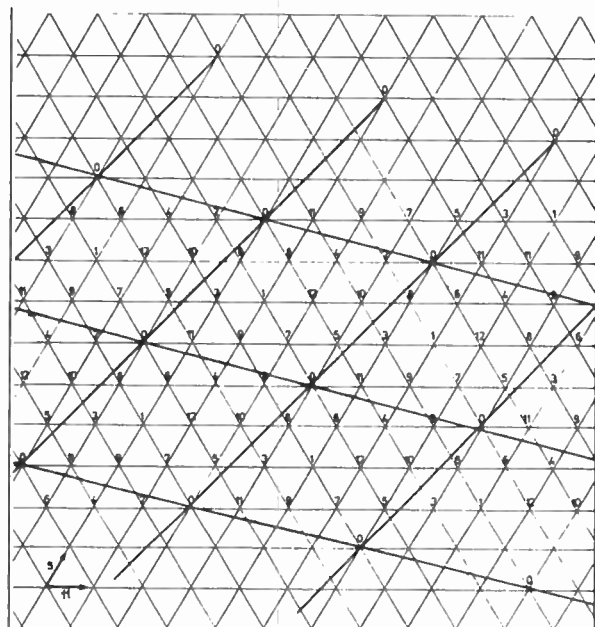


Fig. 2. Example of optimum regular lattice for 13 channels.

mitter and of the interfering one are computed, for given percentages of time [6], [7], on the circle surrounding the service area of the wanted transmitter. D is made long enough for these two field strengths to be different by a number of decibels higher than the protection ratio which is to be found in the pertinent Recommendations or Reports of the CCIR [8]–[11]. The case of multiple interference will be dealt with later.

With N channels, it is possible to cover an area of N elementary rhombi, or $N\sqrt{3}/2$, taking as surface unit a square whose side is equal to the side of the elementary triangle. So another kind of tiling appears and it is logical to stick to the conclusion found in paragraph 4: a given channel will be repeated at the edges of a lattice of rhombi whose shorter diagonal is equal to the side, the surface of which being $N\sqrt{3}/2$. This rhombus will be called "cochannel rhombus" and the length D of its side is $\sqrt{N}$ ($\sqrt{N}$ times the side of the elementary triangle). The characteristics of rhombic lattices will be shown on a simple example, where $N = 13$ (see Fig. 2). It may have some interest for planning VHF television or long waves.

1) *Period*: All the cochannel rhombi are identical. A two-dimensional periodicity appears. It might remind the reader of the theory of elliptical functions.

2) *Channel distribution*: Within one rhombus, channels might be distributed at random, but in every rhombus their locations should be identical. However, a random distribution is not applicable if interference cases, other than cochannel interference, are considered—which happens in practice. For the sake of homogeneity, which is supposed to lead to the most efficient use of frequencies, it is desired that, in the service area of a given transmitter, the interfering signals on any channel have the same strength, wherever the transmitter is. In the case of channel 0 on Fig. 2, that means adjacent channel number 1 will appear at the same intersection in each rhombus. Finally, channel 1 defines the same kind of rhombic lattice as channel 0. From this lattice of channel 1, the location of channel 2 can be derived by the same reasoning which will be extended to the 13 channels. It is obvious that somebody walking along the straight lines of the elementary triangle lattice would find channels regularly spaced. Going west from

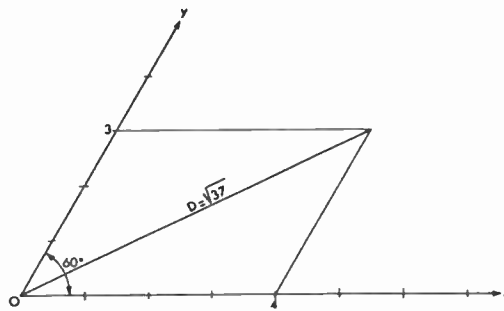


Fig. 3. Reference coordinates of regular lattices.

a \ b	1	2	3	4	5	6	7	8	9	10	11	12
1		7	13	21	31	43	57	73	91	111	133	157
2			19		39		67		103		147	
3				37	49		79	97		139		
4					61		93		133			
5						91	109	129	151			
6							127					

 $N < 160$

Fig. 4. Table of rhombic numbers.

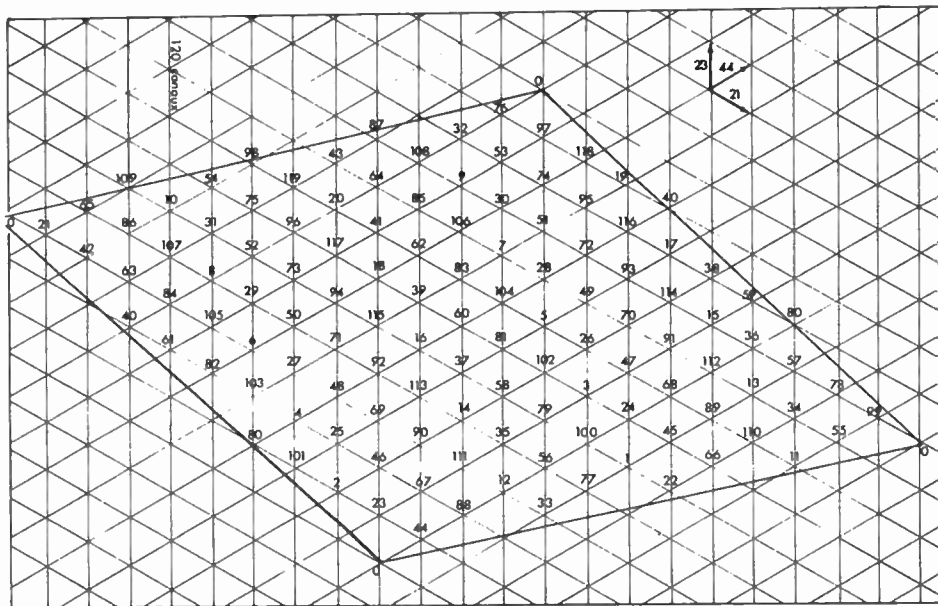


Fig. 5. Nonoptimum network with 120 channels.

channel 0 are found channels 2, 4, 6, 8, 10, 12, and then 1 (= 14 modulo 13), 3 (= 16 modulo 13), etc. Finally, after $N = 13$ steps, channel 0 appears again. The whole lattice can be easily designed: the progression step is +2 towards the left side, and +5 towards the upper right corner.

VI. IDEAL AND NONIDEAL NETWORKS

To make the calculations easier, it is convenient to refer the plan to a system of two coordinate axes, bearing equal scales but making an angle of 60° rather than the conventional 90° (see Fig. 3).

It has been found that the side of the cochannel rhombus has a length equal to $\sqrt{N}$, but it is necessary that the edges of

the rhombus coincide with the intersections of the elementary lattice. In the slant reference system, the distance of any point (x, y) from the origin is

$$(x^2 + xy + y^2)^{1/2}.$$

If two integers a and b can be found such that $a^2 + ab + b^2 = N$, number of channels, then there is a cochannel rhombus whose edges coincide with the intersections of the elementary lattice. $N = 13$ corresponds to the case $a = 3$ and $b = 1$. In the following lines, such numbers will be called "rhombic numbers." Some of them are given on Fig. 4.

There are other conditions for the choice of a and b : they shall not have any common divisor, and neither of them can

be equal to zero. For instance, if they are both even numbers, the cochannel rhombus will split itself in $2 \times 2 = 4$ subrhombi of $N/4$ channels. The other condition will be considered later. The theory still works if N is not exactly a rhombic number. The cochannel rhombus becomes a cochannel parallelogram, with an area equal to N . In this case, the sides of the parallelogram are not equal; one of them is shorter than the other and as a consequence the cochannel distance is slightly smaller than $\sqrt{N}$. It is not an optimal network. Fig. 5 shows a network with 120 channels, 120 not being a rhombic number. The result is still very close to the ideal network, where the cochannel distance would have been $\sqrt{120} = 10.95$. Here the sides of the rhombus are 11.53 and 10.82 in length and the diagonal 10.58, which is not much less than 10.95. This kind of network has been used in MF planning tests.

Sometimes ingenuity has to be exercised to find the progression steps such that the channel assigned to the origin will reappear at the edges of the cochannel rhombus or parallelogram. Referring Fig. 2 to the slant reference system mentioned above, the steps along the x and y axes must verify the following equations (p : step along x ; q : step along y):

$$1 \times p + 3 \times q = kN \quad (k: \text{integer}), \quad \text{and} \quad 4 \times p - 1 \times q = k'N.$$

On Fig. 2, $p = 11$, $q = 5$, $k = 2$, and $k' = 3$, for $N = 13$. Steps are written on Fig. 2. In the case of nonrhombic number, there is more than one parallelogram and many attempts are necessary to find the best one. Even in the case of rhombic numbers it may happen that two different cochannel rhombi exist, as it appears on Fig. 4 for 91 (9 and 1 or 6 and 5).

The case where $b = 0$ is a trivial one. Cochannel rhombus sides coincide with the x and y axes, and $a = \sqrt{N}$. The sum of steps along the axes shall be N ; consequently their value is $\sqrt{N}$. It is then only possible to write on the lattice channels multiple of $\sqrt{N}$.

VII. EVALUATION OF INTERFERENCE

It has been explained in Section V how the minimum necessary number of channels derives from the consideration of propagation curves and protection ratios, but only one interfering transmitter has been taken into account. On Fig. 6 are drawn a few cochannel rhombi for a cochannel distance D , the wanted transmitter being at the center and the eighteen others causing interference. In the case of VHF or UHF broadcasting, the service area is evaluated on the basis of the 50 percent of the time propagation curves of [7], knowing the characteristics of the transmitter (effective radiated power, antenna height, frequency) and the minimum field strength to be protected. In Section IV, the service area radius has been found to be $\sqrt{3}/3$ times the side of the elementary rhombus. So the scale of the lattice is known. The first six interfering transmitters are at a distance $D = \sqrt{N}$, and as an easy approximation it will be assumed here that D is large enough and that the interfering field strength is almost the same at the wanted transmitter location and on the fringe of its service area. In a more accurate study, the ratio wanted/interfering signals should be calculated at the limit of the service area, at least at the six locations shown by roman numbers I-VI on Fig. 6. The receive antenna directivity should be taken into account [12].

D has to be long enough for the ratio of the difference (in decibels) to the useful field strength exceeded for 50 percent of the time minus the sum of the interfering field strengths exceeded for 1 percent of the time, to be greater or equal to the wanted protection ratio. Then it should be checked whether

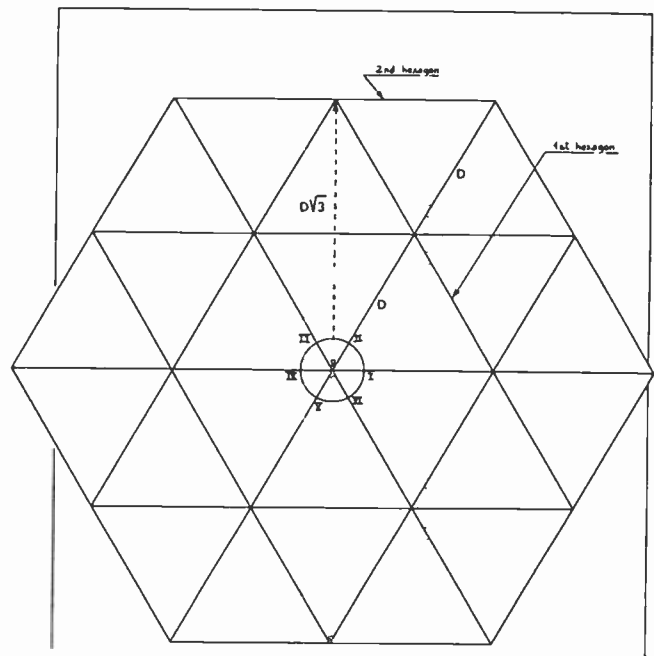


Fig. 6. Location of cochannel transmitters.

the twelve transmitters located on the second hexagon (see Fig. 6) have any influence, but in general this is not the case unless D is very small.

Adjacent channel interference: the network of Fig. 2 will serve as a practical example. D is supposed to have been found to be equal to $\sqrt{13}$. By definition, the network is isotropic and the case of any channel can be studied, except channels 0 and 12 which are only interfered by one other adjacent channel. Take for instance channel 7. The adjacent channel distances are $\sqrt{3}$ and 2. There are 4 adjacent channel interfering transmitters. Their total field strength will be evaluated at the transmitter location first, and then, if the interfering/wanted signal ratio is close to the protection ratio, at some critical points at the limit of the service area. Other adjacent channel transmitters are much more remote. Their distances are $\sqrt{7}$, $\sqrt{12}$, $\sqrt{13}$, etc.

For a wanted transmitter on channel C , there are at least in each cochannel rhombus two adjacent channel interfering transmitters on channels $C + 1$ and $C - 1$. They would be as far from channel C as it is possible if they were at the center of the C channel cochannel rhombus (i.e., the rhombus with a channel C at every edge). It is, of course, impossible to locate two transmitters at the same elementary lattice intersection, but they may be very close to that ideal center. That means that channels $C + 1$ and $C - 1$ would be very close to each other, and it may be troublesome if they are likely to interfere together. Another favorable location is the center of gravity of one of the cochannel triangles. In television networks, cochannel and adjacent channel interferences are only considered. The same applies to LF/MF networks. However, interferences between channels C and $C \pm 2$, C and $C \pm 3$, and even C and $C \pm 4$, must be considered when planning VHF sound broadcasting networks (in Europe, channel spacing is 100 kHz).

VIII. INCOMPATIBILITIES

When planning a certain type of service, some other constraints have to be kept in mind and most of them stem from the receiver design. It is useful to distinguish between internal

and external constraints.

1) *Internal constraints or restrictions:* These have their origin in the design of the receiver of the service which is being planned in order that one receiver doesn't interfere with others. If, for example, we take the problem of UHF television planning in a country where the TV receiver intermediate frequencies are 32.7 MHz for picture and 39.2 MHz for sound, as local oscillators are never perfectly shielded, they will radiate, when the receiver is tuned on channel $C=30$, for instance (picture carrier: 543.25 MHz; sound carrier: 549.75 MHz; standard L of CCIR [13]), a wave centered on 510.55 MHz which will be harmful to channel 26 (picture: 511.25 MHz). Then, if one of the progression steps in the regular lattice is 4, there will be neighboring transmitters on channels 30 and 26. In their zones of overlap, receivers in adjacent houses or apartments may be tuned to either channel 30 or to channel 26. The former's local oscillator will interfere on the later input and there is some risk to the neighbors. Tenants will not get along very well. It should also be mentioned that it is unwise to choose a progression step of 9 as this would mean neighboring transmitters separated by the image frequency where receiver selectivity is often poor (in the above example, channels 21 and 30).

2) *External constraints:* Generally in a given area there are more than one broadcasting service and in many cases more than one transmitter is to be found on the same location (hill, tower). In Europe it is quite common to gather in the same building one VHF television transmitter, three or more FM sound transmitters, and up to three UHF TV transmitters. It will be shown later that theoretical networks are flexible enough to allocate frequencies in this configuration. Assignments should be made carefully in order to avoid harmonics of receiver local oscillator falling in the band of other local transmitters. For instance, the local oscillator of a VHF sound receiver tuned on 89.3 MHz works on 100 MHz (intermediate frequency: 10.7 MHz, supradynic mixer) and harmonic 2 on 200 MHz may be harmful to some VHF television receivers. Unfortunately, this type of constraint does not result in any general law and it has to be enforced on a case per case basis.

IX. AN EXAMPLE OF THEORETICAL NETWORK

VHF/FM sound broadcast transmitters will be considered; the technical characteristics of which are: 100-kW e.r.p. transmitters, 300-m antenna height, minimum field strength (to be protected to achieve a good signal-to-noise ratio) of 1 mV/m, and monophonic programming. The question will be: How many 100 kHz-wide channels are needed to cover an infinite area?

Then, according to the propagation curves of CCIR Recommendation 370 [7], the radius of the service area is 70 km, and it has been seen in Section IV that the distance between transmitters is 70 times $\sqrt{3} = 121$ km. With the European standard (75 kHz maximum excursion and 50 μ s preemphasis) the protection ratio for cochannel interference amounts to 28 dB [9]. Then the interfering field strength anywhere in the service area should not be more than 1 mV/m minus 28 dB, i.e., 32 dB (μ V/m). Consider first the transmitter location, and assume the field strength of the 6 transmitters of the first hexagon (see Fig. 6) add up arithmetically, which is a very pessimistic assumption. The protection ratio is secured if the cochannel distance D is found to be greater than 400 km. It is easy to be sure that the 12 transmitters on the second hexagon have no significant influence. At the limit of the service area, the ratio

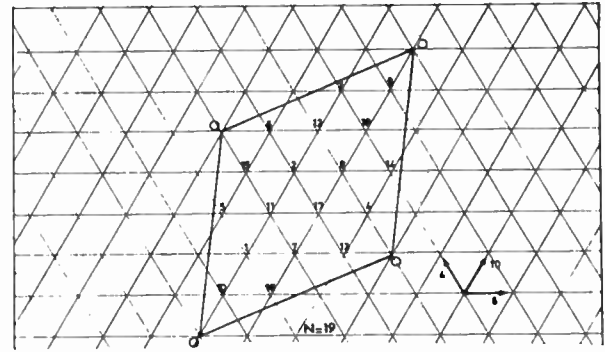


Fig. 7. Example of optimum regular lattice for 19 channels.

wanted/interfering signals is approximately 2 dB lower, so as a matter of safety the distance D will be increased to 420 km to compensate for these 2 dB. Taking as a unit of length the minimum distance between transmitters, the value of D is 3.47 (420:121).

A. Minimum Number of Channels

From the minimum distance between cochannel transmitters, the minimum number of channels is easy to derive by $N = D^2$. Here $D^2 = 12.05$; N being an integer takes the value 13. Fig. 2 shows such a network, which would be perfectly suitable if there were no other interference than cochannel. Service areas of adjacent-channel transmitters should not overlap, as the protection ratio is 12 dB for this frequency spacing. So in each cochannel rhombus six locations are precluded (those which have been assigned channels 5, 6, 7, 8, 10, 11). On the six locations, which are still free, it is not possible to find a configuration where no $C/C+2$ transmitters are neighbors, which would be acceptable if the 200 kHz spacing protection ratio were negative, which is not the case (+6 dB). So 13 is too low a number of channels, and the next rhombic number above 13 is 19 (from 3 and 2). Of course nonrhombic numbers could have been chosen but they do not result in an optimum solution, and for the time being the purpose of this study is only the finding of the minimum number of channels or the narrower necessary bandwidth.

A 19 channel network is given on Fig. 7. The cochannel distance $D = 121 \sqrt{19} = 527$ km. Now a good choice of the progression steps has to be made. They have to be such that $3p + 2q = k \times 19$. As far as possible p and q will be greater than 3 so as not to assign adjacent frequencies to neighboring transmitters. Fig. 7 shows that here steps are 4, 6, and 10 (of course, they are not independent: $4 + 6 = 10$).

B. Channel Assignments (See Fig. 7)

It seems difficult to evolve a thoroughly methodical process and many trials will have to be performed when the number of channels is high. In the case of VHF/FM broadcasting, attention has only to be paid to cochannel, adjacent channel, 2-channel and 3-channel interferences (by Z -channel interference is meant interference between transmitters on channels C and $C+Z$). If the considered cochannel rhombus has channel 0 at its edges, it seems to be wise to put channel 1 near the center of gravity of the cochannel equilateral triangle so channel 2 falls near the gravity center of the other equilateral triangle included in the cochannel rhombus. Then channel 3 is near channel 0 but, in this case, at a suitable distance. The choice of steps would have been bad if channels 0 and 3 had been assigned to neighboring transmitters, as the protection

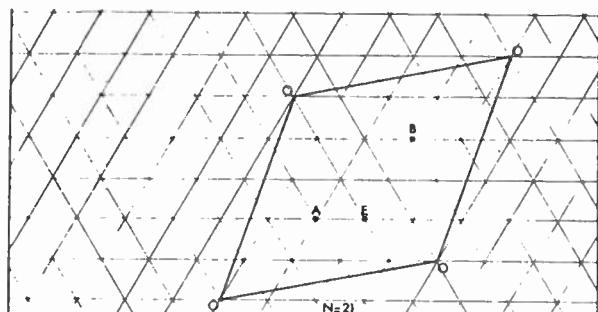


Fig. 8. Scheme of a 21 channels lattice.

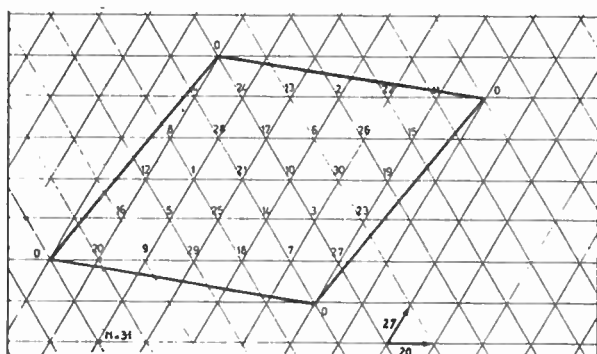


Fig. 9. Example of an optimum regular lattice for 31 channels.

ratio is only slightly negative (-7 dB) which could cause difficulties in the overlapping zone.

The minimum distance between adjacent channel transmitters is then 242 km and the interfering field strength at the more vulnerable point on the fringe of the service area is 48 dB ($\mu\text{V/m}$), which is acceptable, provided the contribution of other adjacent-channel transmitters is negligible. The minimum distance between 2-channel transmitters is 210 km where the interfering field strength is 51 dB ($\mu\text{V/m}$), the ratio wanted/interfering signal being greater than the protection ratio: 6 dB for 200 kHz. The distance is the same between C and $C+3$, so *a fortiori*, it works. Neighboring transmitters are at least 400 kHz apart. The protection ratio is then -20 dB. It may be concluded that 19 channels is the minimum number for monophonic VHF/FM sound broadcasting, although one or two more channels might be welcome.

X. OTHER EXAMPLES

Increasing the number of channels does not always increase the network quality. With the next rhombic number above 19 (i.e., 21), the rhombus has the shape as shown on Fig. 8. When looking for suitable progression steps, some difficulties arise. As there are transmitters exactly at the gravity center of both equilateral triangle (points A and B), they will be assigned channels 7 and 14, so that channel 0 falls on the upper right corner of the cochannel rhombus. Channel 11 will be half way between channel 0 and channel 1 ($1 = 22 \text{ modulo } 21$), so the middle point between 1 and 0 falls on a transmitter site. Finally, the only acceptable position is E , but it is closer to channel 0 than in the 19 channel network. It is an arithmetic paradox which could lead to mathematical recreations. The next suitable rhombic number is 31 (Fig. 9). The reader can easily discuss advantages and drawbacks.

XI. USE OF THEORETICAL NETWORKS

They may be of some help in trying to find out the optimum characteristics of transmitters or the most suitable type of

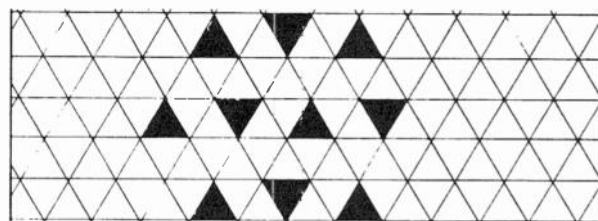


Fig. 10. Clustering of neighboring channels.

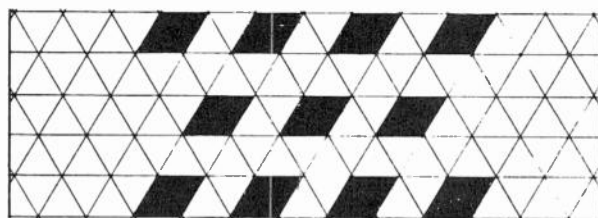


Fig. 11. Clustering of neighboring channels.

modulation parameters or channeling. There is a good probability that a solution found to be optimum in a regular network would be the best one for an actual network as well and it will be, by far, easier to study the former with the help of computerized methods.

An example of application to VHF/FM sound broadcasting is given hereafter, for the frequency range 88–104 MHz. In a first step, only monophonic transmissions will be considered. Then a channel spacing of about 100 kHz seems the most suitable (with the European standard).

A. Plain Network

The allocated band is divided into 160 channels. Below 160 the greater rhombic number is 157 (12 and 1, see Fig. 4). Three channels are then left empty. They may replace channels whose use is precluded by some local constraints (see Section VIII) or fill gaps in mountainous areas or near state boundaries. As a general rule, more than one program is broadcasted from a given location and some geographical neighboring assignments will be moved to the same point. Figs. 10 and 11 show two examples of channel clustering. Assignments made at the edges of the shaded areas are concentrated to the gravity center of each area. It should be checked whether it doesn't involve an unacceptable increment of interferences.

Fig. 12 gives the steps to build a 157 channel network. Their derivation is given in the Appendix. The 1961 Stockholm Plan for UHF TV has been based on a channel clustering C , $C+3$, $C+6$ (see Section II).

B. Multiple Networks

When there is a high number of channels, and if it is desired to broadcast many programs from each transmitting station, it is possible to split the band in subbands, each of them including the same number of channels. If different kinds of service are foreseen (monophonic and stereophonic, for instance) a broader channel spacing will be attributed to the more sensitive service. As an example, with a 31 channel theoretical network, there would be 3 monophonic programs in 100 kHz channels occupying a band of 9.3 MHz, and a stereophonic program in 200 kHz channels, the total bandwidth then being 15.5 MHz. It should be noted that the African plan has been designed on a channeling of 83 kHz, i.e., 192 channels in 16 MHz, for 6 networks of 31 channels or 5 networks of 37 channels (37 is a rhombic number).

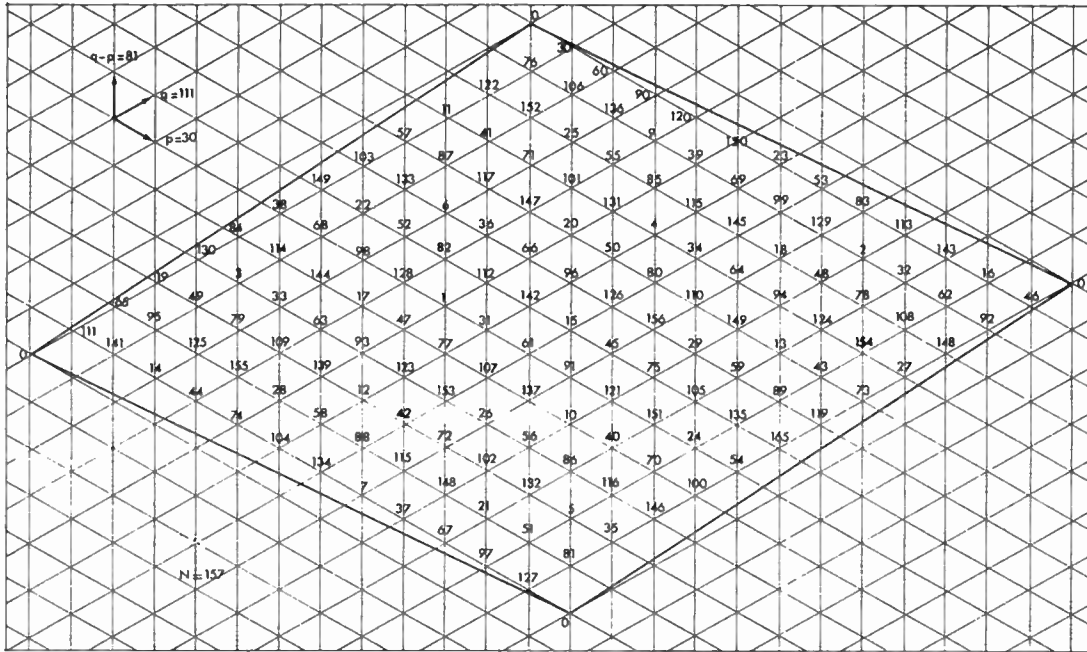


Fig. 12. Example of an optimum regular lattice for 157 channels.

C. Frequency Assignments to Actual Transmitters

The average distance between transmitters is given by the existing network. As a practical case, the French VHF sound broadcasting network will be considered. There are 55 main stations on a 550 000 square km area. The distance between transmitters is given by $\sqrt{2S/\sqrt{3}} = 107$ km. A theoretical network is drawn on a transparent sheet at the same scale as the scale of the map of the country. Then the intersections of the regular lattice are shifted to coincide with real transmitter locations, taking into account the local parameters. According to the multiple network process (see above) with $N = 31$, each station is assigned 5 frequencies, for instance channels 3, 34, 65, 96, and 127. Channels 156–160 are free. In some places one channel has to be cancelled to take into account incompatibilities (see Section VIII). If, somewhere, two channels have been cancelled, one of them may be replaced by channels 156–160.

XII. CONCLUSION

When the number of channels is high, it seems difficult to achieve by purely empirical means the best use of the frequency spectrum. The theory of regular networks appears as an efficient tool to reach an optimum. Moreover, in an area where the surface of the earth is divided amongst many countries, it is a good way to assure them they have obtained a fair share of the spectrum.

APPENDIX

CHOICE OF THE PROGRESSION STEPS IN AN OPTIMUM 157 CHANNEL LATTICE

As $157 = 12^2 + 12 \times 1 + 1^2$, the steps p and q should be such that $12p + q = k \times 157$, p and q integers: p and q must be greater than 3 so that transmitter coverages on channels C and $C + 1$, 2, or 3, don't overlap.

The first values to be tested is $p = 4$ and $q = 109$. Then $q - p = 105$ (see Fig. 12 for definition of p , q , $p - q$). The question now is to find out where channel 1 (or 156) falls, as here the cochannel rhombus of channel 0 is considered. The ideal loca-

tion for channel 1 is near the gravity center of any of the two equilateral triangles which join up to form the co-channel rhombus. The adjacent channel distance would then be $\sqrt{157 \times \sqrt{3}/3} = 7.23$.

For $p = 4$ and $q = 109$, channel 1 will be found at three $(q - p)$ steps: $q - p = 105$; $3 \times 105 = 315 = 1$ modulo 157. Adjacent channel distance is 3, which is far shorter than the optimum.

For $p = 5$ and $q = 97$ ($q - p = 92$) channel 156 will be found at five $(q - p)$ steps plus two p steps: $5 \times 92 + 2 \times 5 = 470 = 156$ modulo 157. Adjacent channel distance is $\sqrt{19}$. Hopefully a better solution exists.

For $p = 6$ and $q = 85$ ($q - p = 79$) channel 1 will be found at two steps, as $2(q - p) = 158 = 1$ modulo 157.

For $p = 7$ and $q = 73$ ($q - p = 66$) channel 156 will be found at three p steps plus four q steps: $3 \times 7 + 4 \times 73 = 313 = 156$ modulo 157. Adjacent channel distance is $\sqrt{37} = 6.08$. Channels 156 and 1 are near the gravity center of triangles; channels 155 and 2 at a short distance of the gravity center of the cochannel rhombus; channels 154 and 3 at a distance $\sqrt{12}$ of channel 0.

A thorough search amongst all the pairs, p and q , shows that there is only a few sets of steps resulting in an adjacent channel distance greater than or equal to 6. They are given in the following table, together with the 2-channel and 3-channel distances.

p	q	adjacent	2-channel	3-channel
7	73	$\sqrt{37}$	$\sqrt{39}$	$\sqrt{12}$
11	25	$\sqrt{48}$	$\sqrt{37}$	$\sqrt{3}$
20	74	$\sqrt{37}$	$\sqrt{21}$	$\sqrt{21}$
24	26	6	1	
30	111	$\sqrt{39}$	$\sqrt{19}$	$\sqrt{21}$
33	75	$\sqrt{39}$	$\sqrt{7}$	$\sqrt{48}$

The final choice depends on the protection ratio for 2 and 3 channel interferences. It is likely that the pair 24 and 26 will hardly be suitable.

If it were planned to cluster channels in groups of 3 or 4 (see Figs. 10 and 11) it would be more appropriate to have all steps greater than, say, 20. Such a favorable network is drawn on Fig. 12 ($p = 30, q = 111$). If no clustering is foreseen, or if a channel spacing of 20 is acceptable for colocated transmitters, then the network $p = 20, q = 74$ is better.

REFERENCES

- [1] Final Acts of the VHF/UHF European Broadcasting Conf. (Stockholm, Sweden, 1961), Doc. ITU.
- [2] Technical data for the VHF/UHF European Broadcasting Conf. (Stockholm, Sweden, 1961), Doc. ITU.
- [3] Regional Agreement for the African Broadcasting Area (Geneva, Switzerland, 1963), Doc. ITU.
- [4] LF/MF Broadcasting Regional Administrative Conf. (Geneva, Switzerland, 1975).
- [5] EBU Monograph, "New methods of producing television frequency assignment," Plans Doc. EBU (European Broadcasting Union, Brussels, Belgium, May 1960).
- [6] CCIR Recommendation 368, vol. V.
- [7] CCIR Recommendation 370, vol. V.
- [8] CCIR Recommendation 560, vol. X.
- [9] CCIR Recommendation 412, vol. X.
- [10] CCIR Recommendation 418, vol. XI.
- [11] CCIR Report 306, vol. XI.
- [12] CCIR Recommendation 419, vol. XI.
- [13] CCIR Report 624, vol. XI.

Spectrum Management Data Bases

GEORGE W. GARBER

Abstract—The Office of Telecommunications in the Department of Commerce (U.S.) supports the Executive Office of the President in the management of federal use of the radio spectrum. A portion of this support is in the maintenance of spectrum-related data files and associated computer programs.

The files describe the expected signal environment, both directly and indirectly. Several of the files are in the form of records of frequency assignments to radio stations in specific geographic locations or areas. Other files in the data base describe physical attributes of the environment, such as the terrain and the expected man-made noise level.

The computer programs associated with the data base have been developed to maintain the files, to retrieve data from them, and to compute information based on the data retrieved.

This paper offers brief descriptions of the files contained in the data base. It also contains a tabulation of the engineering aids programmed for the computer that utilize those files in the automated data base. A short discussion of the information retrieval capability available is given. Finally, there are discussions of needed improvements to the data base system, i.e., costs and savings.

INTRODUCTION

THE U. S. government depends greatly upon access to and use of the radio frequency spectrum for the conduct of communications-electronic operations in support of its responsibilities to the American people. The efficiency with which the frequency spectrum resource is managed, therefore, has a significant effect on the performance and effectiveness of the government's fulfillment of these responsibilities.

The Communications Act of 1934 placed the responsibility for managing nongovernment use of the radio spectrum with the Federal Communications Commission. Management of the federal government's use of the radio spectrum is the responsibility of the President. Reorganization Plan #1 of 1970, which was implemented by Executive Order 11556, delegated that responsibility to the Director of the Office of Telecommunications Policy (OTP). Executive Order 11556 delegated to the Secretary of Commerce the responsibility to support OTP in its spectrum management responsibilities. Within the Department of Commerce, the Office of Telecommunications carries out this responsibility for the Secretary. The Office of Telecommunications' (OT's) support of this structure involves administrative, engineering, and analysis efforts in providing and evaluating information needed for effective management and use of the electromagnetic spectrum resource.

The OTP also is assisted in this function by the Interdepartment Radio Advisory Committee (IRAC) representing 18 major government agency users of the spectrum, plus a liaison representative from the Federal Communications Commission.

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The OT also supports these federal departments and organizations in the day-to-day management and long-range planning of their use of radio frequencies. A major ingredient in the OT support of the OTP and the IRAC agencies is the data base and data base system.

I. DATA FILES

The Government Master File is the central file in the OT spectrum management data base. It consists of records of radio frequency assignments to government radio stations recommended by the Frequency Assignment Subcommittee (FAS) of the IRAC to the Director, OTP, and authorized by him on behalf of the President. This file has evolved, during the history of the IRAC, from a file of "five-by-eight" cards initiated with the committee in 1922 through Hollerith record techniques in 1953, to magnetic tape storage in 1965, and, in 1973, to magnetic disc storage. It is one of a total of ten major files maintained in the OT data base. Eight of these files are automated and two are in hard copy or microfiche form only. Table I summarizes the size and status of these files. Of the eight files in the data base that have been automated, six are in a format acceptable to the generalized information retrieval programs in use at the OT computer center. Three of the six files available for retrieval purposes are assignment record files. These are the Government Master File, the FCC file, and the ITU file. The others are collateral files, containing information related to the assignment process but not necessarily tied directly to individual assignment records. The Government Master File typifies assignment-oriented files. The Allocations Table File is typical of the collateral files. Appendices A and B contain definitions of the primary data elements contained in these files. The Major Federal System File is available in hard copy as well as in abbreviated (index) form in the computer system. Two files, the radio noise file and the terrain file, are highly specialized in nature and are usable by a restricted number of computer programs. All the files, including those not automated, are discussed below.

A. Assignment Record Files

1) *The Government Master File (GMF)*: To speed the processing of applications for frequency assignment, a system of computer programs was introduced in 1966 to aid in distributing applications to the IRAC member agencies for review and to update the GMF. This system, with modification, is in use today. The applications are distributed in the form of an agenda for meetings of the Frequency Assignment Subcommittee (FAS). The recommendations of the FAS to the OTP concerning these applications are then recorded and the decisions of the OTP in regard to these recommendations are reflected in

TABLE I
DATA FILES SUMMARY

FILE NAME	TYPE	APPROXIMATE NUMBER OF RECORDS	STATUS	DATE CURRENT	SOURCE(S)	LOCATION	COMMENT
GOVERNMENT MASTER FILE	Frequency Assignment	128,000	Automated Operational	See Comment	IRAC (FAS)	OT/DC	Updated Monthly
NON-GOVERNMENT MASTER FILE	Frequency Assignment	597,000	Automated Operational	November 74	FCC	OT/DC	Does not include Chicago Region Land Mobile Data
INTERNATIONAL TELECOMMUNICATION UNION FILE	Frequency Assignment	700,000	Automated Operational	May 76	ITU	OT/DC	
ALLOCATION TABLE FILES	Frequency Allocation	U.S. 1083 ITU 900	Automated Operational	July 74 January 74	OTP ITU/RR	OT/DC	
EQUIPMENT CHARACTERISTICS FILES	Electronic Equipment	21,000	Automated Operational	January 73	ECAC FCC & SPS	OT/DC	Updated through IRAC systems review procedure and on a case-by-case basis
MAJOR FEDERAL SYSTEMS FILE	Documents	70	Automated and Hardcopy Operational	See Comment	IRAC/SPS	OT/DC	Input to ECF; maintained by Secretary, SPS
REMS DATA FILE	Documents	-----	Hardcopy Operational	FY 76/4	ITS/Boulder	OT/DC	Raw data retained at ITS/Boulder
CANADIAN ASSIGNMENTS FILE	Frequency Assignments	28,000	Microfiche Operational	July 76	Canadian Government	OT/DC	
RADIO NOISE FILES	Noise Source Description	----	Automated and Hardcopy Operational	----	ITS/Boulder ECAC Defense Mapping Agency	ITS/Boulder OT/DC	
TERRAIN/TOPOGRAPHY FILE	Terrain Description	----	Automated Operational	----			

the GMF. Since 1966, this system has been modified, improved, and augmented with additional programs to edit input data and to aid in the substantive review process. We are now engaged in major revisions in this system to simplify it, to reflect new programming techniques and to take advantage of our current computer configuration.

The GMF forms the core of the data base being developed to aid in the spectrum management process. This file contains 45 data elements of substance in frequency management. These can be characterized as either administrative or technical in nature, with some that fall into both categories.

The administrative data elements in the GMF—such as agency, serial number, authorization date, docket number—are part of each record in the file. The technical data content of a record in the GMF depends on the frequency and service involved. A complete and detailed enumeration of these data requirements is found in the Manual of Regulations and Procedures for Radio Frequency Management, published and maintained by the Office of Telecommunications Policy. An abbreviated list of these data elements is found in Appendix A. Approximately 128 000 records are in the GMF.

2) *The Federal Communications Commission Master File:* The licensee file of the Federal Communications Commission, with the exception of the citizens' and amateur services, is incorporated into the OT/OTP data base. This file represents nonfederal uses of the spectrum in the United States. It contains many data elements in common with both the GMF and the International Frequency List (IFL) described below. As with the IFL, the FCC file is maintained in the OT/OTP data base through periodic replacement. It contains approximately 650 000 records.

3) *The International Telecommunication Union File:* The International Telecommunication Union (ITU) file contains listings of frequency uses throughout the world, concentrated heavily in the HF portion of the spectrum and in the space services. Many of the data elements in the ITU file correspond to those in the GMF, but the file also contains certain additional administrative data elements, such as date of notification and date of putting into use, intended for the settlement of international interference cases. It contains approximately 700 000 records.

B. Other Data Files

An examination of the data contained in the files discussed above reveals that they were developed to aid the administrative aspects of the frequency assignment process under conditions of plentiful spectrum and real estate. As these items become scarce and the development of increasingly complex electronic equipments becomes more expensive, more data describing the characteristics of the signals being emitted is needed to improve the depth of technical analysis performed. No longer is frequency, power, emission, and location information adequate. Additional detail concerning sidebands and spurious emissions, antenna patterns and scan rates, is required for the solution of spectrum engineering problems and the development of useful spectrum allocations. As the need for these additional data elements has evolved, effort has been expended within the federal government to include them in the GMF record, the data being collected and submitted by the applicant agency.

This method of data collection has been found to be practical, however, only in those cases where the data included is unique to the particular location and/or system being registered. Where it is possible to augment the data base with typical equipment data, regulatory data, or other data gathered outside of the FAS process, steps have been taken to do so. Descriptions of files of these types that have been added to the data base are given below.

1) *Equipment Characteristics File:* A file of equipment characteristics identified by military nomenclature or by manufacturer's model number is now being stored. It is updated with data obtained through the system review process of the IRAC Spectrum Planning Subcommittee. The data requirements for this file are specified in Chapter 8 of the OTP Manual. (The IRAC agencies include available nomenclature or model number information in the GMF record, making it possible to relate the data in the two files as needed.)

2) *Allocation Table Files:* Two files, identical in structure but differing in content, are maintained: one of the U.S. Table of Frequency Allocations and the other of the International Table. These are useful for studies of spectrum allocation. The national table file also is used for an automated

review of the applications for frequency assignment to determine compliance. A definition of the National Table of Frequency Allocations file may be found in Appendix B.

3) *Major Federal Systems File*: Two files, one automated and one in hardcopy form, are maintained which deal with those major Federal communications-electronics systems which have been reviewed by the Spectrum Planning Subcommittee of the IRAC. The automated file serves as an index to the hardcopy file, containing such information as: nomenclature of the system, frequency range or ranges involved, anticipated date of operation, and satellite location (if a geostationary satellite is part of the system). The hardcopy file contains the systems data received by the SPS for review, plus the OT analysis of the probable impact of the system on the environment.

4) *RSMS Data File*: The Radio Spectrum Measurement System (RSMS) file consists of raw data and processed reports concerning field measurements of the incidence, signal levels, and emission characteristics of federal radio stations and facilities in selected areas, frequency bands, and time periods. This file consists of the raw measurements data on magnetic tape and the summary reports produced therefrom.

5) *Canadian Assignments File*: This file contains particulars of Canadian frequency assignments to stations within the border zone. (The border zone is defined by treaty, and is described in the OTP manual.) This file is in microfiche form and is replaced three times per year by the Canadian government.

6) *Radio Noise Files*: These files of man-made and atmospheric noise are maintained in the laboratory for use and analysis. These files are in graphic, tabular, digital, and analog form.

7) *Terrain/Topographic File*: This file contains altitude/location data throughout the majority of the contiguous United States. Data storage available has limited the active file to 30-min increments of longitude and latitude.

II. DATA BASE UTILIZATION

The data base described has been assembled to provide both administrative and technical support to the Office of Telecommunications Policy, its IRAC Secretariat, and the IRAC agencies. Each of these groups has different requirements. Typically, the OTP is interested in statistical studies. Certain divisions of the OT are interested in samples of the various files for the development of EMC techniques. Other OT groups use the files and techniques for EMC analysis. The IRAC Secretariat requires detailed listings of file transactions and of the complete GMF for technical review and for administrative and clerical control. The IRAC agencies require complete printouts of the GMF and of their records in the file for administrative control and for frequency selection.

The OT provides data processing services to all the above groups through the use of a library of computer programs. It supports the day-to-day activities of the FAS members with the Frequency Management and Records System (FMRS), a generalized information retrieval and editing capability, and a number of aids to engineering analysis.

A. The Frequency Management and Records System (FMRS)

The FMRS is a system of computer programs which deal with the editing, review, and publication of federal applica-

TABLE II
SUMMARY OF ANALYSIS AIDS

ANALYSIS AID	FUNCTION	LOCATION	ACCESS METHOD	COMMENTS
RAPIT	Terrain Dependent Propagation Loss	ITS Boulder	Interactive Time-Share	Does not accept path profile data per se
SHADO	Determines Areas Within Line of Sight	ITS Boulder	Hybrid Batch	Limited by terrain file granularity and omissions
HORIZON	Calculates Radio Horizon Angles Using Terrain Data	ITS Boulder	Hybrid Batch	Limited by terrain file granularity and omissions
PROFILE	Generates Great Circle Propagation Path Profiles	ITS Boulder	Hybrid Batch	Limited by terrain file granularity and omissions
INMOD	Calculates Intermodulation Products and Determines if they are In-Band	ITS Boulder	Hybrid Batch	Limited to 50 equipments and theoretical mixes through 7th order
ATTIC	Calculates S/I for Terrestrial Microwave Receivers from Airborne Transmitters	ITS Boulder	Batch	Uses "Box Car" filter characteristics
A28	Calculates Coordination Distance Contours for Earth Stations	OT/DC	Interactive Time-Share	Based on Appendix 28 of the ITU Rules and Regulations
A29	Calculates Interference from One Geostationary Satellite to Another Satellite System	OT/DC	Interactive Time-Share	Based on Appendix 29 of the ITU Rules and Regulations
GRAPHIC DISPLAY	Selects and displays frequency assignment information by band and area	OT/DC	Interactive Time-Share	Uses data from GMF
GEOGRAPHIC PLOTTER PROGRAM	Plots geographic locations of telecommunications systems	OT/DC	Batch	Uses data from GMF
HF Propagation Prediction Model	Calculates predicted propagation path loss at HF	OT/DC	Batch	Uses data from GMF
HF Interference Prediction Model (LINTC)	Calculates received S/I at HF	OT/DC	Batch	Uses data from GMF
ORBITCHECK	Checks compliance of Terrestrial Stations with pointing angle restrictions	OT/DC	Interactive Time-Share	
FOOTPRINTS	Calculates and Plots Satellite Antenna Patterns on the Earth's Surface	OT/DC	Interactive Time-Share/Batch	
SINR	Calculates statistical Interference-to-Noise Ratios between Terrestrial Systems	ITS Boulder	Batch	
FRED	Calculates and Plots Histograms and Density Plots of GMF and non-GMF Frequency Assignments	ITS Boulder	Batch	Available by Arrangement with ITS
SPEC PLOT	Plots Radar Emission Spectrum Envelopes	ITS Boulder	Interactive Time-Share	
CULL	Predicts Potential Interference Between Space & Terrestrial System in the 7.25-8.4 GHz Band	OT/DC	Interactive Time-Share	Uses data from the GMF

tions for frequency assignment action and with the update of the GMF. (It was discussed in some detail earlier in the description of the GMF). The FMRS has been developed specifically for the processing of the GMF and transactions to it.

B. Information Retrieval

The generalized information retrieval programs deal with six of the files in the data base, providing selected and sorted lists of records or parts of records (data elements) formatted as required and/or providing counts of selected data elements as required. Records may be selected from these files on the basis of criteria related to any data element in the record. These programs are also used to provide subsets of the GMF on magnetic tape for distribution to other interested federal agencies.

C. Automated Aids to Engineering Analysis

The computer program library developed to utilize one or more of the automated files in the data base is always changing and enlarging. Table II is a tabulation of the engineering aid programs now considered operational, a brief description of their function, a note indicating their location, the access

method(s) possible, and, in some cases, a brief comment. The location note also implies the computer on which the program is operational. Those programs located at ITS/Boulder, CO, are functional on a CDC 6600 computer; those located at OT/Washington, DC function on a UNIVAC 1108 machine. Close coordination is maintained between the Boulder and Washington offices in the development of programs to assure interchangeability between computers where desirable and practical.

III. OPERATIONAL IMPROVEMENTS

Most of the computer programs supporting the data processing activities described above are currently operational in the batch mode of operation. Some are also available in the time sharing mode. Delayed batch operation is used with those of our engineering aids dealing with the GMF and other classified files because of the need for exclusive operation of the computer when these files are involved. This is an intermediate step toward the long-term goal of full time-shared direct access to all data files and analysis programs in the classified mode of computer operations. To this end, direct access storage and retrieval techniques are being developed for use through time-shared terminals.

IV. COSTS AND SAVINGS

The frequency management support budget in OT is approximately 4.2 million dollars. The development, maintenance, and utilization of the data base just described is an important cost factor in the overall program. These costs will

increase as additional data is acquired and as more sophisticated EMC analysis techniques are developed. However, the savings realized because of this effort, although difficult to quantize accurately, are no less real. For example, over the last ten years most IRAC agencies have been able to transfer basic record keeping and publication functions to the IRAC Secretariat, concentrating their limited resources on the collection of additional data, the verification of existing records, and the more substantive engineering-oriented aspects of spectrum management. During this same time period, the IRAC Secretariat has been able to improve the processing of an ever-increasing number of applications without increasing staff.

V. SUMMARY

Technically, the existence of an increasingly complete description of the radio environment results in improved spectrum management at all levels; in frequency management, in the solution of EMC problems, and in the allocation of spectrum. The objectives of the OT data base activity are 1) to collect as much data as is needed to meet the requirements of spectrum management at the least cost to the IRAC agencies, 2) to improve the quality of the data accepted into the data base through judicious use of human and computer resources, 3) to provide data processing and computer analysis services to OT and OTP as required, 4) to provide data to frequency managers throughout the federal government, and 5) to present the data and data analyses to the appropriate decision makers in convenient clear form.

APPENDIX A—GOVERNMENT MASTER FILE (GMF)

FIELD CODES AND DESCRIPTIONS

Identification Item: (Maximum: 1)

Data Field Name	Size	Mnemonic	Description
Assignment Item	10	ANU	Characters 1-4 identify the agency to which the assignment was made. If the assignment is a joint assignment, the letter Q or W will appear as the first character and characters 2-4 will be blank. Characters 5-7 if completed, are a series number. Characters 8 and 9 are an area code.
Area Code	2	AST	A numeric code indicating the state, country, or geographical area. (Characters 8 and 9 of the ANU.)
Frequency	11	FRQ	Authorized frequency of the assignment. If the authorization was for a frequency band, the value represents the lower limits of the authorized band. The first character will be either blank, M, G, or T indicating kilohertz, megahertz, gigahertz, or tetrahertz. The seventh character of the field will always be a decimal point.
Joint Assignment	1	JNT	The presence of Q or W indicates that the assignment is held jointly among several agencies. W is recorded if all the agencies are military. Otherwise, Q is recorded. (Character 1 of the ANU.)
Net Control	5	NET	Identifies the specific user of the assignment within an agency. The data may be alpha or alphanumeric.

Transmitter Item: (Maximum: 1)

Data Field Name	Size	Mnemonic	Description
Agency	4	AGC	Agency authorized to use the assignment. (First 4 characters of SER.)
Assignment Type	1	ASM	The field is blank for regular assignments. An S indicates space project assignments. An E indicates temporary assignments, and a T indicates trial assignments.
Frequency Band Indicator	1	BIN	The presence of a dash (—) indicates the assignment authorizes the use of a band of frequencies. Otherwise this field will be blank. (Character 2 of CRL.) The frequency recorded in FRQ represents the lower limit of the authorized band in this case. The upper limit is recorded in *FRB. (SEE RM1 field in the circuit remarks item.)
Bureau	4	BUR	Indicates the bureau or other organizational subunit of the agency authorized to use the assignment.
Canadian Coordination	1	CAN	This field will contain a C if the assignment has been coordinated with Canada. Otherwise it is blank. (Characters of CRL.)
Assignment Expiration Date	6	EXD	The year and month on which a temporary or trial (ASM = E or T) assignment will expire, the field is blank for regular or space project assignments. The date is expressed in year/month/day (YYMMDD) order. The day portion always contains zeros (00).
Assignment Review Year	2	RYP	Indicates the year in which the assignment was reviewed under the 5-year review program (Characters 5 and 6 of CRL.)
Assignment Serial Number	10	SER	The abbreviated agency name (four characters), current calendar year (two digits), and four-digit number (unique to the agency) make up this field. The field is designated as the unique identifier of an assignment.
Time	4	TME	The presence of one of the codes 1, 2, 3, 4, H24, HJ, HN, HT, or HX indicates the period of time during which it is intended that the frequency will be either monitored or used for transmission.
Transmitter Antenna Location	8	XAL	Normally, this field contains the name of the city or geographical subdivision in which the site of the transmitting antenna is located. In some cases, no specific name can be applied to the area of operation. Therefore, additional remarks pertaining to the location are contained in the Circuit Remarks (REM) field. Samples of non-geographical entries include: aircraft, balloon, ships, SPCE (for space station), or moon.
Transmitter Station Call Sign	6	XCL	The call sign or navigational aid identifier of the transmitting station
Transmitter Antenna Latitude	7	XLA	This and the next field (XLG) contain the geographical coordinates of the antenna position recorded in XAL. The coordinates are expressed in degrees, minutes, and seconds. An XX entry in the seconds position indicates that the seconds are unknown. This field may be blank if coordinates could not be assigned for the location recorded in XAL
Transmitter Antenna Longitude	8	XLG	
Transmitter Station	8	XRC	Identifies the facility that controls, either electrically or administratively, the transmitting station.
Transmitter Antenna State/Country	4	XSC	Identifies the state, country, or area in which the site of the transmitting antenna XAL is located.

Receiver Item: (Maximum: 30)

Data Field Name	Size	Mnemonic	Description
Associated Transmitter Call Sign	6	ACL	The call sign assigned to the station which will receive transmissions from the station whose call sign appears in the transmitter call sign field (XCL).
Receiver Antenna Dimensions	24	RAD	When used for assignments to stations other than mobile stations in selected bands, the field indicates the antenna gain, name, height above mean level, and height above ground. If more than one antenna is to be used, the data in this field pertains to the antenna used most frequently.
Receiver Antenna Location	8	RAL	Normally, this field contains the name of the city or geographical subdivision in which the site of the receiving antenna is located. In some cases, no specific name can be applied to the area of operation. Therefore, additional remarks pertaining to the location are contained in the circuit remarks (REM) field. Samples of non-geographical entries include: aircraft, balloon, ships, SPCE (for space station), or moon. The abbreviation REFLECTR may also be used for selected passive reflectors.
Receiver Antenna Polarization	3	RAP	The codes D, E, F, H, J, L, R, S, T, V, and X indicate the polarization of the receiving antenna. For receiving space stations, polarization may be listed for up to 3 antennas entered in the same sequence as antenna data entered in the RAD field.
Receiver Antenna Azimuth	3	RAZ	Contains the geographic direction of the beam (main lobe) measured in degrees East of True North of the receiving antenna entered in the receiver antenna dimensions (RAD) field. For nondirective antennas, entries may be ND—nondirective, R—rotating through full 360 degrees, SSH—horizontal scanning, in a limited sector, SSV—vertical scanning, and T—tracking.
Receiver Antenna Latitude	7	RLA	This and the next field (RLG) contain the geographical coordinates of the antenna position recorded in RAL. The coordinates are expressed in degrees, minutes, and seconds. An XX entry in the seconds position indicates that the seconds are unknown. This field may be blank if coordinates could not be assigned for the location recorded in RAL.
Receiver Antenna Longitude	8	RLG	
Receiver Station	8	RRC	Identifies the facility that controls, either electrically or administratively, the receiving station.
Receiver Antenna State/Country	4	RSC	Identifies the state, country, or area in which the site of the receiving antenna (RAL) is located.
Space Power Density	4	SPD	This field contains the power density data. It occupies the first four (4) positions of the DST field. The last 2 positions are unused at the present time.

Emission Item: (Maximum: 20)

Data Field Name	Size	Mnemonic	Description
Emission Designator	12	EMS	Identifies emission authorized for use on an assignment. These 12 characters identify, from left to right, the bandwidth, type of modulation, type of transmission, and supplementary characteristics.
Power	11	PWR	Indicates the transmitter output power normally supplied to the antenna transmission line.

Station Class	4	STC	The authorized symbol for class of station appears in this field. (See Sections 6.1.3 and 6.1.4 of OTP Manual.)
Authority Item: (Maximum: 10)			
Data Field Name	Size	Mnemonic	Description
Authorization Date	6	AUD	Indicates the date on which the assignment was originally authorized. Displayed in year/month/day order. However, the day positions contain zeros (00).
Authorization Docket Number	11	AUT	Indicates the approving body, docket number year, and docket number of the assignment.
Revision date	6	RVD	The date when the assignment was most recently revised. Shown in year/month/day order. However, the day positions contain zeros (00).
Notes Item: (Maximum: 10)			
Data Field Name	Size	Mnemonic	Description
Notes	4	NTS	This field contains an entry selected from the lists of emission, limitation, priority, and special notes, and applies to the frequency assignment as a whole. Sample entries include: S034 meaning disaster communications, P048 meaning NIB other government services, and L036 meaning restricted to use in Gulf of Mexico only.
Circuit Remarks Item: (Maximum: 10)			
Data Field Name	Size	Mnemonic	Description
Circuit Remarks Item	40	REM	This field is used primarily to record frequency characteristics that have no specific fields elsewhere in the record. Additional amplifying data regarding the frequency (band limits and excluded band data), antenna location (authorized radius, states areas, etc.), and equipment characteristics (tunability, pulse characteristics, etc.).
Transmitter Antenna Item: (Maximum: 1)			
Data Field Name	Size	Mnemonic	Description
Transmitter Antenna Dimensions	24	XAD	Identifies the characteristics of the transmitting antenna. This field cannot be retrieved, i.e., it cannot be used in the FIND statement. It may be displayed (edited), however, once the record is retrieved via the parameters expressed in the FIND statement.
Transmitter Antenna Polarization	3	XAP	The codes D, E, F, H, J, L, R, S, T, V, and X indicate the polarization of the transmitting antenna. For transmitting space stations, polarization may be listed for up to 3 antennas entered in the same sequence as antenna data entered in the XAD field.
Transmitter Antenna Azimuth	3	XAZ	Contains the geographic direction of the beam (main lobe) measured in degrees East of True North of the transmitting antenna entered in the transmitter antenna dimensions (XAD) field. For nondirective antennas, entries may be ND—nondirective, R—rotating through full 360 degrees, SSH—horizontal scanning in a limited sector, SSV—vertical scanning and T tracking.
Supplementary Item: (Maximum: 10)			
Data Field Name	Size	Mnemonic	Description
Supplementary Details	120	SUP	Indicates information to justify the assignment and/or to explain how the assignment will be used.

APPENDIX B—ALLOCATION TABLE FILE (ALCT)

FIELD CODES AND DESCRIPTIONS

Identification Item: (Maximum 1)

Data Field Name	Size	Mnemonic	Description
Frequency Band Lower Limits	11	LFQ	The lower limit of the allocation frequency band. The first character will be either blank, M, G, or T indicating kilohertz, megahertz, gigahertz, or terahertz. The seventh character of the field will always be a decimal point.
Frequency Band Upper Limit	11	UFQ	The upper limit of the allocation frequency band. The format is the same as the lower limit.

Service Item: (Maximum: 10)

Data Field Name	Size	Mnemonic	Description
Amateur Allocation	2	AAL	If the service is allocated to amateur use, AM is entered in this field.
Additional Use	12	AUS	Footnotes may provide for classes of radio service that are not included in the main portion of the national table. The name of a radio service provided by a footnote is entered in this field. If there is an entry in this field, the service field (SVC) will be blank, and vice versa.
Division of Allocation	7	DAL	This field is subdivided into three fields: GAL, NAL, and AAL.
Document Date	6	DCD	The date of the IRAC document indicated in the document number field (DCN) entered in year/month/day order.
Document Number	6	DCN	The latest IRAC document number that contains the specifications for the allocation record.
Function Note	60	FNT	If the effect of a footnote is represented in the SPR, GAL, NAL, GSA, or FUI fields of the service item, function item, or station class item, the footnote is entered in this field. Ten six-character notes are stored in this field.
Function	60	FUN	A coded entry that represents the functional use for the allocation radio service. The function is based on the parenthetical entries in columns 3 and/or 4 of the national table, on the FCC radio service as entered in column 5 of the national table, or on footnotes. Ten three-character functional use codes are stored in this field.
Function Incomplete	1	FUI	If the national table contains information concerning (but not clearly indicating) a function, X is entered in this field.
Government Allocation	2	GAL	If the service is allocated to government use, G is entered in this field.
Government Remarks Indicator	1	GRI	If there is a remark concerning government use, G is entered in this field.
Government Sub-Allocation	2	GSA	Indicates the allocation within the government. ME exclusive military use MP primary military use NE exclusive nonmilitary use NP primary nonmilitary use
Nongovernment Allocation	2	NAL	If the service is allocated to nongovernment use, NG is entered in this field.
Nongovernment Remarks Indicator	2	NRI	If there is a remark concerning nongovernment use, NG is entered in this field.

Other Note	60	ONT	If a footnote that pertains to this allocation record has not been entered in one of the above footnote fields, it is entered here. Ten six-character notes are stored in this field.
Remarks Indicator	3	RMI	This field is divided into fields GRI and NRI.
Service Priority	1	SPR	The priority of the radio service that is indicated in the service (SVC) field or the additional use field. P primary M permitted S secondary X priority is not stated (used only for services entered in the AUS field).
Service Item	94	SRI	Entire service item.
Station Class	270	STC	The station class symbols are given in the OTP manual. They are four-character codes. When a symbol is entered, it is always followed by a blank character for convenience in retrieval.
Service	12	SVC	The radio service to which the band is allocated. This entry is obtained from columns 3 and/or 4 of the national table. The entry here is a coded abbreviation, e.g., AERO-RADVAN for aeronautical radionavigation.
Additional Use Note	60	UNT	If the additional use field (AUS) contains an entry, the footnote(s) which specify the additional use are entered here. Ten six-character notes are stored in the field.
Remarks	72	REM	Used primarily to record frequency characteristics which do not have specific fields in the record, additional amplifying data on frequency (band limits and excluded band data), antenna location (authorized radius, states, and areas, etc.), and equipment characteristics (tunability, pulse characteristics, etc.).
	9		

THE USE OF COMPUTERIZED ANALYTICAL TECHNIQUES IN SPECTRUM MANAGEMENT

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The problem of efficiently managing the spectrum is becoming one of the main tasks of modern telecommunications. Techniques that automate data sorting and analyses are becoming increasingly necessary to efficiently accomplish the spectrum management process.

Spectrum utilization problems generally involve data storage, retrieval and analysis. Many aspects of these activities are amenable to automation on relatively small computers while other aspects (e.g., terrain data or large-scale frequency assignment problems involving large matrices) require a large computer with extensive capacity. Data bases and analytical tools can be implemented readily on minicomputers; larger, more complex problems can be handled on one or more large central facilities.

Within the C.C.I.R., an Interim Working Party (IWP) 1/2 has been formed to study the use of analysis techniques and computers in frequency management. Specifically, this working party has been tasked "to develop the necessary technical bases to facilitate the introduction of automated frequency management procedures and the development of standard interference analysis techniques with the aim of obtaining more efficient spectrum utilization" [1]. The current status of this C.C.I.R. working group will be discussed. The U.S.A. participates in the work of the IWP 1/2 and presented in this paper are examples of the computerized analysis techniques currently being used in the U.S.A. for spectrum management.

IWP 1/2 and Current C.C.I.R. Interference Analysis Models

IWP 1/2 was formed to study the use of analysis techniques and computers in spectrum management in order to obtain more efficient spectrum utilization. The first task of IWP 1/2 is to prepare a report about "Computer-Aided Techniques in Spectrum Management," which will be compiled in late 1979. This report is to form the basis for a CCIR handbook. At the present time, 14 Administrations are

preparing material for this report. Particular sections of the IWP report will be devoted to efficient spectrum utilization, EMC analysis techniques, data bases, computer techniques, and system application examples.

Volume I (Spectrum Utilization and Monitoring) of the C.C.I.R. texts contains interference analysis models which can be implemented on a digital computer. These models can be used to determine interference criteria between telecommunication equipments. Within the U.S.A. most of these C.C.I.R. models are automated and used for spectrum management purposes. These C.C.I.R. Reports include: 519, 520-1, 521-1, 522-1, 523, 524, 528, 654, and AC/1.

These reports were written in partial response to C.C.I.R. Question 44/1 which asks for additional work by the member administrations of the C.C.I.R. to develop "System Models for the Evaluation of Compatibility in Spectrum Use". The following will summarize some of these C.C.I.R. models.

The models in C.C.I.R. Reports 519 and 520-1 are computational models which utilize exact mathematical expressions to describe the IF filter, detector, and baseband filter effects on receiver performance. Reports 519 and 520-1 describe digital computer models which can be used to examine the performance degradation of receivers for cochannel and adjacent channel interfering signals. Report 519 describes a digital computer simulation of the performance of a coherent phase detector receiver. Report 520-1 is a non-coherent receiver model which describes the following systems: amplitude modulation, phase modulation, frequency modulation, single sideband, and frequency division multiplex. The receiver performance model of Report 520-1 can process interfering signals having any of the following types of modulation: amplitude, phase, frequency, single sideband, frequency division multiplex, pulse, noise, and general band limited periodic waveform.

C.C.I.R. Reports 524-1, 523, 654, and 522-1 describe a set of models that utilize measured data and/or empirical functions. Report 524-1 is a cosite analysis model which employs empirically derived transfer functions and Monte Carlo processes to calculate the mutual interference among many equipments at a single site. Reports 523 and 654 are mathematical models for calculating adjacent channel interference using measured equipment data, and Report 522-1 describes a method for modelling receiver intermodulation characteristics using measured data.

The modelling of a receiver performance sometimes includes the receiver front end non-linear effects such as cross-modulation, intermodulation, and desensitization. Report 521-1 discusses how to model these non-linear effects. In general, this type of problem can be handled by a Volterra series expansion of the non-linear input-output relations. This problem can be analyzed in either the time or frequency domain.

Computerized Spectrum Management Techniques in the United States

The spectrum management effort in the United States is focused on the use of computerized data bases and analytical techniques to obtain efficient spectrum utilization. The analytical techniques which have been computerized are primarily programs to determine interference criteria between telecommunication equipments and/or systems. These criteria are used to assure that a proposed new system to be placed in the electromagnetic environment will be compatible with the existing systems and also to determine solutions to operational interference problems. These analytic techniques are also used for national and international spectrum planning purposes and spectrum resource assessments. A description of 17 computerized analysis programs currently used in the U.S. Federal Government sector spectrum management was prepared by the National Telecommunications and Information Administration (NTIA), Office of Federal Systems and Spectrum Management [2].

The present U.S. computer hardware used for spectrum management can be classed into three types: 1) programmable calculators and other microprocessors, 2) minicomputers, and 3) large-scale computers. Included in Table 1 are examples of analytic computer models which are used for spectrum management applications. The outputs of the models are specific engineering results such as basic transmission loss, probability of interference, signal levels and signal to interference ratio, etc. The spectrum manager must relate these results to those conditions which permit acceptable operational performance of telecommunication equipments.

Table 1

Model Name	Purpose
Programmable Calculator	Basic EMC Calculations
Radar Frequency Assignment (mini-computer)	Graphic display of radar denial areas
Cull	Sub-file of equipments which are potential EMC problems
A28, A29	A28: coordination distance A29: percent increase in noise temperature
NLAMBDA	Basic Transmission Loss
ARPROP	Basic Transmission Loss
POPROP	Basic Transmission Loss
HF Propagation Prediction	Ionospheric propagation
PRODSIR (Probability Distribution Signal Interference Ratio)	Performance of a statistical telecommunications environment
Random Interference Analysis	Probability of Interference to spaceborne receiver
Random walk in non-gaussian environment	Probability distribution of S/I

Many of the models listed in Table 1 require some form of data base input. C.C.I.R. Report 669 [3] discusses data bases generally required for national spectrum management. The U.S. spectrum management data bases have been described by Garber [4]. The computer models of the Federal Systems and Spectrum Management (FSSM) Office of the NTIA utilize many different automated files, but primarily the U.S. Government Master File (GMF). The GMF is a computerized data base consisting of records of radio frequency assignments to U.S. Government radio stations and is consistent with C.C.I.R. Report 669.

The last three technical models of Table 1 are statistical and require as inputs statistical descriptions of the spectrum environment such as probability density functions (pdf's) and geographical distributions.

The following paragraphs will describe the models of Table 1.

Programmable Calculators for Spectrum Management Use

Some basic but frequently used analytical techniques for spectrum management can be simply calculated on programmable calculators. The U.S. Electromagnetic Compatibility Analysis Center (ECAC) has developed analytical models for programmable calculators.

A programmable calculator method was developed to calculate using a small number of inputs, the quantities signal to noise, interference to noise, or signal to interference ratio for an EMC interaction containing a wanted signal, interfering signal and receiver. Additional programs calculate power densities in the far field region, intermodulation frequencies, and transmitter emission spectra. Among the ECAC programs is a propagation program to calculate the tropospheric basic transmission loss for distances 1-300 miles in the frequency range 30-10,000 MHz.

Radar Frequency Assignment by Use of A Minicomputer

A minicomputer method has been developed [5] to aid in choosing radar frequency assignments. This method, which utilizes graphic display, helps to choose the frequency assignment for an additional radar to be deployed in an existing radar environment.

This automated radar assignment procedure is best illustrated with the example shown in Figure 1. The dots in Figure 1 are the geographic locations of existing radars. Each of the numbers refers to a different radar. An additional radar is to be placed in this existing environment and a location and frequency for this new radar must be chosen.

The necessary data base inputs consist of geographical data, transmitter powers, antenna gains, transmitter emission spectrum characteristics, and receiver transfer functions. Using this data base, the minicomputer calculates for each separate frequency a radius of a denial area around each existing transmitter site. The denial area is a measure of the geographic area denied to other users of the spectrum by contributions of both receivers and transmitters. The basis for the calculation is the Frequency Distance Trade-Off analysis [6], which calculates the distance (radius) required for interference free operation.

The size of the denial areas are functions of both the existing and planned radar characteristics. In the example of Figure 1, denial areas have been plotted using a graphics display for the frequency $f = 2710$ MHz. Each different operating frequency for the new radar results in different denial areas. The denial areas

shown are for airport surveillance radar (ASR) in the Los Angeles area operating in the 2700-2900 MHz band. If the new radar were placed in these denial areas, the degradation to receiver performance would be unacceptable. Since terrain effects are not included in the propagation analysis, the denial areas are independent of azimuth and thus are circular around each existing radar site (octagons represent the denial areas only to facilitate display purposes).

In a typical assignment problem, a set of denial plots are prepared for a number of frequencies being considered for the proposed radar. The spectrum manager visually examines these plots to choose spectrum coordinates (frequency and geographical location) which places the new radar outside a denial area. This results in a compatible operation between the proposed new radar and the existing radar equipment.

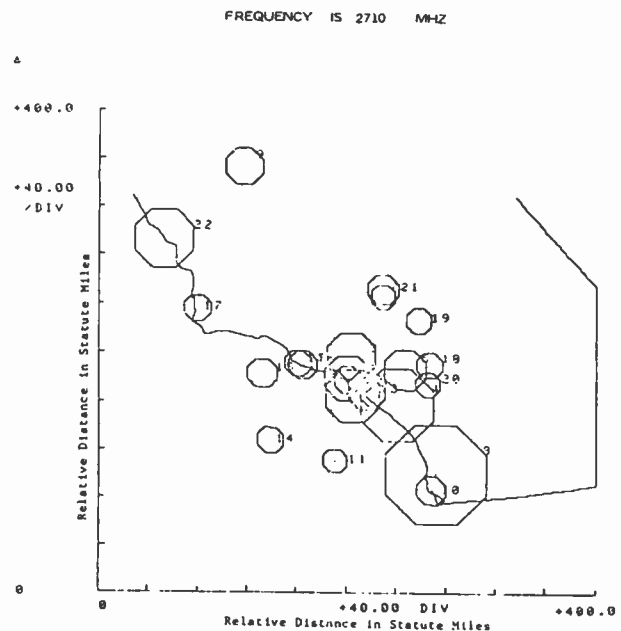


Figure 1. Denial Areas for Los Angeles Area

A Cull Program

The purpose of a "cull" program is to cull out from a data base a subset of only those equipments which have the potential to cause or receive interference and require more detailed technical analysis. The "cull" is an often used technique in spectrum management. An automated "cull" capability was developed [7] to make an initial assessment of the potential interference between a proposed satellite earth station and existing terrestrial microwave systems. Some existing programs already in the FSSM computer library were linked to make this fully automated cull procedure.

A block diagram of the procedure is shown in Figure 2. First, an Appendix 28 computer library program is executed to generate the coordination area as defined by the Appendix 28 of the ITU regulations around the proposed earth station. A sort program called RETRIEV is then executed to select a subfile from the Federal Government Master File (GMF) of those frequency assignments for terrestrial microwave equipments that operate in the same frequency band of the proposed earth station and are also located within the previously computed Appendix 28 coordination area. The cull program is then executed, using the subfile of the GMF, to identify those stations that are considered to be potential sources or victims of interference. Within the cull program, the INR (interference-to-noise ratio) at the IF output of receivers is calculated and compared with interference criteria. The transmitter receiver links which exceed the interference threshold are identified by the cull program as requiring further analysis.

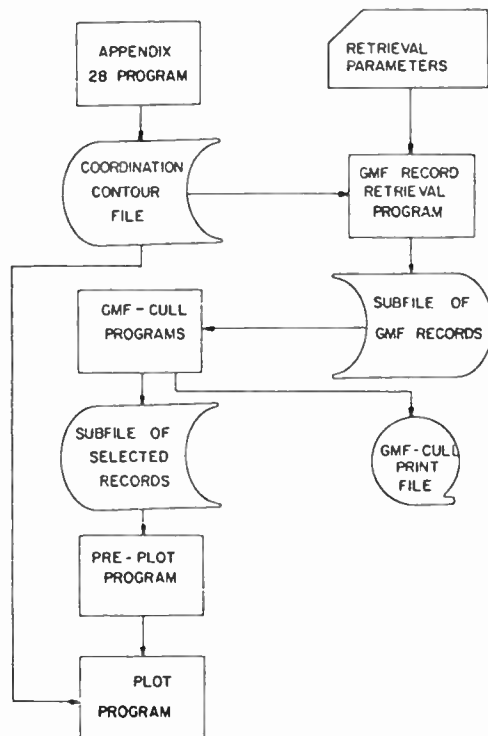


Figure 2. Automated Initial EMC Assessment Within Earth Station Coordination Area. Source: Ref. (7)

Computerized Propagation Models

Propagation information is essential to most spectrum analysis. Within the United States, many propagation models have been automated and are executed on a continuous basis for spectrum management purposes.

When doing a technical analysis, it is necessary to choose among a variety of similar propagation models. The NTIA is developing standard reference propagation models that can be used by different users. This makes it possible to compare the results of EMC evaluations using the same standardized propagation calculation.

The computer program library of the U.S. Federal Systems and Spectrum Management (FSSM) program includes the propagation models NLAMBDA, ARPROP, POPROP, and HF Propagation Prediction, which are listed in Table 1. The NLAMBDA model, developed at ECAC, is a standard reference model which computes basic transmission loss over a smooth curved earth. The ARPROP computer model (Area Propagation) is the NTIA standard area basis transmission loss model, and was developed using measured data. The model requires only general inputs such as terrain type and antenna siting criteria. It is useful for mobile environments characterized by unspecified propagation path end points. The POPROP model (pointwise propagation) is the standard for calculating basic transmission loss between two specified end points. The POPROP model uses a terrain profile extracted from a digitized terrain data base. The technical basis for the ARPROP and POPROP models are contained in [8] and [9].

The HF Propagation Prediction model is a fully automated (ionospheric) propagation model. It is used to determine compatibility among skywave paths. The program calculates such things as path lengths, Maximum Usable Frequency (MUF), Optimum Traffic Frequency (FOT), Lowest Usable Frequency (LUF), system loss, signal-to-noise ratio and path reliability.

Statistical Spectrum Management Models

For a spectrum environment, a computer can calculate the interactions between pairs of equipments on a one on one basis. This type of calculation is possible when an adequate data base is available of the characteristics and locations of the equipments. Such calculators can assess the compatibility of the existing environment and also can tell if a new equipment will be compatible with the existing environment. This procedure is often followed in spectrum engineering.

When the data base is unavailable or if the interactions are too numerous, an alternative is to use a statistical

representation of the spectrum environment to analyze potential interference problems. Berry [10] has developed the computer model PRODSIR (Probability Distribution Signal Interference Ratio) to analyze the interactions in a statistical environment and has used the method to determine the effects of local and skywave interference on Citizens Band (CB) radio operational range [11]. The CB environment is aptly suited to a statistical analysis. There are many equipments with numerous mobile transmitters and receivers. Unlike other models which utilize deterministic inputs, the Berry model includes statistical inputs.

A block diagram of the computer computation is shown in Figure 3. Among the necessary statistical distributions required as inputs include probability density functions (pdf's) of antenna heights, transmission loss, antenna gains, angle between mainbeam boresight and path, and transmitter powers. Also required are geographical distributions of wanted and interfering transmitters and frequency distribution of interferers. These input data are available from data bases, use studies, or may be hypothesized. From these inputs are computed probability distributions of wanted signal (Block I) and interfering signals (Blocks II and III). Within Block IV, the powers from all interfering sources are added incoherently. The output of the model (Block VIII) is a table of the probability that the signal to interference or signal to (interference + noise) ratio exceeds certain values. Berry used this model to show the effects of solar cycle variations on the range dependence of CB radio. The density of CB equipments was shown to be an important factor.

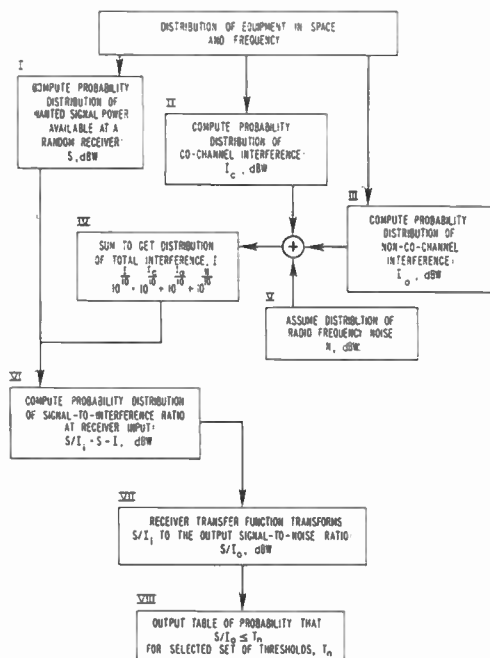


Figure 3. Block Diag. of Computation
Source: Reference (10)

There are additional methods to analyze interference in spectrum environments which include randomly located interferers and receivers. C.C.I.R. Report 656 [12] provides several examples of probabilistic analysis techniques. A Monte Carlo simulation on a computer often can answer many questions. The computer can use random number generators to geographically randomize emitting sources with antennas which point in random directions. For a given receiver location, the computer calculates the interference and then another random configuration of emitters is generated and its interference effect is calculated. Meaningful results about the EMC environment can be obtained by iteratively repeating the above calculation many times to obtain a statistically significant number of samples. NASA [13] used this procedure in its Random Interference Analysis Program to compute the cumulative interference effects of numerous terrestrial stations simultaneously in the field of view of a satellite borne radiometer. Berry [10] used this Monte Carlo simulation approach to obtain some, but not all, of the pdf's used in his CB analysis.

Middleton [14] has sought to eliminate the need for these Monte Carlo simulations and has developed models which describe in general the random non-Gaussian spectral environment. A particular application of the Middleton work has been to compute the probability distribution function of S/I for an EMC environment consisting of many Poisson distributed (time and geographical location) interfering sources and a wanted signal source doing a random walk. Such a model may be used to describe a land mobile environment.

Conclusions

The use of computerized techniques is encouraged for spectrum management applications. Computerized data bases and analytical techniques are necessary resources for making more efficient use of the spectrum. An overview of the present computer modelling status indicates that appropriate sized computers can model all but the most complicated processes. The future will see increased use of computer processes for spectrum management. The C.C.I.R., realizing the importance of the computer, has formed IWP 1/2 to develop technical bases for utilization of computers in spectrum management.

References

- [1] CCIR Circular from Study Group 1 Chairman, March 1977.
- [2] NTIA, "Data Bases and Analysis Aids", Office of Federal Systems and Spectrum Management, National Telecommunications and Information Administration, November, 1978.

- [3] CCIR Report 669, "National Spectrum Management Data Bases," ITU, Geneva 1979.
- [4] Garber, G.W., "Spectrum Management Data Bases", IEEE Trans. on Electro-magnetic Compatibility, Vol. EMC-19, No. 3, August 1977, pp. 204-212.
- [5] Cohn, S.I. and W.M. Moran, "Radar Frequency Assignment", IEEE Trans. on Electromagnetic Compatibility, Vol. EMC-19, No. 3, August 1977,
- [6] CCIR Report 654, "A Method for Calculating Adjacent Band Interference, Frequency Dependent Rejection and Frequency Distance", ITU, Geneva, 1979.
- [7] Moran, W.M., C. Winkler and W. Gamble, An Automated Procedure for Predicting Potential Electromagnetic Interference Between Space and Terrestrial Systems Within the Coordination Areas in the Bands Between 7.25 and 8.4 GHz, OT Report 76-100, Office of Telecommunications, August 1976.
- [8] Longley, A.G. and P.L. Rice, Prediction of Tropospheric Radio Transmission Loss Over Irregular Terrain, A Computer Method-1968, ESSA ERL79-ITS67, July 1968.
- [9] Rice, P.L., A.G. Longley, K.A. Norton, and A.P. Barsis, Transmission Loss Predictions for Tropospheric Communication Circuits, Vol. 1&2, NBS Tech. Note 101 (Revised).
- [10] Berry, L.A., Probabilistic Tradeoffs for Efficient Spectrum Use with a "CB" Example, OT Report 77-117, Office of Telecommunications, April 1977.
- [11] Berry, L.A., Effects of Local and Skywave Interference on CB Radio Range, NTIA Report 78-1, National Telecommunications and Information Administration, May 1978.
- [12] CCIR Report 656, "Efficient Spectrum Utilization Using Probabilistic Methods", ITU, Geneva, 1979.
- [13] NASA, Frequency Band Justifications for Passive Sensors 10.0-300 GHz, Chapter II, December 1976.
- [14] Middleton, D.M., Performance of Telecommunication Systems in the Spectral Use Environment, IV. Statistical Criteria, EMI Environments and Scenarios, Office of Telecommunications Policy Research Paper, September 1977.

Microcomputers for spectrum management

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1. Introduction

OVER the last 20 years there has been a rapid growth in the demand for radiocommunication services. This in turn has created an urgent need for administrations to find adequate methods and tools for meeting this demand and for ensuring efficient utilization of the spectrum.

In general this demand has been met by the opening up of new frequency bands and by applying new engineering methodologies and innovations in the technology that guarantee better sharing and use of frequency assignments.

The growing demand, along with the constant search for improved methods of satisfying it, has transformed the management of the spectrum into an increasingly complex field, both technically and administratively, which is progressively becoming more dependent on the use of computers.

On an international level, to assist the various national administrations in solving these complex problems, the International Radio Consultative Committee (CCIR) was given the task of describing the application of computer-aided techniques in spectrum management. Several spectrum management tasks which can be considerably aided by the use of computers have been identified by the CCIR and include:

- Resolving potential interference problems between users.
- Providing administrative assistance through licence record-keeping and the processing of frequency applications.
- Frequency analysis to accommodate new radio systems or techniques.
- Frequency assignment to individual units, systems or class of systems to minimize potential interference.
- Evaluation of technical specifications of equipment and their spectrum use methodologies.
- Development of tabular and graphic engineering aids (such as frequency-distance separation curves) to assist spectrum planning.

Some administrations are using computer-based procedures to aid in performing the above-mentioned tasks. However, the majority of administrations are still, at least at present, studying and planning the introduction of computer systems for spectrum management.

The successful introduction of computers to aid spectrum management functions is extremely dependent on the computer hardware and software to be used. The methodology for selecting and introducing computer facilities in the ongoing oper-

ations of administrations requires a phased approach and is based on obtaining or developing computer programs (software) to perform the required tasks, as well as the training of personnel who will man the new facilities.

This paper reviews the above-mentioned issues in the light of the plans and programs being made in the Department of Communications (DOC) to select and deploy 8-bit and 16-bit microcomputers to assist in performing the various tasks associated with spectrum management in Canada.

Specifically, this paper describes the program currently under way in the Department of Communications to use microcomputers to support the engineering and administrative functions of spectrum management. The experience, to date, indicates that many nations could readily use microcomputers to meet many of their spectrum management computing needs; with the added benefits of low cost, portability and serviceability plus access to proven software from Canada.

Section 2 of this paper summarizes the advances made in software and hardware technology which led to the availability of powerful low-cost microcomputers. The section also summarizes some of the advantages of using these microcomputers in spectrum management. Section 3 provides two examples of complex spectrum management programs that have been developed in partnership with Canadian industry and which are currently running on these 8- and 16-bit microcomputers shown in photographs 1 and 2 in the Department of Communications. Section 4 elaborates on the issues related to the technology transfer process. Finally, some future directions that these developments are likely to take are outlined in Section 5. Appendices A and B contain further information on these microcomputers.

2. Advances in microcomputers

The use of microcomputers has, until very recently, been confined to small control and communications applications. This was because, until 1978/1979 microcomputers had very limited processing capabilities, small memories and restricted peripheral storage capabilities.

Technological advances in large scale integrated circuits and memory technologies have led, however, to the emergence of a new generation of powerful microcomputers. These microcomputers are extremely reliable and of very low cost, offering speed and ease of programming along with memory capacity, which until recently had been found only on much more expensive full-sized computers. The improvement in cost/perfor-



Photograph 1

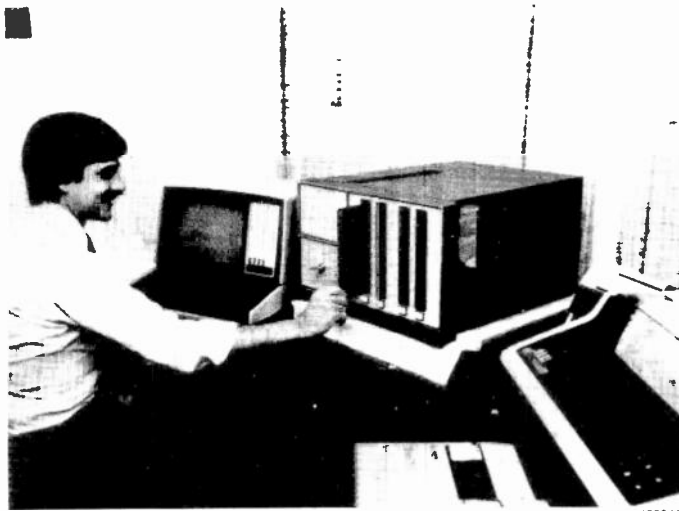
mance ratio over the last two years has been simply breathtaking and the future promises to be even more spectacular.

With advances in microcomputer equipment and technology have come an ever-increasing availability of high level programming languages (FORTRAN IV, COBOL, FORTH, PASCAL, C, APL, etc.), transportable software packages, operating systems, application programs and, perhaps most significant of all, highly versatile data base management systems. Efforts are already well under way to standardize the most commonly used operating systems, interface hardware and software and programming languages so as to ensure a high degree of program portability between various microcomputer systems.

Appendix A presents a summary of the most important characteristics of microcomputers, their secondary storage devices, operating systems and programming languages. Appendix B presents a brief summary of the two microcomputer architectures (photographs 1 and 2) being used by the Department of Communications in Canada, along with the hardware and software capabilities currently resident on these machines.

Microcomputers hold a real promise for allowing cheap and efficient transfer of spectrum management computer programs between administrations. Specifically, microcomputers offer the following features to spectrum managers:

1. Low cost: administrations will be able to introduce powerful microcomputers into spectrum management with a relatively low initial capital investment. As the requirements for increasing computing capability grow, these microcomputers can also be expanded, again at very low cost relative to what would have been the cost of expanding large computer systems only a few years ago.
2. Expandability: microcomputer systems can be expanded in two basic ways. These are:
 - a) each microcomputer system unit can be expanded in memory, secondary storage and numbers of user terminals; and
 - b) several microcomputers can be interconnected into a network configuration accessing a centralized mass storage memory system to accommodate almost unlimited growth in data base and program size.
3. Ease of operation: it is easier to manage and control growth and operation with these systems than with large computers, and this can usually be done by a very small team of professionals. This feature is extremely important for applications involving low computer utilization and where large numbers of skilled computer personnel are not readily available.



Photograph 2

4. Reliability: the relatively low cost and high reliability of microcomputers is now proven. In addition, it is easy to build into these installations spare capacity in the form of extra microcomputers. This feature is extremely important in locations where maintenance and servicing may not be readily available.

5. Software transportability: the widespread use of certain types of computers especially in the 8-bit family make it possible to exchange and transfer readily available, cheap, "off-the-shelf" software programs easily among these systems. This will have the advantage of reducing or minimizing the time and costs associated with the development of software and will prove to be a real benefit to administrations who do not wish to go to the expense of writing their own programs in their entirety.

3. Spectrum management applications

In the Department of Communications, the following two examples illustrate the use of microcomputers to solve spectrum management problems that had previously only been possible by the use of a large computer. The first of these applications involves propagation prediction using a computer program which is now resident on a 16-bit microcomputer system (photograph 1). This program runs with a topographical data base which makes it useful for performing calculations for radio systems operating in different terrains.

The second application involves the use of an 8-bit microcomputer (photograph 2) to house a frequency record data base that is used for administrative purposes and for conducting electromagnetic compatibility analysis (EMC). This program is in the prototype stage, but it already is demonstrating the power and facilities of the database management system. Additional details are as follows.

3.1 The propagation prediction computer program

An existing [1] comprehensive propagation program originally developed and running on a main frame computer system at the Communications Research Center of the DOC was modified and implemented on the microcomputer system. This program incorporates several propagation models that cover the VHF/UHF band from 30 MHz to 1 GHz. The models included in the program cover a wide range of propagation conditions, terrain types and clutter features in the vicinity of the transmit and receive antennae. The program is further enhanced by a

topographical data base that resides in the microcomputer and which permits detailed propagation analyses to be made.

The program is designed so that it can be used by engineers who are not familiar with programming techniques or details of the operation of the microcomputer system. The program's overall capabilities are that it contains:

1. A conversational (interactive) sub-routine called "Predict", which acts as an interface between the user and the computer. "Predict" constructs a data input file based on user responses to questions set by the computer, and sets a series of flags that identify the specific types of calculations to be carried out.
2. A topographical data base called "Topo", which contains previously stored information about the terrain. For instance, a rectangular area of $M \times N$ km² may be scaled in the form of a grid with a resolution of 1 or 5 km. Each of the points in the $M \times N$ grid of "Topo" will consist of the co-ordinates of the grid point as well as the average terrain elevation within the 1 km² cell centred on that point.
3. A computational sub-routine called "Run", which contains the propagation equations and computational algorithms.

Figure 1 illustrates the general structure of the propagation prediction program. The user enters all input parameters and selects one of four terrain options:

Option 1 is selected when terrain features are not known. A "smooth-earth" model is automatically assumed by the program for this case.

In *option 2*, the user selects to specify the terrain features from a given stored list.

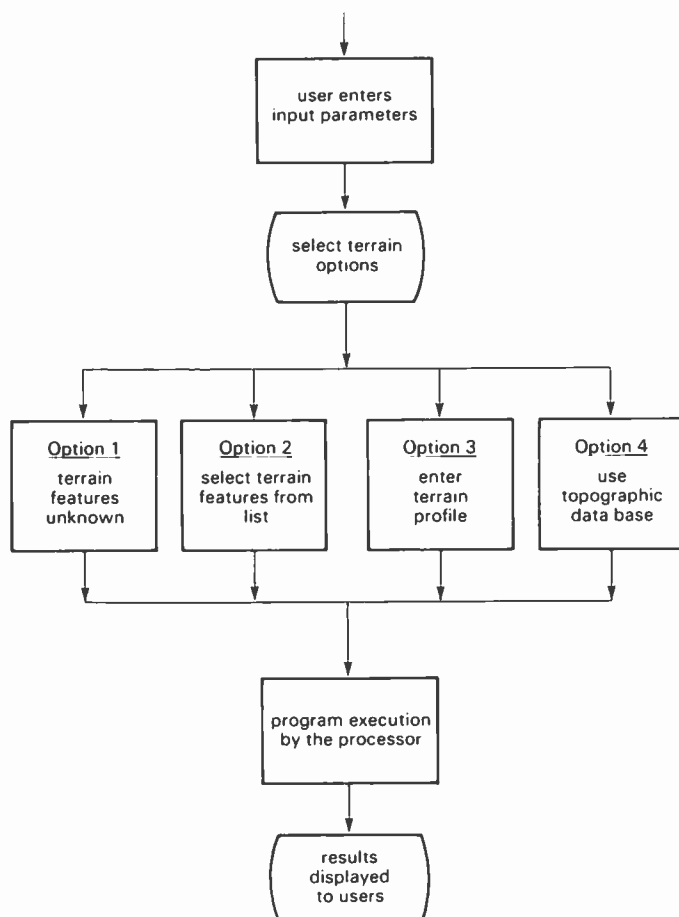


Figure 1—General structure of the propagation prediction program

In *option 3*, the user enters the profile of the terrain point by point.

Finally, *option 4* can be selected if the terrain in question falls within the boundaries of a previously stored topographic data base.

Once the terrain option is selected and completed, the program goes into execution mode, produces the results and displays them to the user. The main memory storage requirement for this program is approximately 128 kilobytes. The storage requirement for the topographic data base is such that 5 bytes are required for each square kilometre. Thus, assuming the existence of 100 maps, each covering an area of 10 000 km², the secondary storage currently on a hard disk is:

$$100 \times 5 \times 10\,000 = 5 \text{ megabytes}$$

The above storage requirements indicate that the program can be fully supported by the 16-bit microcomputer configuration shown in photograph 1 and more fully described in Appendix B.

3.2 Electromagnetic compatibility test (EMC)

An EMC program which accesses a stored frequency data base is described in this section. The program, which was developed in collaboration with outside consultants and their data base, has been implemented on another microcomputer (photograph 2). The program has the following capabilities:

- 1) a screen-oriented data entry and edition facility to allow the user to enter the data on the proposed new radio station which is to be evaluated against existing stations;
- 2) a data base which contains the records of existing stations and all their related data;
- 3) a frequency analysis program which permits:
 - a) co-channel analysis,
 - b) interstitial analysis, and
 - c) adjacent channel analysis;
- 4) a natural "plain English" language retrieval feature that allows users to retrieve records and produce reports on the basis of one or more simple "plain English" requests. This is an extremely powerful feature and underlines the usefulness of the data base management system.

From the user viewpoint the system functions as follows:

Step 1—Record entry

The user enters the data of the proposed station so that frequency analysis can be performed. Specifically the following data items are entered:

— licence number	7 numeric	(optional)
— name of licensee	35 characters	(optional)
— call sign	8 characters	(optional)
— address of licensee	35 characters	(optional)
— district office	2 numeric	(optional)
— name of station	35 characters	(optional)
— company code	9 numeric	(optional)
— record ID	9 numeric	(optional)
— frequency (MHz)	7 real number	(compulsory)
— latitude (degrees, minutes, seconds)	9 real number	(compulsory)
— longitude (degrees, minutes, seconds)	9 real number	(compulsory)
— antenna AMSL (m)	4 numeric	(optional)
— ground elevation AMSL (m)	4 numeric	(optional)
— antenna gain (dB)	3 real number	(compulsory)
— total losses (dB)	3 real number	(compulsory)
— effective radiated power (dBW)	3 real number	(compulsory)
— station mode (TX or RX)	1 character	(compulsory)

If any of the (compulsory) fields is not entered, the system will request the user to enter the missing field value before moving to the next step.

Step 2—Entering parameter values

The user on request of the system enters the values of the following parameters:

- a) Receiver noise code: this is entered as a 1, 2 or 3
- b) Interstitial channel rejection ratio called IC in units of dB. In this instance if no value is entered for IC, the following default values are automatically used by the system, depending on the frequency band under consideration:

Frequency band (MHz)	IC (dB)
27-50	—
138-174	15
410-470	12.5

- c) Adjacent channel rejection ratio, AC, in dB units. Here, if no value is entered for AC, the following default values are automatically used by the system:

Frequency band (MHz)	AC (dB)
27-50	75
138-174	74
410-470	72

- d) Value for the receiver threshold power. P_{min} , in dBW. Here, if no value is entered for P_{min} , the following default values are automatically used by the system:

Frequency band (MHz)	Noise code (dB)		
	1	2	3
27-50	-143	-139	-131
138-174	-148	-139	-131
410-470	-146	-145	-138

Step 3—Analysis

The system allows the user to select one of the following five analysis options:

1. Co-channel analysis:
This option displays all of the records satisfying the co-channel interference criterion.
2. Interstitial analysis:
This option displays all of the records satisfying the interstitial channel interference criterion.
3. Adjacent analysis:
This option displays all of the records satisfying the adjacent channel interference criterion.
4. Enter station:
The proposed station record can be entered into the data base containing existing station records.
5. Quit:
The system will give the user the option of entering another station record or of terminating the session.

The program for carrying out all of the above requires a main memory of only 32 kilobytes, which means it easily runs on an 8-bit or a 16-bit microcomputer. Each data base record has a maximum size of 200 bytes. Thus, a 10 megabyte disk space would accommodate a data base with a total volume of 50 000

frequency records. In addition to being able to study the potential interference impact of a proposed radio station, the user is also allowed to exploit the capabilities of the data base management system. Using the natural language features of a data base management system, record retrieval and report preparation can be accomplished in a very simple and straightforward manner. For example, if a user wished to retrieve the licensee name (LNA) and address (LAD) for all radio stations whose frequencies (FREQ) exceed 150 MHz and whose latitude (LAT) is between 45°, 30', 25" and 45°, 30', 35" this could be accomplished by typing the following "plain English" statement:

DISP LNA, LAD FOR FREQ >= 150 AND (LAT >= 45.30.25).
AND. (LAT <= 45.30.35)

Alternatively, as another example, a user might want to have a listing of all call signs (CALL.SIGN) corresponding to radio stations whose antenna heights (ANT.HEIGHT) are greater than 30 m and whose location is within the administrative boundaries of district office (DIST.OFF) 35. In this case the user would enter the following statement:

DISP CALL.SIGN FOR ANT.HEIGHT >= 30 AND DIST.OFF = "35"

The retrieval capabilities provided by the microcomputer and the data base management system are however not limited to the two examples given above. Various other "simple English" retrieval capabilities can be readily generated including, for instance, the calculation of averages of antenna heights, effective radiated power, etc.

4. The acquisition of microcomputer technology

Many administrations are continuously facing the problem of deciding which specific spectrum management technology is more appropriate to their environment. The technology (hardware, software) and know-how (brainware) continue to be developed at phenomenal rates that reduce the existing technology to obsolescence within 2 to 5 years. Hence, decisions concerning the acquisition of computers to support spectrum management are increasingly difficult to make. Costly and difficult to rectify mistakes will most likely result if the most cost/effective computer technology and software are not selected from the outset.

Canada is convinced that the transfer of technology and know-how in the area of spectrum management must be undertaken so as to allow administrations to acquire and build their own skills progressively and generate applications actually tailored to their own environment. Administrations wishing to ensure the flow of technology in harmony with their local cultural realities have always to take into account the scarcity of human and financial resources. Indeed, the mere fact that the technology (hardware and software) to support spectrum management is available in one administration is no guarantee that it can be effectively transferred to another administration without careful attention being given to human factors and local cultural realities. There must be a commitment by administrations wishing to deploy spectrum management technology successfully to develop the necessary skills (brainware) to the extent required through comprehensive training programs.

Transferring technology to a milieu where resistance to change is built-in often leads to problems of a non-technical nature. In such circumstances the failure of technology is not only measurable in terms of quantifiable costs such as equipment but also in socio-economic and cultural terms. However, if the stra-

tegy of modernization through technology transfer is both limited and regulated, the risk of it failing will be minimized. This implies that a pragmatic approach of progressive deployment of human, technical and financial resources has to be instituted. In the particular case of microcomputer technology as applied to spectrum management it is important that the program of technology transfer be structured according to the following phases:

4.1 Technological absorption

During this phase an administration would, as a first step, acquire a minimum configuration system consisting of a microcomputer, visual display terminal, printer and floppy disk secondary storage. Software-wise the microcomputer would have a single user operating system capable of supporting three computer languages (BASIC, PASCAL and FORTRAN) together with a set of demonstration programs. These demonstration programs would allow users:

- to experiment with creating and retrieving records of information pertinent to a limited set of radio stations via a file management system;
- to use the system in the word processor mode; and
- to run some simple programs providing, for instance, calculations of the coverage area of a land mobile base station.

This experience would allow users to become rapidly familiar with both the hardware and software capabilities of a microcomputer.

4.2 Expansion of technological absorption

In this phase, hardware and software capabilities are expanded to include a number of visual display terminals, printers and a hard disk drives with a minimum of 20 megabytes of storage. A time-shared operating system would also be installed along with a relational type data base management system. An additional option would be a plotter and corresponding graphics package that would allow the displaying of path profiles using stored terrain data, or the drawing of coverage contours of, for example, broadcasting stations. The data base management system would allow users to gain experience in the retrieval of administrative or technical data elements from a spectrum management data base using "simple English" instructions. Demonstration packages would allow the user to study the frequency assignment problem in a congested radio environment and gain a feel for the overall operation of the system.

During this phase the users will interact closely, and become thoroughly familiar, with the equipment, learning how best to configure it and utilize it for the various applications. User skills and familiarity with software are expanded in parallel and, by the end of this phase, users should be able to write programs in BASIC or FORTRAN IV.

4.3 Creative development

At the end of the first two phases, the capabilities of microcomputers to aid spectrum management will have been fully demonstrated. In this third phase, users begin creative development and customizing of programs by exploring new applications and tailoring the existing programs to their own specific needs. In this phase, the capabilities of hardware and software are stretched to their limits and users gain experience with generating documentation while undertaking limited software and hardware maintenance. A methodology for human resource development is established during this phase to qualify and train personnel, particularly in the areas of software design and hardware maintenance. More efficient operating systems, other languages (COBOL, C, FORTH, APL, etc.) and a library of mathematical sub-routines are then installed. At the end of this

phase, the spectrum management microcomputer system would have the capability to study propagation and antenna models, frequency allocation plans, and provide licensing.

4.4 Consolidation of creativity

During this phase, the user is expected to achieve a limited technological autonomy, particularly in the software sense. The user would now be in full control of the microcomputer-based spectrum management system and all of its programs. The need may arise to extend the intelligence of the spectrum management system to other offices of the administration located in other parts of the country, in which case access to telecommunication channels will have to be provided. This however will not modify to any substantial degree the technical characteristics of the spectrum management system but rather will impact on its operational and administrative aspects.

The capacity for innovation is stimulated by an appropriate training program that emphasizes the brainware aspects of spectrum management. To be able to perform a full-scale maintenance program it will be necessary to train personnel in the use and understanding of technical service data and drawings as well as automated trouble-shooting and diagnostics programs including the replacement of printed circuit boards.

In the past, the cost of technology transfer involving large-scale computers has been very high. However, in the future, spectrum management technology based on microcomputers can be transferred to administrations at relatively low cost. This will ensure that the financial burden is kept at a very modest level while allowing the recipient administrations to carry on their national and international spectrum management obligations in a framework of creativity and innovation.

Canada looks forward to working with interested administrations in this vitally important area.

5. Conclusion

Meeting the growing demand for radiocommunication continues to be a principal preoccupation of administrations. As radio waves do not respect international boundaries, the increasing and diversified use of radiocommunication has led, in recent years, to a realization of the necessity for managing the spectrum properly. Most administrations are therefore planning to, or have already introduced modern and sophisticated computer tools and associated engineering techniques. Such a trend is typified by the increasing involvement of the International Telecommunication Union (ITU) and its organs in spectrum management related projects and programs.

Canada has realized that, in the future, spectrum management will be based extensively on the use of microcomputers. In the past, large-scale computers were utilized at great cost as they were the only ones available. With the advances in technology, however, it has become clear that spectrum managers can utilize microcomputers which have now attained capabilities that in many instances exceed those of the large-scale computer of a few years ago. Administrations can now avail themselves of these Canadian innovations and experience gained by Canada, thereby minimizing the financial and human resources that would otherwise be required to develop and maintain effective spectrum management facilities. Canada, in collaboration with its industry, would be pleased to assist national administrations to develop a program in this vitally important and dynamic area.

(Original language: English)

APPENDIX A

Essential features and characteristics of microcomputers

The main features used to determine and evaluate the capabilities of microcomputers are:

- (0) Cost
- (1) Word length
- (2) Main memory size
- (3) Central processing unit (CPU) capabilities
- (4) Input/output support
- (5) Second storage devices
- (6) Number of users that can be supported
- (7) Communications interfaces
- (8) Software (applications and operating system)
- (9) Price and delivery time (including service)
- (10) Continuity of compatibility

A description of each of the above categories is presented below. More details of commercially offered microcomputers, and available software is given in references [2] and [3]. Additional information can also be found in various trade journals and magazines.^[4, 5]

0. Cost

All microcomputers with fully expanded main memory, but exclusive of software and peripherals such as disc drives, printers and CRTS, currently cost less than 8000 Canadian dollars at the retail level in single quantities. Complete systems of high quality have hardware costs of between 15 000 and 60 000 dollars depending on the amount and type of the peripheral devices utilized.

1. Word length

The word length refers to the number of bits (binary digits) that can be retrieved or stored from memory during a single cycle. Microcomputers with longer word length tend to be, in general, more efficient and accurate. All existing microcomputers have an 8- or 16-bit word length.

2. Main memory size

The storage type can be either magnetic core (as in early computers) or semiconductor memory (as in modern computers). The demand for higher performance at lower cost, coupled with continuing improvements in semiconductor technology, have accelerated the trend toward the use of semiconductor memories. The maximum memory size of 8-bit microcomputers is 64 kilobytes and of 16-bit microcomputers is 256 kilobytes.

3. Central processing unit (CPU) capabilities

The majority of currently available microcomputers are parallel, binary processors with single address instructions and fixed word lengths of 8, 12, 16 bits. It is now expected that 32-bit microcomputers will be on the market by 1985. The important factors to be considered when evaluating the central processing units' capabilities are:

3.1 Address space, or the maximum size of directly addressable main memory. The shorter the word length, the smaller the size of the directly addressable main memory. This in turn places constraints on the size and number of data records and size of application programs. The most common techniques used to minimize the restrictions of word length in 8- and 16-bit microcomputers are based on techniques such as multiword instructions, indexing or indirect addressing.

3.2 Hardware multiply/divide logic. When this hardware is not specifically a part of the CPU, operations of multiplication and division must be performed by programmed routines. This leads to a reduction in the speed at which these operations can

be performed. Thus it is always desirable to have all arithmetic as well as many as possible mathematical operators directly as part of the hardware of the central processing unit.

3.3 Microprogrammability. In place of conventional hardwired logic, a microprogrammed computer uses sequences of microinstructions stored in a special read-only-memory to define the effects of each instruction in its repertoire. Microprogrammability increases the flexibility of the computer by allowing the user or the vendor to alter the microprograms. However, this feature usually reduces the speed and/or increases the cost, and the added flexibility may not be sufficient to justify its use.

3.4 Hardware floating point facilities. These are needed in most scientific applications and are useful in reducing the execution times of certain programs which would otherwise use time-consuming floating point sub-routines. Many microcomputers offer a small "chip" called a "floating point processor", which can be plugged in directly on the main CPU board. The cost of this chip is typically of the order of 300 dollars.

3.5 Battery back-up. This is essential to preserve the contents of the solid-state memory in the event of a power failure.

4. Input/output support

The transfer of data from a peripheral device, such as a disc unit, to the main storage may take place either under program control or via a direct memory access channel (DMA). Generally speaking, DMA has two significant advantages over program controlled I/O:

- a) it can accommodate higher I/O data rates, and
- b) it causes less interference to internal processing operations.

For applications of a real-time nature, an effective "program interrupt" facility is an essential requirement. An interrupt is a signal that causes a temporary suspension of normal program execution so that the specific condition that caused the interrupt can be dealt with. In real-time applications, an external interrupt usually indicates that a particular peripheral device requires attention. The number of external interrupt levels provides a reasonable indication of the power of the computer's interrupt system. It indicates the number of different external devices the computer can support.

5. Secondary storage devices

The most commonly available secondary storage devices for microcomputers are:

- floppy disk drives with storage capacity of 1 to 2 megabytes per drive, at a cost of 2000 to 4000 dollars for a high quality double drive system with its own power supply and controller;
- disk pack/cartridge drives with storage capacity of 5 to 9 megabytes per disk. A typical high quality 9-megabyte hard disc system for an 8-bit or 16-bit microcomputer currently costs under 10 000 to 12 000 dollars;
- drum/fixed-head disk with storage capacity similar to cartridge drives;
- magnetic tape drives in standard 9-track 22 megabyte format cost around 12 000 to 14 000 dollars.

6. Number of users that can be supported

"Users" refers to the number of individual data processing devices of terminals that can be connected to the microcomputer. An important factor to consider in an applications environment is the number of such devices or terminals which can be concurrently supported by the microcomputer in a time-shared mode. If the microcomputer system is being used in "time-sharing" environment, it must be capable of interfacing to, and serving, several users who may share the same set of applica-

tions or, alternatively, run their own special programs. The computer will appear to each user as if it is dedicated to running his individual job despite the fact that it is serving several other users at the same time. This "time-sharing" feature, in the past an exclusive preserve of the large computer, is now readily implementable on microcomputers.

7. Communications interfaces

A special interface is usually employed to enable the microcomputer to send and receive data over a telephone channel. Three main factors define this communications interface, these are:

- the maximum number of communications lines that can be handled by the microcomputer system;
- the type of interface (synchronous or asynchronous) and the transmission speed in bit/s that it supports;
- the type of communications protocol supported by the computer in the form of a software or a hardware facility.

8. Software

The software is defined as the programming packages and languages used to program the computer. The availability of software for any given microcomputer is a very important factor to be considered when evaluating the usefulness of that microcomputer for the applications under consideration. It is possible to classify software into the following three categories:

8.1 The operating system: forms the core of the computer's software and handles functions such as scheduling, loading, initiating and controlling I/O operations and devices, supervising the execution of programs, dealing with errors, handling all interfaces to human operators and organizing multiprogramming or time-sharing operations. Operating systems are usually licensed for use with a given microcomputer and costs range from a few hundred, for 8-bit microcomputers, to several thousand dollars for 16-bit microcomputers.

8.2 Programming languages and compilers: the programming language (e.g. BASIC, FORTRAN IV, COBOL) allows users to write complex programs in a straightforward fashion. The compiler of the language converts the program into executable machine language code. The compiler thus shifts part of the program preparation task from the user to the computer itself. Examples of programming languages include FORTRAN IV, BASIC, APL, COBOL, PASCAL, C and FORTH and their associated compilers are now available for microcomputers. The costs of these compilers, usually licensed for a given system, run from a few hundred to a few thousand dollars.

8.3 Data base management systems: these software packages are the wave of the future, and allow the user to specify a logical structure for the data he wishes to store and then retrieve later. The user is also provided with facilities for updating or modifying the data. He can specify, retrieve and manipulate his data using a high level procedure. The data base system translates the logical structure into a physical layout, stores it on secondary storage devices and controls all access operations to the stored data. A high quality data base management system is available for 8-bit microcomputers for under 600 dollars. Data base management systems are also available for 16-bit microcomputers. One recent offering for a relational data base management system is available for under 5000 dollars. The operating system under which this data base runs supports several high-level programming languages and offers transportability of software between 8- and 16-bit microcomputers.

9. Price and delivery time (including service)

Four important factors must be considered in regard to price and availability:

9.1 The price of CPU, power supply, minimum memory (and memory increments), secondary storage, I/O devices, hardware options such as floating point processor. The price of various software packages must also be considered.

9.2 Delivery date—the time lies between issuing a purchase order and the installation of the facility. Typical delivery dates and installation times should be kept within 6 months.

9.3 Availability of field support and maintenance for the hardware and the software components. In this regard a parallel "back-up" system will minimize down time between repairs in any location.

9.4 Costs of software tailored to given applications are always expensive, however, the widespread use of data base management promises to minimize the costs of developing and transporting software between microcomputers.

10. Continuity of compatibility

This factor refers to how long a given microcomputer will be produced and whether or not successive generations of improved microcomputers will "run" the software of earlier generations without major modifications.

APPENDIX B

The following is a summary of the microcomputer system configurations and software currently in the Telecommunication Regulatory Service of the Department of Communications and being used for spectrum management applications.

Photograph No. 1—DEC LSI-11/23 (total of 3 microcomputer systems)

*Processor:

16-bit LSI 11/23—hardware floating point and memory management by Digital Equipment Corporation

*Memory:

256-kilobyte dynamic memory

*Storage:

- a) floppy disks single and double density, 2 megabytes
- b) hard disk cartridge 20 megabytes, 10 megabytes removable; also hard disk cartridge 96 megabytes, 20 megabytes removable. Note both also usable with Cromenco system III using different controllers
- c) 9-track magnetic tape drive, 800/1600 bits per inch, 22 megabytes per reel

*In/out:

8 serial ports, video console, printer, modem and 4 other ports

*Printers:

dot matrix; spin wheel—low, high speed

*Operational systems:

RT-11-IV, RSX-11M, UCSD PASCAL, IDRIS, XENIX

*Languages:

BASIC, PASCAL, FORTRAN, COBOL, FORTH, C

*Application packages and data base systems:

EZEDIT wordprocessor, MCBA filemanagement, PIRATE data base; "MISTRESS"

Photograph No. 2—Cromenco system III (total of 5 systems)

*Processor:

Z80 (8-bit microprocessor)

*Memory:

64-kilobyte dynamic memory

*Storage:

- a) floppy disks, dual side, double density, 2 megabytes storage
- b) 96 megabytes hard disc also 10 megabytes hard disc

***In/out:**

3 parallel ports, console, printer, modem

***Printers:**

same as for LSI-11/23

***Operational systems:**

CP/M 2.2, CDOS, CHROMIX

***Languages:**

CBASIC, MBASIC, FORTRAN, COBOL, UCSD, PL 1,
PASCAL, PASCAL/Z, PASCAL/MT, C, FORTH

***Application packages and data base system:**

PEARL, HDBS, T/MAKER, DBASE II, WORDSTAR
DATASTAR, AMETHYST, MINCE, CALCSTAR,
MUMATH, MILESTONE

References

- [1] *VHF-UHF prediction program*. Communications Research Center, Department of Communications, Ottawa (Canada)
 - [2] *Databook—The EDP buyers's bible*. Datapro Research Corporation, Delran, NJ 08075 (United States)
 - [3] *Data World*. Auerbach Publishers Inc., Pennsauken, NJ 08109 (United States)
 - [4] *Byte the small systems Journal*. Byte Publications Inc., Peterborough, NH 030458 (United States)
 - [5] *Mini-microsystems*. Cahners Publishing Company, Boston, MA 02116 (United States)
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Classification and Designation of Emissions

WILLIAM A. LUTHER

Abstract—A new, much more complex, but needed, system of designating emissions has been agreed and incorporated into the Final Acts of WARC-79. Its use will be mandatory for frequency registration with the International Frequency Registration Board (IFRB) after January 1, 1982. Full designation is with nine alphanumeric characters in two parts; four characters for necessary bandwidth followed by five symbols for emission classification. Of the five classification symbols, three are mandatory and are found in the lists of Article 4. The last two symbols, which are optional for use, may be taken from lists in Appendix 6. WARC-79 made provision for expanding the choices of the optional symbols to give future flexibility as technology develops. The complete method for designating emissions is contained in this paper.

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AFTER TWENTY YEARS of study, trial, and error, the world's community of frequency administrators has been able to reach agreement on a modern, useful method of designating emissions (transmissions) according to their necessary bandwidth and their classification. The new method will become effective with entry into force of the Final Acts [1] of the 1979 World Administrative Radio Conference (WARC-79)¹ occurring on January 1, 1982, subject, of course, to ratification under national procedures and terms of the International Telecommunication Union (ITU) Convention [2]. The Appendix to this paper contains the new method.

¹ The author uses the form "WARC-79" for consistency throughout this publication. The form "1979-WARC" is preferred in the conformance with the official U.S. Delegation Report to the United States Secretary of State.

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271

that unimportant characteristics were included in (and that important characteristics were excluded out of) the new method.

ive Radio Conference, 1979, Report of the joint meeting of CCIR Study Groups Special Preparatory Meeting for the WARC-79.

273

283

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device has been found to repeatedly cause harmful interference to radio communications, the Commission may classify such a computing device as a Class B computing device, regardless of its intended use.

A definition for personal computers was also adopted, since these products must meet the Class B limits and be certified by the Commission. It reads as follows:

Personal computer. An electronic computer that is marketed for use in the home, notwithstanding business applications. Such computers are considered Class B computing devices. Computers which use a standard TV receiver as a display device or meet all of the following conditions are considered examples of personal computers:

- marketed through a retail outlet or direct mail order catalog
- notices of sale or advertisements are distributed or directed to general public or hobbyist users rather than restricted to commercial users
- operates on a battery or 120 volt electrical supply.

If the manufacturer can demonstrate that because of price or performance the computer is not suitable for residential or hobbyist use, he may request that the computer be considered to fall outside the scope of this definition for personal computers.

The radiated and conducted emission limits are given in Tables II and III, respectively. The limits proposed in the 1976 NPRM are also shown for comparison purposes.

On reconsideration, the Commission temporarily exempted the following four categories of devices from complying with the new rules. They are still subject, however, to operating on a non-interference basis, pursuant to Section 15.3 of FCC Rules.

- (1) a computing device utilized in any transportation vehicle including motor vehicles and aircraft.
- (2) an electronic control or power system utilized by a public utility or in an industrial plant.

- (3) industrial, commercial, and medical test equipment.

- (4) computing device utilized in an appliance, e.g. microwave ovens, dishwasher, clothes dryer, etc.

The exemption for medical test equipment applies only to equipment used to test medical equipment and does not apply to medical diagnostic equipment.

The rationale for these exemptions is given in paragraphs 52-65 of the Reconsideration Order (Reference 7).

As noted above, the new rules were to become mandatory for computing devices manufactured after July 1, 1980. This date was subsequently postponed in the Reconsideration Order in accordance with the following schedule:

- January 1, 1981 for personal computers and electronic games
- October 1, 1981 for all other computing devices first placed into production after October 1, 1981
- October 1, 1983 for all computing devices, regardless of date of first production.

A label is required on computing devices manufactured after January 1, 1981, which has not been tested for compliance.

TEST METHODS

The measuring methods for determining compliance with the new rules will follow the general methodology in a number of measurement procedures the Commission has used for many years (Reference 10-14). In this instance, however, the test procedures were proposed in a new rule making proceeding released in June 1980 to give all interested parties an opportunity to comment on the test procedures (Reference 15). In general, the proposed procedures follow the format of the draft American National Standard Method of Measurement of Radio Noise Emissions From Low Voltage Electrical and Electronic Equipment in the Range of 10 kHz to 1 GHz, ANSI C63.4, Draft No. 7 which at the time of writing of this paper was out for ballot to become an approved standard.

Briefly, measurements shall be made in an open field or on a test site that produces results that are correlateable to open field test results. Measurements shall be made with a spectrum analyzer using a dipole antenna. Alternatively,

TABLE II

Frequency (MHz)	Class A $\mu\text{V/m}$ @ 30m	Class A $\mu\text{V/m}$ @ 3m (1)	Class B $\mu\text{V/m}$ @ 3m	NPRM $\mu\text{V/m}$ @ 3m (2)
30-88	30	300	100	100
88-216	50	500	150	100
216-1000	70	700	200	100

Notes: (1) Limits specified at 30 meters, but extrapolated here for purposes of comparison using inverse distance relationship.

(2) Limits below 30 MHz proposed, but not adopted.

TABLE III

Frequency (MHz)	Class A μV (1)	Class B μV (1)	NPRM μV (2)
0.45-1.6	1000	250	200
1.6 -30	3000	250	100

Notes: (1) Based on using a $50\Omega/50\mu\text{H}$ line impedance stabilization network.

(2) Limit below 450 kHz proposed, but not adopted.

measurement may be made with the instrumentation recommended by CISPR in their publication 16 (Reference 14). The bandwidth of the measuring instrument shall be set not less than 100 kHz for radiated measurement and 9 kHz for conducted measurements. Measurements shall be made around the device under test, rotating search antenna and varying its height to search for maximum emissions. Line conducted measurements shall be made using a 50 ohm/50 microhenry Line Impedance Stabilization Network.

The test methods should be finalized or in the final stages of being published by the time this paper is presented at the Symposium in October 1980.

MANUFACTURER'S RESPONSIBILITIES

Under the new rules, the manufacturer has the responsibility of not only meeting these technical standards but in addition informing the user about the interference potential of the computing equipment he is marketing. He is required to do this in two ways. He must place a label containing a warning statement on the equipment, AND he must include a warning statement in the instructions furnished to the purchaser.

The warning label and statement in the instructions take a number of different forms. These labels and warning statements are intended to serve a dual purpose. For one, they tell the user whether the equipment was tested and to what standards it was tested. Secondly, they warn the user not to use a Class A equipment in a residential area where equipment should meet the tighter--Class B--standards. If the user does so, he is warned that it will be his--the user's--responsibility to remedy the interference.

For some equipments--a personal computer, peripherals thereto, coin operated video games, and some few others--the manufacturer must get certification from the Commission before he markets the equipment. Under this procedure, the manufacturer submits test data to the Commission.

For all other Class B computing equipment and for all Class A computing equipment, the manufacturer must verify compliance before marketing. Verification is a form of self certification with nothing submitted to the Commission. We expect to determine compliance by random sampling of products in the marketplace. I would call your attention that we reserve the right to require the manufacturer to obtain certification--

which means submitting test data to the Commission--as a prerequisite for continued marketing.

In both cases, certification and verification, testing to determine compliance is a prerequisite for legal marketing under Part 2 Subpart I (47 CFR Part 2-I). Administrative sanctions for failure to comply are given in Sections 501-503 of the Communications Act of 1934 as amended (47 USC 501-503) and in Section 1.80 of Part 1 of our Rules (47 CFR 1.80).

INTERNATIONAL HARMONIZATION

The technical standards for computing devices adopted by the Commission to a large extent was based on the comments and studies submitted by CBEMA, as noted above. These same standards, with a few minor exceptions, are being considered by CISPR--Comite International Special des Perturbations Radio-electrique (International Special Committee on Radio Interference), a special committee of the International Electrotechnical Commission (IEC).

The basic objective of CISPR is to achieve international harmonization of standards for devices capable of causing interference to communications. To this end, CISPR prepares formal statements and recommendations setting out technical standards designed to limit interference. These recommendations are voluntary standards and impose no legal obligations. However, a number of countries have incorporated CISPR recommendations in their national laws which makes them binding requirements on vendors selling such equipment in that country. See Reference 16 for a good discussion of the international and national voluntary standards making organizations.

International harmonization of the standards for computing devices is, therefore, possible. The benefits derived from such harmonization is obvious and will not be discussed here.

CONCLUDING REMARKS

The standards adopted by the Commission are, in our opinion, minimum standards for controlling the interference potential of digital equipment. They were not developed, nor were they intended to replace all internal company or trade standards, which should be developed for particular applications. For example, a computer terminal controlling a communications network juxtaposition to one another would probably

require greater suppression of emissions than what is stipulated in Part 15. In different words, the FCC limits should only be used as a guide for protecting communication, they provide no guarantee that interference problems will not occur.

As with any new program, especially one of this complexity, numerous questions and problems arise. To handle the large number of questions about the new standards, the Commission has established a Computing Device Panel to provide orderly and consistent replies to the inquiries.

Questions about the new FCC Rules for computing devices should be addressed to :

Chairman, Computing Device Panel
Federal Communications Commission
1919 M St., NW, Room 7208
Washington, D.C. 20554

Each inquiry addressed to the panel will be answered. The significant questions along with their replies will be published in a series of public notices. Ultimately, these interpretations will be compiled and issued in an OST Bulletin. This is the same procedure that was followed by the TV Tuning Panel established in the early 70's to answer questions about the all-channel requirements for TV receivers.

One final comment. In general, this paper is a consolidation of a number of different documents. However, any views expressed in this paper are those of the authors and do not necessarily reflect those of the Commission.

REFERENCES

1. Notice of Inquiry on Radio Frequency Interference to Electronic Equipment, FCC 78-801, Adopted November 14, 1978, Released November 21, 1978, 43 FR 56062, 70 FCC 2d 1685.
2. Ristorcelli, Charles T., Electromagnetic Interference From Pocket Calculators, IEEE EMC Transactions, Vol. EMC-18 No. 1, February 1976, pages 42-45.
3. FCC Laboratory Report on "Personal Computers as Restricted Radiation Devices", Project No. 62502, August 1979.
4. Notice of Proposed Rule Making In the Matter of Amendment of Part 15 to redefine and clarify the rules governing restricted radiation and low power communication devices,

FCC Docket No. 20780, adopted April 14, 1976 and published in the Federal Register on April 23, 1976 at 41 FR 17938.

5. CBEMA Report, ESC5/77/29, Limits and Methods of Measurements of Electromagnetic Emanation from Electronic Data Processing Office Equipment, 20 May 1977.
6. First Report and Order--Technical Standards for Computing Equipment in FCC Docket No 20780, adopted 9/18/79 and published in the Federal Register on 10/16/79 at 44 FR 59530.
7. Order Granting in Part Reconsideration of First Report and Order in FCC Docket 20780, adopted 3/27/80 and published in the Federal Register on 4/9/80 at 45 FR 24154.
8. Order Granting Waiver in Part In the Matter of Petition by Texas Instrument, Inc. for waiver of Section 15.4(m) and Section 15.7 of FCC Rules, adopted 9/18/79, FCC 79-557, Vol. 76 FCC 2d 720.
9. Notice of Proposed Rule Making In the Matter of Amendment of Part 15 of the FCC Rules to provide for the operation of a TV Interface Device, GEN Docket 79-244, FCC 79-556, 44 FR 59570.
10. Institute of Electrical and Electronics Engineers Standard 213 (formerly 61 IRE 27S1) for conducted interference measurements from frequency modulated and television broadcast re-

ceivers in the range 300 kHz to 25 MHz.

11. Institute of Electrical and Electronics Engineers Standard 187 (formerly 51 IRE 17S1) for radiation measurements.
12. Electronics Industries Association Standard RS-378, dated August 1970, entitled, "Measurement of Spurious Radiation from FM and TV Broadcast Receivers in the Frequency Range of 100 to 1000 MHz-Using the EIA-Laurel Broad-Band Antenna."
13. International Electrotechnical Commission Publication No. 106 (1959) and Supplement 106A (1962) for measurement of radiated interference from broadcast receivers.

NOTE: This publication and supplement may be purchased from the American National Standards Institute (formerly United States of America Standards Institute), 1430 Broadway, New York, NY 10018.

14. International Special Committee on Radio Interference (C.I.S.P.R.) specification for radio interference measuring apparatus and measurement methods. CISPR Publication No. 16.
15. Notice of Proposed Rule Making In the Matter of Amendment of Parts 2 and 15 of FCC Rules relating to verification and methods of measurement of computing devices, Adopted June 1980.
16. Mason, John, Why parts 'fit': the role of IEC, pp. 42-44, The IEEE Spectrum, June 1980.

Part III

Spectrum Engineering

INTRODUCTION

AS the spectrum becomes more and more congested, greater reliance must be placed on spectrum engineering techniques to accommodate the needs of the various individuals and groups requiring spectrum. Since the spectrum is a limited resource, the needs can usually only be fulfilled by spectrum sharing. Indeed, the frequency allocation tables of the ITU, United States and other countries contain many parts where the spectrum is shared by two or more services. An evaluation is usually made prior to the introduction of an additional service into the allocation table where sharing is required. Such an evaluation is usually based on spectrum engineering techniques that, at times, impose restrictions or coordination procedures on the newly allocated service in order that harmful interference does not occur. The ITU has the CCIR as its technical advisory body, and it is the CCIR where such sharing techniques based on spectrum engineering are frequently developed. In the United States, the two regulatory bodies, the NTIA and FCC, both have technical staffs, as do other government agencies where spectrum engineering is conducted. The regulatory agencies of many other countries also have technical staffs for such purposes. Private corporations and groups of spectrum users, both in the U.S. and in other countries, often have technical staffs engaged in spectrum engineering, either as their main function or as an adjunct to other functions such as communications engineering.

In addition to the sharing of positions of the allocated spectrum by two different services, specific frequencies are often shared. This can be an international situation when signals traverse borders or a domestic situation when it is desired to reuse the same frequency or an adjacent frequency. Spectrum engineering techniques (also termed electromagnetic compatibility or EMC analyses) are used to develop the conditions under which such sharing or frequency reuse is made possible. In the case of the international situation, the sharing arrangements can be based on the ITU Radio Regulations, or some other mutually agreed to arrangement be it a CCIR recommendation or a bilateral agreement. The arrangements can also be either a formal agreement or an informal mutual understanding under which coordination takes place.

Spectrum engineering consists of many different parts. A sharing, or EMC criteria, is one of the fundamental requirements. Some knowledge of the technical characteristics of transmitters, receivers, and antennas

is needed in many cases, although the knowledge need not always be exact. Propagation path loss predictions are a factor used to determine separation distances required to achieve amicable sharing. Information concerning noise and intermodulation is required in more localized problems. All of the various relevant parameters associated with sharing criteria, transmitters, receivers, antennas, propagation loss values, noise, and intermodulation are often used in modeling sharing problems. Models are useful when the same problem reoccurs frequently, and can be very valuable because of the time saved. Many computerized models are used frequently in solving spectrum engineering problems. Knowledge of radio frequency noise should also be regarded as a factor in spectrum engineering. Other factors are data bases, computers, and radio monitoring. Harada has integrated all of these factors plus transmitters, receivers, antennas, and propagation into a comprehensive paper on spectrum engineering [1].

SHARING CRITERIA

Sharing criteria or EMC criteria differ greatly among the various telecommunications services using the spectrum. It is easy to see that such services as land mobile communications, aeronautical radionavigation, and radio astronomy must have different sharing criteria because of different user requirements and the widely different types of signals and equipment technical characteristics that are used. In the paper presented herein by Wojnar, three different types of criteria are discussed: station spacing, level-spacing, and output performance [2]. Wojnar also makes appropriate references to reports and recommendations on protection ratios, noise and receiver sensitivity, and voice measures that have appeared in the CCIR Green Books. Protection ratios also appear in other CCIR reports, e.g., Report 358-4 on protection ratios in the mobile services [3].

One example of a performance criterion is that based on listeners of radio receivers or radio operators. The criterion is developed from measures of voice transmission performance and is based on articulation index or articulation score. These terms are defined in the CCIR Report 526-1 [4]. Earlier studies on speech performance have been made by acoustics scientists [5]–[8].

The development of suitable criteria for radar systems is difficult because of the many different types of radars that are used in different applications such as aeronautical radionavigation, air defense, and meteorol-

ogy. Radars also have different types of displays and signal processing techniques some of which are designed to eliminate interfering signals. The paper included herein by Katz is one approach wherein the criteria are different scope conditions on the radar display [9]. Studies of interference in radar systems have also been conducted by Caprio [10], Aasen [11], Lustgarten and Grigg [12], Nichols [13], and Hinkle *et al.* [14]. The emission spectrum of the radar transmitter is often needed when conducting sharing analyses. For analysis purposes, the spectrum is very often synthesized from the parameters of the transmitted pulse, described in work by Regimbal [15], Newhouse [16], and CCIR Report 837 [17]. Interference rejection techniques in radar systems have been studied by Hinkle *et al.* [18] and the CCIR [19]. The Federal Government has developed a standard for radars that is applicable to many radar systems used by U.S. government agencies [20]. A major part of the government standard concerns the bounds on the emission of the transmitted spectrum.

Picture quality is the criteria used for the evaluation of degradation effects of interference to television signals. Picture quality is determined through subjective tests involving many people viewing the television picture. Much work on picture quality and testing was performed in the late 1950's by the Television Allocations Study Organization (TASO) [21]. The picture quality was divided into six levels: excellent, fine, passable, marginal, inferior, and unusable, and viewers were required to score the various pictures as the signal was disturbed by various levels of interference [22], [23]. Work on picture quality has also been done in Europe [24].

Coordination criteria for various services appear in the ITU Radio Regulations, the CCIR, the FCC Rules and Regulations, the NTIA Manual, and the regulations of various countries. Appendices 28 and 29 of the ITU Radio Regulations involve space systems and are examples of regulations that contain coordination criteria [25], [26]. Additional material on space system sharing can be found in Part 25 (Satellite Communication) of the FCC Rules and Regulations, and in volumes 2, 4/9-2, and 4-1 of the CCIR.

Sharing criteria for systems using data and analog modulations operating in the fixed service below about 30 MHz can be found in Volume 3 of the CCIR and in Volume 9 for systems above 30 MHz. The Electronic Industries Association (EIA) publishes a bulletin presenting carrier-to-interference ratios for microwave communication systems [27]. The latter is of interest to licensees and planners of microwave systems operating under Part 94 of the FCC Rules. The criteria presented in the EIA bulletin have also been successfully employed in the development of microwave networks in other bands besides those covered under Part 94.

There are many papers, reports, and regulations that deal with permissible interference levels and

sharing criteria. The previous discussion herein has presented only a few examples of where such criteria are published.

ADJACENT BAND OR CHANNEL

Some frequency bands are channelized in order to achieve an orderly frequency assignment process, thereby providing an optimum or near optimum use of that particular part of the spectrum. Channel plans are developed by taking into consideration such factors as modulation methods, transmitter emission spectra, receiver sensitivity and selectivity, and performance measures. The paper by Buesing is an example of developing channel separation in the land mobile services [28]. It was written during the transition period when land mobile channels were being spaced at 25 kHz from the previous 50 kHz. It is presented here because it is considered to be a classic paper that is still referenced by many. However, some of the terminology has changed since the late 1960's when the paper was developed. One example is Buesing's use of the "sliverband" that is now referred to as narrow-band FM.

EMC analyses of adjacent channel or adjacent band problems often rely on the factor "frequency dependent rejection," or FDR. FDR is important in the calculation of the total effective power accepted by a receiver and considers transmitter emission spectra, receiver selectivity, and the degree of "off tuning" between the transmitter and receiver. Although in widespread use in EMC analyses programs for many years, a definition in the open literature appeared in 1979 [29]. The CCIR has adopted the FDR method in Report 654-1 [30].

MODELS

Spectrum engineering problems are becoming increasingly complex as the number and different types of spectrum users increase. Spectrum engineering models serve to reduce the time required to solve such problems. A model may consist of a few graphs or equations or by a complex computer program including data bases, analysis models, and graphic output results. In many cases, models using large high-speed computers are the only way by which a very complex problem can be solved.

The paper by McMahon presented herein is an example of a land mobile model [31]. It includes factors such as antenna height, transmitter power, adjacent channels, intermodulation, and noise. Further information on land mobile modeling is presented in Pannell [32].

The paper by Northrup is included because it presents some basic equations used in modeling, also useful in general spectrum engineering analyses [33].

The CCIR has established Interim Working Party 1/2 to develop and publish a handbook on computer-aided techniques in spectrum management. Such a handbook has been published containing descriptions of engineering analysis techniques required for spectrum management. The handbook also contains a catalog of data files and computer programs and the points of contact where additional information can be obtained [34].

Models have been developed for many spectrum management problems. Computerized techniques are discussed in Part II, and their applications to propagation models are listed in the Propagation Bibliography in Appendix C. An additional bibliography of spectrum engineering models is presented herein.

PROPAGATION

The accurate determination of propagation path loss values is important to the spectrum engineer because in many cases it is the sole factor that will determine if harmful interference will occur or if desired coverage is achieved. Propagation path loss values are not always easily determined and in many cases such are extremely difficult requiring computer models and data bases. Indeed, the spectrum manager's task would be greatly alleviated if more precise and easier evaluations of path loss values could be made.

The papers by Bullington [35] and Egli [36] are considered to be classical, and were selected for inclusion herein. Extensive worldwide interest in land mobile communications has prompted the inclusion of the papers by Durkin [37] and Neham [38]. There have been many papers written on propagation. Appendix C is a listing of some of the more representative and widely referenced papers.

INTERMODULATION

There are situations where many frequencies are used by systems in close proximity to each other. Interference can occur via intermodulation products produced by mixing of the signals of two or more frequencies. Extensive research work has been undertaken in the development of intermodulation-free frequency lists. The paper by Edwards *et al.* is comprehensive and is included herein [39]. Other excellent papers are by Amin and Benson [40]; Babcock [41]; Chase *et al.* [42]; and Lustgarten [43].

NOISE

In some situations, particularly those involving site engineering, the frequency manager must take man-made noise sources into consideration in addition to other sources of interference. The portion of the spectrum or the location under consideration may be free of interference from conventional transmitters but noise from such devices as automobile ignitions, power

lines, railroad yards, or even pocket calculators may limit the performance of receivers. Natural phenomena such as atmospheric noise and lightning are also electromagnetic noise sources and should be taken into consideration in some cases. Vincent presents examples of the spectra of noise sources and other signals in his 1977 paper [44]. Additional information can be obtained from the works referenced in the Vincent paper, from Skomal [45], White [46], Herman [47], or from the various papers that have been published in the IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY. The IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY have contained 68 papers on natural noise, powerline noise, ignition noise, other noise sources, area surveys, and noise models from 1959–1983. An index of these is provided in note [48].

The C.I.S.P.R. has developed limits for the maximum radiation levels of some man-made devices [49]–[53]. (Refer to Part I and the paper by Jerzy Rutkowski for information on C.I.S.P.R.) In the United States, limits are presented in Part 15 of the FCC Rules and Regulations [54].

ANTENNAS

The directivity patterns of antennas are frequently the determining factors in frequency-sharing situations. This is particularly true in the microwave frequency bands where parabolic reflector types of antennas are in widespread use and in the medium wave broadcasting bands where directional arrays are employed. No antenna paper is presented herein because of the lack of a single paper covering the many types of antennas and frequency ranges used. Instead, a bibliography on antennas is presented.

One significant, recent development is the use of large high-speed computers in the development of precise antenna patterns. Many antennas have been modeled using the Numerical Electromagnetics Code (NEC) and compared with measurements with favorable results [55].

REFERENCES

- [1] W. I. Harada, "Techniques for implementing a frequency spectrum engineering system," *Telebras Rev.*, year VI, no. 4, Dec. 1982.
- [2] A. Wojnar, "Objective EMC criteria for radio systems: Do they exist?" presented at the Int. Symp. Electromagn. Compat., Wroclaw, Poland, 1980.
- [3] "Protection ratios and minimum field strengths required in the mobile services," Rep. 358-4, CCIR Green Book, Vol. 8, Mobile Services, XVth Plenary Assembly, Geneva, 1982.
- [4] "Measures of voice transmission performance applicable for electromagnetic compatibility analysis," Rep. 526-1, CCIR Green Book, Vol. 1, Spectrum Utilization and Monitoring, XVth Plenary Assembly, Geneva, 1982.
- [5] N. R. French and J. C. Steinberg, "Factors governing the intelligibility of speech sounds," *J. Acoust. Soc. Amer.*, vol. 19, no. 1, Jan. 1947.

- [6] G. A. Miller and J. C. R. Licklider, "The intelligibility of interrupted speech," *J. Acoust. Soc. Amer.*, vol. 22, no. 2, Mar. 1950.
- [7] K. D. Kryter, "Validation of the articulation index," *J. Acoust. Soc. Amer.*, vol. 34, no. 11, Nov. 1962.
- [8] —, "Methods for the calculation and use of the articulation index," *J. Acoust. Soc. Amer.*, vol. 34, no. 11, Nov. 1962.
- [9] L. Katz, "PPI interference prediction," *IEEE Trans. Electromagn. Compat.*, vol. 7, no. 2, June 1965.
- [10] S. J. Caprio, "The need for realistic susceptibility levels for radar receivers," *IEEE Trans. Electromagn. Compat.*, vol. EMC-21, no. 4, Nov. 1979.
- [11] M. D. Aasen, "Methods for predicting interference effects in tracking radars," *IEEE Trans. Electromagn. Compat.*, vol. 6, no. 3, October 1964.
- [12] M. N. Lustgarten and R. D. Grigg, "Effects of radar interference on search-radar operator performance," *IEEE Trans. Electromagn. Compat.*, vol. EMC-22, no. 4, Nov. 1980.
- [13] J. J. Nichols, Jr., "Cochannel interference analysis between spaceborne and terrestrial radars," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-14, no. 14, Sept. 1978.
- [14] R. L. Hinkle, R. M. Pratt, and J. S. Levy, "Radiodetermination spectrum utilization conservation," Conference Record, IEEE Nat. Telecommun. Conf., Washington, DC, Dec. 1979.
- [15] R. Regimbal, "A transmitter-spectrum synthesis technique for EMI prediction," *IEEE Trans. Electromagn. Compat.*, vol. 7, no. 2, June 1965.
- [16] P. D. Newhouse, "Bounds on the Spectrum of a CHIRP pulse," *IEEE Trans. Electromagn. Compat.*, vol. 15, no. 1, February 1973. (See also correction in vol. 15, no. 3, Aug. 1973.)
- [17] "Methods for calculating pulsed radar emission spectrum bandwidth," Rep. 837, CCIR Green Book, Vol. 1, Spectrum Utilization and Monitoring, XVth Plenary Assembly, Geneva, 1982.
- [18] See note [14].
- [19] "Efficient use of the radio spectrum by radar stations in the radiodetermination service," Rep. 914, CCIR Green Book, Vol. 8, Mobile Services, XVth Plenary Assembly, Geneva, 1982.
- [20] *Manual of Regulations and Procedures for Federal Radio Frequency Management*. Washington, DC: National Telecommunications and Information Administration, latest edition, ch. 5 (Tech. Standards).
- [21] G. R. Town, "The television allocations study organization—A summary of its objectives, organization and accomplishments," *Proc. IRE*, vol. 48, no. 6, June 1960.
- [22] G. L. Fredendall and W. L. Behrend, "Picture quality—Procedures for evaluating subjective effects of interference," *Proc. IRE*, vol. 48, no. 6, June 1960.
- [23] C. E. Dean, "Measurements of the subjective effects of interference in television reception," *Proc. IRE*, vol. 48, no. 6, June 1960.
- [24] K. Bernath, F. Kretz, and D. Wood, "The EBU method for organizing subjective tests of television picture quality," *EBU Rev.—Tech. Part*, no. 186, Apr. 1981.
- [25] Appendix 28, "Method for the determination of the coordination area around an earth station in frequency bands between 1 GHz and 40 GHz shared between space and terrestrial radiocommunication services," Radio Regulations, ITU, Geneva, 1982.
- [26] Appendix 29, "Method of calculation for determining if coordination is required between geostationary—Satellite networks sharing the same frequency bands," Radio Regulations, ITU, Geneva, 1982.
- [27] "Interference criteria for microwave systems in the private radio services," Bulletin 10-D, Electronic Industries Association, Washington, DC, 1983.
- [28] R. T. Buesing, "Modulation methods and channel separation in the land mobile services," *IEEE Trans. Veh. Technol.*, vol. VT-19, no. 2, May 1970.
- [29] W. Kuebler and S. Cameron, "The definition of frequency dependent rejection," *IEEE Trans. Electromagn. Compat.*, vol. EMC-21, no. 4, Nov. 1979.
- [30] "A method for calculating adjacent band interference," Rep. 654-1, CCIR Green Book, Vol. 1, Spectrum Utilization and Monitoring, XVth Plenary Assembly, Geneva, 1982.
- [31] J. H. McMahon, "Interference and propagation formulas and tables used in Federal Communications Spectrum Management Task Force land mobile frequency assignment model," *IEEE Trans. Veh. Technol.*, vol. VT-23, no. 4, Nov. 1974.
- [32] W. M. Pannell, *Frequency Engineering in Mobile Radio Bands*. London: Granta Technical Editions, 1979.
- [33] G. M. Northrup, "Aids for the gross design of satellite communications systems," *IEEE Trans. Commun. Technol.*, vol. COM-14, no. 1, Feb. 1966.
- [34] *Handbook—Spectrum Management and Computer-Aided Techniques*. Geneva: CCIR, 1983.
- [35] K. Bullington, "Radio propagation at frequencies above 30 megacycles," *Proc. IRE*, vol. 35, no. 10, Oct. 1947.
- [36] J. J. Egli, "Radio propagation above 40 MC over irregular terrain," *Proc. IRE*, vol. 45, no. 10, Oct. 1957.
- [37] J. Durkin, "Computer prediction of service areas for VHF and UHF land mobile radio services," *IEEE Trans. Veh. Technol.*, vol. VT-26, no. 4, Nov. 1977.
- [38] E. A. Neham, "An approach to estimating land mobile radio coverage," *IEEE Trans. Veh. Technol.*, vol. VT-23, no. 4, Nov. 1974.
- [39] R. Edwards, J. Durkin, and D. H. Green, "Selection of intermodulation-free frequencies for multiple-channel mobile radio systems," *Proc. IEE*, (London), vol. 116, no. 8, Aug. 1969.
- [40] M. B. Amin and F. A. Benson, "Coaxial cables as sources of intermodulation interference at microwave frequencies," *IEEE Trans. Electromagn. Compat.*, vol. EMC-20, no. 3, Aug. 1978.
- [41] W. C. Babcock, "Intermodulation interference in radio systems," *Bell Syst. Tech. J.*, vol. 32, no. 1, Jan. 1953.
- [42] W. M. Chase, J. W. Rockway, and G. C. Salisbury, "A method of detecting significant sources of intermodulation interference," *IEEE Trans. Electromagn. Compat.*, vol. EMC-17, no. 2, May 1975.
- [43] M. Lustgarten, "A method of computing intermodulation free frequency lists," IEEE Electromagn. Compat. Symp. Record, Seattle, WA, 1968.
- [44] W. R. Vincent, "Examples of signals and noise in the radio-frequency spectrum," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Aug. 1977.
- [45] E. N. Skomal, *Man-Made Radio Noise*. New York, NY: Van Nostrand, 1978.
- [46] D. R. J. White, *Electrical Noise and EMI Specifications*. Gainesville, VA: Don White Consultants, Inc., 1981.
- [47] J. R. Herman, *Electromagnetic Ambients and Man-Made Noise*. Gainesville, VA: Don White Consultants, Inc., 1979.
- [48] EMC Society Silver Anniversary Issue, *IEEE Trans. Electromagn. Compat.* Part I, vol. EMC-25, no. 3, Aug. 1983.
- [49] C.I.S.P.R. 11, "Limits and methods of measurement of radio interference characteristics of industrial, scientific and medical (ISM) radio-frequency equipment (excluding surgical diathermy apparatus)," Int. Electrotechnical Commission, Geneva, Switzerland, 1975. (See also Amendment No. 1 (1976) and C.I.S.P.R. 11A, First Supplement.)
- [50] C.I.S.P.R. 12, "Limits and methods of measurement of radio interference characteristics of vehicles, motor boats, and spark ignited engine-driven devices," Int. Electrotechnical Commission, Geneva, Switzerland, 1978.
- [51] C.I.S.P.R. 13, "Limits and methods of measurement of radio interference characteristics of sound and television receivers," Int. Electrotechnical Commission, Geneva, Switzerland, 1975.
- [52] C.I.S.P.R. 14, "Limits and methods of measurements of radio interference characteristics of household electrical appliances,

portable tools and similar electrical apparatus," Int. Electrotechnical Commission, Geneva, Switzerland, 1975. (See also Amendment No. 1 (1980).)

- [53] C.I.S.P.R. 15, "Limits and methods of measurement of radio interference characteristics of fluorescent lamps and luminaires," Int. Electrotechnical Commission, Geneva, Switzerland, 1981.
- [54] "Radio frequency devices," Part 15, Rules and Regulations, Federal Communications Commission, Washington, DC, 1984.
- [55] G. J. Burke, "The numerical electromagnetics code (NEC)," in *Application of the Method of Moments to Electromagnetic Fields*, B. J. Strait, Ed. Kisamee, FL: Southern Center for Electrical Engineering Education (SCEEE) Press, 1980.

BIBLIOGRAPHY OF SPECTRUM ENGINEERING MODELS

- [1] A. T. Adams and B. J. Strait, "Modern analysis methods for EMC," in *Proc. 1970 Symp. Electromagn. Compat.*, Anaheim, CA, July 1970.
- [2] T. E. Baldwin *et al.*, "Intrasystem analysis program (IAP) model improvement," Rome Air Development Center, RADC-TR-82-20, Dec. 1981.
- [3] R. J. Balestri, T. R. Ferguson, and E. R. Anderson, "General electromagnetic model for the analysis of complex systems," Rome Air Development Center, RADC-TR-77-137, Apr. 1977.
- [4] L. Beall *et al.*, "An automated FAA frequency assignment system," Rep. FAA-RD-73-184, Federal Aviation Administration, Washington, DC, Dec. 1973.
- [5] D. J. Ben, W. Segal, and W. Waszkis, "Model of topographical environment of VHF/UHF broadcasting systems," presented at the 5th Symp. Electromagn. Compat., Wroclaw, Poland, Sept. 1980.
- [6] J. L. Bogdanor, R. A. Pearlman, and M. D. Siegel, "Intrasystem electromagnetic compatibility analysis program," Rome Air Development Center, RADC-TR-74-342, Dec. 1974.
- [7] S. A. Cohen, "Interference effect of pseudo-random frequency-hopping signals," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-7, no. 2, Mar. 1971.
- [8] W. G. Duff and W. P. Seneker, "Radar EMI to voice communication receivers," Int. Electromagn. Compat. Symp. Record, IEEE, Arlington Heights, IL, July 1972.
- [9] A. H. Feller, "The role of an electromagnetic environment model in spectrum management," presented at the IEEE Veh. Tech. Conf., Washington, DC, Apr. 1981.
- [10] G. Groschel, "A mathematical model for the calculation of the adjacent-channel interference in single-sideband and double-sideband AM sound-broadcasting systems," *EBU Rev. — Tech. Part*, no. 169, June 1978.
- [11] A. L. Hiebert and S. A. Scharff, "An electromagnetic compatibility program for the 1970's (selected issues)," Rep. R-1114/1-PR, Rand Corp., Santa Monica, CA, Aug. 1974.
- [12] A. L. Hiebert, "An intrasystem analysis program (IAP): Appendix to R-1114/1-PR," Rep. R-1690/1-PR, Rand Corp., Santa Monica, CA, July 1975.
- [13] A. Ishimaru, "A statistical model of electromagnetic interference," presented at the 1980 IEEE Int. Symp. Electromagn. Compat., Baltimore, MD, 1980.
- [14] G. S. Kalagian, "VHF-TV channel assignment program (VCAP)," Rep. RS-74-01, Federal Communications Commission, Aug. 1974.
- [15] —, "UHF-TV channel assignment program (UCAP)," Rep. RS-75-02, Federal Communications Commission, Mar. 1975.
- [16] M. Lustgarten, "COSAM (co-site analysis model)," *Electromagn. Compat. Symp. Record*, Anaheim, CA, IEEE, July 1970.
- [17] M. N. Lustgarten and D. J. Hughes, "Co-site analysis model (COSAM) validation," Int. Electromagn. Compat. Symp. Record, IEEE, Arlington Heights, IL, July 1972.
- [18] A. S. May and M. J. Pagones, "Model for computation of interference to radio-relay systems from geostationary satel-

lite," *Bell Syst. Tech. J.*, vol. 50, no. 1, Jan. 1971.

- [19] D. A. Miller, Ed., "Final report of ad hoc committee on an electromagnetic compatibility figure of merit (EMC FOM) for single-channel voice communications equipment," *IEEE Trans. Electromagn. Compat.*, vol. EMC-17, no. 1, Feb. 1975.
- [20] D. Parreaux, "A graphical method of determining protection ratios in the case of LF and MF amplitude-modulated transmissions," *EBU Rev. — Tech. Part*, no. 134, Aug. 1972.
- [21] G. Petke, "Determination, by calculation, of the RF protection ratio for AM transmission systems," *EBU Rev. — Tech. Part*, no. 141, Oct. 1973.
- [22] F. M. Prout, L. E. Polisky, and J. J. Oliva, "Empirical formula for the prediction of near field antenna coupling," presented at the IEEE Symp. Electromagn. Compat., Seattle, WA, July 1968.
- [23] A. Rosen, D. Leung, and M. Maiuzzo, "Nonlinear communications receiver model," presented at the 1980 IEEE Int. Symp. Electromagn. Compat., Baltimore, MD, 1980.
- [24] D. B. Sailors, "Estimation of the mean and standard deviation from quantities in interference modeling," presented at the 1980 IEEE Int. Symp. Electromagn. Compat., Baltimore, MD, 1980.
- [25] K. R. Siarkiewicz, "An introduction to the general electromagnetic model for the analysis of complex systems (GEMACS)," Rome Air Development Center, RADC-TR-78-181, Sept. 1978.
- [26] J. F. Spina *et al.*, "Nonlinear circuit analysis program (NCAP) documentation (engineering manual)," Rome Air Development Center, RADC-TR-79-245, 1979.
- [27] P. G. Tremper and G. L. Stanford, "AM analysis model," presented at the 1980 Int. Symp. Electromagn. Compat., Baltimore, MD, 1980.
- [28] J. B. Valente and S. Stratakis, "Nonlinear circuit analysis program (NCAP)(users manual and computer programmers manual)," Rome Air Development Center, RADC-TR-79-245, 1979.

ANTENNA BIBLIOGRAPHY

General

- [1] J. B. Anderson and F. Hansen, "Antennas for VHF/UHF personal radio: A theoretical and experimental study of characteristics and performance," *IEEE Trans. Veh. Technol.*, vol. VT-26, No. 4, Nov. 1977.
- [2] *The ARRL Antenna Book*, 14th ed. Newington, CT: American Radio Relay League, 1983.
- [3] D. Bensoussan, *Les Antennes*. Paris: Dunod, 1980.
- [4] CCIR, *Antenna Diagrams*, International Telecommunication Union, Geneva, Switzerland, 1978.
- [5] F. L. Cain, C. E. Ryan, and B. J. Cowan, "Prediction of Near-Field Antenna Coupling in the Presence of Obstacles," Int. Electromagn. Compat. Symp. Record, IEEE, Arlington Heights, IL, July 1972.
- [6] H. E. Gihring, "Antennas for television broadcast," in *National Association of Broadcasters Engineering Handbook*, G. W. Bartlett, Ed. Washington, DC: Nat. Assoc. of Broadcasters, 1975, ch. 14.
- [7] O. Harris and P. Blevins, "Making right 800-MHz antenna choice requires analysis for top performance," *Commun. News*, vol. 20, no. 6, June 1983.
- [8] H. Jasik and R. C. Johnson, *Antenna Engineering Handbook*, 2nd ed. New York: McGraw Hill, 1984.
- [9] E. A. Laport, *Radio Antenna Engineering*. New York: McGraw-Hill, 1952.
- [10] M. Massucci, "Plotting transmitting-aerial radiation patterns by means of a helicopter," *EBU Rev. — Tech. Part*, no. 173, Feb. 1979.
- [11] P. K. Onnigian, "Antennas for FM broadcasting," in *National Association of Broadcasters Engineering Handbook*, G. W. Bartlett, Ed. Washington: Nat. Assoc. of Broadcasters, 1975, ch. 13.

- [12] C. E. Smith, "Standard Broadcast antenna systems," in *National Association of Broadcasters Engineering Handbook*, G. W. Bartlett, Ed. Washington: Nat. Assoc. of Broadcasters, 1975, ch. 9.
- [13] K. Takao and K. Korniyama, "An adaptive antenna for rejection of wideband interference," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-16, no. 7, July 1980.
- [14] G. A. Thiele, "Wire antennas," in *Computer Techniques for Electromagnetics*, R. Mittra, Ed. New York: Pergamon Press, 1973.
- [15] D. J. Torrieri, *Principles of Military Communication Systems* (Chapter 5, Adaptive Antenna Systems). Dedham, MA: Artech House, 1981.
- [16] B. Widrow, P. E. Mantey, L. J. Griffiths, and B. B. Goode, "Adaptive antenna systems," *Proc. IEEE*, vol. 55, no. 12, Dec. 1967.
- Aperture, Satellite, and Microwave Communications**
- [17] F. Carmassi, "Calculation of optimum transmitting antennae for a satellite broadcasting service," *EBU Rev. — Tech. Part*, no. 171, Oct. 1978.
- [18] P. J. B. Claricoats and G. T. Poulton, "High-efficiency microwave reflector antennas—A review," *Proc. IEEE*, vol. 65, no. 10, Oct. 1977.
- [19] A. Dion and L. Ricardi, "A variable coverage satellite antenna system," *Proc. IEEE*, vol. 59, no. 2, Feb. 1971.
- [20] D. F. DiFonzo, W. S. Trachtman, and A. E. Williams, "Adaptive polarization control for satellite frequency reuse systems," *COMSAT Tech. Rev.*, vol. 6, no. 2, Fall 1976.
- [21] A. Farrar and A. T. Adams, "An improved model for calculating the near field power densities of aperture antennas," 1980 IEEE Int. Symp. Electromagn. Compat., Baltimore, MD, 1980.
- [22] A. B. Harris, B. Claydon, and K. M. Keen, "Reducing the sidelobes of earth-station antennas," Conference Record, Int. Conf. Commun., Boston, MA, June 1974.
- [23] P. R. Karmel, "Statistical properties of antenna sidelobes," *COMSAT Tech. Rev.*, vol. 9, no. 1, Spring 1979.
- [24] E. W. Matthews, W. G. Scott, and C. C. Han, "Advances in multibeam satellite antenna technology," Conference Record, EASCON, Washington, DC, Sept. 1976.
- [25] R. Mittra, W. A. Imbriole, and E. J. Maanders, Eds., *Satellite Communication Antenna Technology*. Amsterdam: Elsevier Science Publishers, 1983.
- [26] T. T. Taylor, "Design of circular apertures for narrow beamwidth and low side-lobes," *IRE Trans. Antennas Propagat.*, vol. AP-8, no. 1, Jan. 1960.
- [27] L. C. Tillotson, "A model of a domestic satellite communication system," *Bell Syst. Tech. J.*, vol. 47, no. 10, Dec. 1968.
- [28] M. Shinji *et al.*, "Shaped beam horn-reflector antenna for domestic communication satellite," *Trans. Inst. Electron. Comm. Eng.*, Japan, vol. 57-B, June 1974.
- [29] I. P. Shkarofsky and H. J. Moody, "Performance characteristics of antennae for direct broadcasting satellite systems including effects of rain depolarization," *RCA Rev.*, vol. 37, no. 3, Sept. 1976.
- [30] M. J. Gans, "Cross-polarization in reflector-type beam waveguides and antennas," *Bell Syst. Tech. J.*, vol. 55, no. 3, Mar. 1976.
- [31] P. L. Rice, "Idealized pencil-beam antenna patterns for use in interference studies," *IEEE Trans. Commun. Technol.*, vol. 18, no. 2, Feb. 1970.
- [32] "Special issue on adaptive antennas," *IEEE Trans. Antennas Propagat.*, vol. AP-24, no. 5, Sept. 1976.
- [33] R. H. Turrin, "A multibeam, spherical-reflector satellite antenna for the 20- and 30- GHz bands," *Bell Syst. Tech. J.*, vol. 54, no. 4, July-Aug. 1975.

Antenna Reports from CCIR Green Books (1982)

Report	Title	Green Book Volume
32-4	Transmitting antennas in HF broadcasting	X-1
106-1	Improvement obtainable from the use of directional antennas	III
107-1	Directivity of antennas at great distances	III
301-3	Transmitting antennas for sound broadcasting in the tropical zone	X-1
327-3	Diversity reception	III
356-2	Use of directional antennas in the bands 4 to 28 MHz	III
390-4	Earth-station antennas for the fixed-satellite services	IV-1
391-4	Radiation diagrams of antennas for earth stations in the fixed-satellite service for use in interference studies and for the determination of a design objective	IV-1
393-3	Intersections of radio-relay antenna beams with orbits used by space stations in the fixed-satellite service	IV/IX-2
401-4	Transmitting antennas in LF and MF broadcasting	X-1
554-2	The use of a transportable earth station with a small antenna for relief operation in the event of natural disasters and similar emergencies	IV-1
555-2	Discrimination by means of orthogonal circular and linear polarizations	IV-1
558-2	Satellite antenna patterns in the fixed-satellite service	IV-1
614-2	Reference radiation patterns for radio-relay system antennas	IX-1
675	Radiation diagrams of antennae at space research earth stations for use in interference studies	II
676	Shaped beam antennae	II
677-1	Low side-lobe antennae for space research earth stations	II
709-1	Consideration of the coupling between an earth-station antenna and a terrestrial link antenna	IV-1
810-1	Broadcasting-satellite service (sound and television)—reference patterns and technology for transmitting and receiving antennas	X/XI-2
868	Contributions to the noise temperature of an earth-station receiving antenna	IV-1
921	System aspects of low G/T ship earth stations	VIII
922	Reference radiation pattern for ship earth station antennas	VIII
925	Factors affecting the choice of antennas for mobile stations of the land mobile-satellite service	VIII

Antenna Recommendations from CCIR Green Books (1982)

Recommendation	Title	Green Book Volume
80-1	Directional antennas in HF broadcasting	X-1
139-1	Transmitting antennas for sound broadcasting in the tropical zone	X-1
140-1	Receiving antennas for sound-broadcasting reception in the tropical zone	X-1
162-2	Use of directional antennas in the bands 4 to 28 MHz	III
414	Presentation of antenna diagrams	X-1
419	Directivity of antennas in the reception of broadcast sound and television	XI-1
465-1	Reference earth-station radiation pattern for use in coordination and interference assessment in the frequency range from 2 to about 10 GHz	IV-1
509	Generalized space research earth station antenna radiation pattern for use in interference calculations, including coordination procedures	II
580	Radiation diagrams for use as design objectives for antennas of earth stations operating with geostationary satellites	IV-1

Techniques for Implementing a Frequency Spectrum Engineering System

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The present article is aimed at elucidating some of the main topics related to implementing a frequency spectrum engineering system at national level.

Electromagnetic compatibility techniques and the respective interference and propagation forecast models are approached. Information on the importance of the propagation medium for radio waves in utilizing and allocating frequencies are displayed, which serve to orient the working out of basic propagation formulae for the mathematical models. The characteristics of an automatized data base in a spectrum management system are pointed out, mainly in what regards the aspect of contained information, filing management and processing of information. Finally, suggestions and recommendations are displayed for the technical detailing and implementation of a spectrum engineering system.

1. INTRODUCTION

The Nation has been growingly needing services involving the use of the radioelectric spectrum.

The frequency spectrum is a limited natural resource, and limitations in the management of the spectrum resource may render more difficult, in the near future, its effective utilization.

Whereas some of these limitations are caused by spectrum management decisions, others are partially due to limitations in the present technical capacities, which serve as support to the spectrum management.

If such capacities are improved, it is possible that a more complete and rational use of the spectrum is attained.

Within the spectrum management philosophy outlined in the article "Model of a Frequency Spectrum Engineering System at National Level", of the same author of the present article, theoretical and practical technical bases for implementing a Spectrum Engineering System, as well as suggestions and recommendations, are displayed.

Throughout the said article it is insistently highlighted how advantageous it is to have an Automatized System for the Spectrum Management.

Is it really necessary to automatize a general data base and a system for processing information and for technical analyses in a spectrum management system?

An argument against such may be the fact that the present system is extensively operated through a manual process, which is likely to become more effective through some rearrangements in the procedures and records.

Although this is probably true, the significant frailty of the present spectrum management operations, which cannot be improved through rearrangements or renovations of the manual operations, is due to the lack of a definable system.

Since it is of the public interest to provide the agencies in charge of such operations with tools which allow an effective control of the whole area of spectrum management, the answer to the question as to whether a spectrum engineering system and a spectrum management should be automatized, as well as the respective systems of data

base, management and processing of information, must be, without a shadow of a doubt, *affirmative*.

As an example of how urgent it is to effectively automate the functions of spectrum management, the spectrum occupancy in the VHF, UHF and SHF bands in the metropolitan area of São Paulo, which reaches levels close to saturation, may be cited.

The sequence of the matters discussed in the present article is as follows:

Initially, information is displayed which point out how important the propagation characteristics of radio waves in the utilization and allocation of frequencies are, and which serve to orient the working out of the required propagation basic formulae for elaborating mathematical models aimed at forecasting radiopropagation and interferences, since it is essential to surely know the propagation characteristic of the electromagnetic waves in order that the spectrum resource is optimally used.

Since it is impossible to completely separate the propagation characteristics which influence the spectrum utilization from the characteristics of the antennae and of the transmitting and receiving equipment, these factors are also discussed according to their effect in their radiocommunication functions.

In the following items, comments are displayed on the technical analysis of electromagnetic compatibility, as well as a description of the main mathematical models used in a spectrum engineering system, such as propagation forecast models, interference forecast models, models for analyzing equipment and models for gathering topographic data.

Proceedingly, the conceptualization of a computerized data base in a spectrum engineering system is displayed in detail, including its creation, maintenance and operation. Within such structure, specific project considerations on the data base specifications are discussed.

The reason which leads at to approach in detail the DATA BASE subject is the fact that the spinal cord of a spectrum engineering system is its data base, which may include accessible computer data, data in physical files, catalogs of manufacturers and a library of reference documents.

Due to the great mass of data involved, the automated data base in computer represents one of the most important factors for optimizing the use of the radioelectric spectrum.

Radio monitoring and the need for carrying out a pilot project are discussed in the subsequent chapters, and as a conclusion to the article, recommendations for implanting a spectrum engineering system are displayed, as well as suggestions on its technical detailing, when it is implemented.

2. TECHNICAL FACTORS REGARDING PROPAGATION AND TRANSMISSION IN UTILIZING THE RADIOFREQUENCY SPECTRUM

The medium through which the electromagnetic waves are propagated between the transmission and reception points strongly influence the operation of radiocommunication systems.

Aiming at attaining an optimum utilization of the frequency spectrum, that is, accommodating a maximum number of users in a limited spectrum of usable frequencies, it is essential to know the propagation characteristics of the radioelectric waves.

The information displayed is aimed at highlighting the importance of the radio waves' propagation characteristics in the utilization and allocation of frequencies, and they serve as a general guidance for working out the required basic propagation formulae for constructing radio propagation forecast mathematical models.

It is impossible to completely separate the propagation characteristics which influence the spectrum utilization from the equipment characteristics. Antennae and the transmitting and receiving equipment also play important roles, and therefore each of these factors is discussed according to their effects, in their radiocommunication functions.

2.1. GENERAL CHARACTERISTICS OF RADIOCOMMUNICATION SYSTEMS

A typical communication circuit basically involves the function of transmitting informations from one location to another.

A communication circuit performance measure involves the volume of information which can be transmitted during a certain period of time, as well as the capacity to faithfully reproduce in the output the same information introduced in the input. Such information can be digital or analog, in several forms.

In the concept of a communication circuit having a radioelectric propagation path, the original message is introduced in the transmission system, in which it is modulated and transformed in RF signals and broadcasted through the transmitting antenna.

The receiving antenna picks up an infinitesimal portion of the broadcasted power, as well as undesirable radiations from many interference sources.

The receiver itself contributes with its thermal noise. In the receiver's output, the signal containing the desired information must have enough power, in relation to the total amount of undesirable signals and noise, to make possible a satisfactorily faithful reproduction of the original message.

There are many sources of interferences and RF noises. Some of them can be controlled, from the standpoint of an appropriate receiver design and/or location, and others are probably present in all cases.

During the planning and installation phases of the radiocommunication systems, serious problems are encountered regarding selection of locations, choice of frequencies and in determining the necessary types of terminal equipment to comply with the specified communication requirements. It is important to distinguish equipment performance from system performance. The latter includes equipment performance and the path's propagation characteristics.

It is of the utmost importance for the radioelectric systems' engineering that reliable radiopropagation forecast theoretical models are developed, as the practical measures of radiowave propagation usually take a lot of time and require expensive equipment. For such, a program for measures of wide proportions would be required, in order that appropriate statistical samples are obtained for all the set of variables which influence the radiopropagation medium formed by the earth's surface and the surrounding atmosphere.

In telecommunications, the problem of suiting the radiopropagation data is strengthened by the fact that the planning must take into consideration the worst communication conditions, which take place in relatively short periods of time, as compared to the median conditions.

Similarly, the problem of an optimum frequency allocation is structured through a more complex approach, due to the possibility of an intermittent occurrence of high propagation modes (even if these are of short duration) and associated increase in the interference potential.

A reliable theoretical model of the propagation mechanism, duly circumscribed in terms of its physical validity for certain types and application bands, such as the frequency band, the distance range, assumed properties for the medium, etc., is a potentially useful tool, provided that within the limits of its applicability it renders unnecessary the extensive practical measures.

On the other hand, through the feasibility of the transmitters' power increase, larger antennae, more extended bandwidths, more sensitive receiving devices, higher frequencies, etc., propagation modes which were neglected or unknown before in the theoretical foundations were discovered, which demonstrated how valuable the experimental measures can be as a support to the development of theoretical models which are more faithful to the properties and characteristics of the propagation medium.

The concept of service probability (and, extensively, reliability and availability) is extremely useful for formulating the several available alternatives in a radiocommunication project. It represents the probability of obtaining a service of a certain quality during a specific percentage of one year's hours. Such concept supplies an objective way for balancing the success probabilities against the installation and operation costs. Basically, it takes into account all uncertainties in a statistical sense, analyzing the probabilities of success with the several assumptions related to equipment and frequencies to be used. For in-

stance, it is important to be able to calculate the success probability increase if the transmitter power is increased in a certain portion of the circuit. This can be directly measured in terms of service probability.

Propagation factors, in addition to those related to the system's loss, must be considered in a study on service probability. The improvement which can be obtained diversifying transmission and reception depends on the degree of similarity (correlation) in the occurrence of simultaneous fading in the propagation paths, separated by space or frequency, or with different polarizations. As the modulation bandwidths are increased, the selective fading becomes more problematic.

Before any useful propagation forecast formula can be established, the fundamental propagation mechanisms must be meticulously understood and appropriate propagation models must be postulated. Even if there is a vast amount of data showing the attenuations measured on almost any conceivable type of propagation path, any effort to develop a completely empirical forecast method based only on these data, without referring to the causes and effects of the specific factors, would be of little significance. Quantitative propagation forecasts are largely based on theoretical models, which on their turn describe the mechanisms and are useful for the mathematical treatment. Once the form of the several factors is duly determined, the data become useful to determine the empirical constants.

The quantity of transmitted energy which truly reaches a receiver through a propagation path depends on several factors. One of the most important factors is the propagation mode or combination of propagation modes which predominate in the path. In estimating the performance of telecommunication systems, it is important to identify which is the predominant mechanism in order to work out a reliable forecast of the system's loss and its variations.

The medium through which the waves propagate has characteristics which highly depend on the frequency. Equipment components are also highly dependent on the frequency as to their operation. Further, the amount of information which can be transmitted on a radiocommunication circuit fundamentally depends, among other factors, on the frequency in which the circuit is operated. Such frequency dependence of electromagnetic waves in radiocommunication operations results in a logical treatment or the several portions of the radiofrequency spectrum in different modes, depending on the dominant propagation phenomena in the frequency band in question. Using the propagation characteristics as criterion for dividing the spectrum, certain logical frequency bands result.

The useful frequencies for radiocommunications are between 10 kHz and 300 GHz. Below 10 kHz, components become too expensive, particularly antennae. Further, the width of the utilizable band in such frequencies greatly limits the information transmission rates. The upper utilizable limit results from the signal absorption by the several atmospheric components. The recent develop-

ment of masers and lasers which are capable of producing signals consistent with very high power densities in the region above 300 GHz and in the region of visible and almost visible light of the spectrum, propitiated the opening of this portion of the spectrum for certain radiocommunication applications. Since this portion of the spectrum can contain around 10,000 times the bandwidth of a now existing SHF system, its development and utilization become attractive. The planning of allocations within these bands should be accomplished as quickly as the technical progress being attained.

2.2. TRANSMISSION SYSTEMS

The characteristics of the radiocommunication transmission systems are important factors for an effective utilization of the radioelectric spectrum. In order to transmit information it is necessary to modulate the fundamental frequency of the transmitter's operation. Independently of whether the modulation is analog or digital, or if the modulation employed is related to amplitude, phase, frequency or if it is of other type, the output signal will contain several frequency components, other than the fundamental.

In designating the bandwidth for a radiocommunication service, it is utmost important to know the necessary bandwidth of the emission. Emissions out of the necessary band, that is, spurious emissions, may produce interferences in other channels, resulting in degradation of the performance or in the need for safety bands against interferences, which results in a non optimum use of the spectrum. Working on the modulated signal to minimize spurious emissions and/or filtering the transmitter's output to reduce emissions out of the necessary bandpass, are important aspects in optimizing the spectrum utilization. Since the transmission power for a certain transmitter consequently determines the power level of the spurious emissions, ideally the power should not be greater than

the required one, in order to provide the set service level for the particular radiocommunication circuit.

As it becomes harder to obtain spectrum space, new techniques which allow transmission of a same information in a more narrow frequency band must be used. A typical example was the DSB — double side band — amplitude modulation which was widely used, even though at the time it was used it was known that the same information could be transmitted in only one of the side bands, which occupies approximately half of the band. Economic considerations have always prevailed and frequently determined delays in the utilization of the state of the art. However, the growing demand and the saturation of the radioelectric spectrum determined that measures were taken aimed at optimizing the spectrum, and within the present example, the economic solution was to use amplitude modulation using only one of the side bands (SSB — single-side band).

2.3. CHARACTERISTIC PARAMETERS AND PROPAGATION MECHANISMS

2.3.1. NOMENCLATURE OF THE FREQUENCY BANDS

The several frequency bands commonly used are represented by abbreviations or expressions. Such nomenclatures are displayed in Table I.

2.3.2. PROPAGATION MECHANISMS

Radio waves propagate from the transmission point to the reception point through the earth, along the earth's surface, through the atmosphere, through reflection and wave scatter of the ionosphere or man-made or natural reflectors, within or above the atmosphere.

FREQUENCY BANDS						
FREQUENCY BANDS	WAVE LENGTH RANGE	METRIC SUBDIVISION	ABBREVIATURE	DESIGNATION	USUAL NAME	
3 — 30kHz	100 — 10 km	myriametric	VLF	very low frequency	very long waves	
30 — 300kHz	10 — 1 km	kilometric	LF	low frequency	long waves	
300 — 3000kHz	1000 — 100 m	hectometric	MF	medium frequency	medium waves	
3 — 30 MHz	100 — 10 m	decametric	HF	high frequency	short waves	
30 — 300 MHz	10 — 1 m	metric	VHF	very high frequency	very short waves	
300 — 3000 MHz	100 — 10 cm	decimetric	UHF	ultra high frequency	ultrashort waves	
3 — 30 GHz	10 — 1 cm	centimetric	SHF	super high frequency	microwaves (also upper UHF)	
30 — 300 GHz	10 — 1 mm	milimetric	EHF	extremely high frequency	microwaves	
300 — 3000 GHz	1 — 0.1 mm	decimilimetric	—	—	—	

TABLE I — Nomenclature of the frequency bands

The particular propagation mechanism to be used by a radiocommunication system will depend on several factors, such as the type of information with which the service is to deal and its performance or required service level, geographical and economic considerations and availability of frequencies.

a) (Soil) Surface Waves

The conductivity and dielectric constant of the soil greatly vary as compared to those of the atmosphere. The attenuation to which a radio wave is subject as it propagates along the soil surface depends on the type of soil, and it grows as the frequency increases.

In VLF frequencies, the soil waves can propagate with low propagation loss for distances of thousands of kilometers. In HF frequencies great propagation losses in surface waves are observed, and the useful signals of such waves can only be received for distances of a few hundreds of kilometers. Above the HF frequencies, the propagation of surface waves is frequently of no importance due to the limitation produced by soil losses and the predominance of tropospheric waves.

Certain radiocommunication systems, such as underground or underwater systems, use the soil penetration characteristics of VLF and LF radio waves. The propagation loss of such waves on the earth's surface depends on the dielectric characteristics of the soil, and it is lower in high conductivity paths, such as sea water. Since the horizontally polarized soil waves are highly attenuated, the propagation of these waves is usually limited to those which are vertically polarized.

In the MF and HF bands, deep fadings may occur in the received signals, where the wave amplitudes through the soil and the ionosphere have magnitudes of the same order. The phase of the ionospheric wave signal changes continually, in such a way that it may stay in phase or in phase opposition to the soil wave.

b) Tropospheric Waves

The lowest atmospheric region, that is, the troposphere and the stratosphere, extends at approximately 80 km from the soil, and it is the main medium for radio waves propagation in the VHF and higher frequencies. Below the VHF band, the effects of the lowest atmospheric region are secondary as compared to other effects influencing the propagation. The refraction index of the atmosphere is a preponderant factor which rules the propagation characteristics in VHF and higher frequencies.

Both variants, space and time, depend on the temperature, density and water vapor content of the atmosphere. Non homogeneities in the form of the layers, which are usually horizontal stratifications, may produce transmission ducts that can substantially increase the transmission capacities or produce an almost complete reduction of the

signal by confining the energy out of the receiving antenna's reach. For frequencies comprised between 100 MHz and some GHz, the radio wave scatter due to the non homogeneity in the atmosphere can be used to provide communication services for distances above several times the line-of-sight distance (tropospheric wave scatter).

Variations in the atmospheric structure time can produce both fast (in the order of a few seconds) and slow (in the order of hours or days) variations in the propagation loss. For frequencies of 30 GHz and above, absorption in the atmosphere fastly grows. Frequencies close to that of resonance of elements constituting the atmosphere along the propagation path can be highly attenuated. Due to the high absorption in frequencies above 30 GHz, such frequency spectrum region is still used in small scale for radiocommunication purposes.

There are reliable theoretical models aimed at forecasting the performance of tropospheric radiocommunication systems, which were compared and approved by the practical results of measures as they were being developed. It is possible to forecast an expected performance of a system using tropospheric propagation, by means of only our present knowledge, if certain information on the transmission path are available.

The transmission loss of signals propagating through the troposphere display daily and seasonal variations, as well as fast (short period) fadings. The tropospheric transmission, as expected, also depends on geographical and atmospheric factors. In certain areas, the duct is a regular occurrence, whereas in other areas such phenomenon rarely takes place.

c) Ionospheric Waves

The ionosphere is the region in the atmosphere located at 60 to 500 km above the earth's surface, even though occasionally there may occur considerable ionizations below 60 km and above 500 km. Ionization is produced by the sun radiation action. The four main layers, from the lowest upwards, are referred to as D, E, F₁, and F₂. Ionization density in such layers usually increases with height.

The presence of ionization deeply affects the propagation of radio waves up to around 30 MHz. The upper frequency, which may be identified as the higher frequency of a radio wave from a transmitter located on the earth's surface, capable of being transmitted through the ionosphere (MUF), depends on the maximum ionization density, which on its turn considerably varies according to one day's hours, season, number of sunspots and geographical location (mainly latitude). The greater the frequency, the greater the wave penetration in the ionosphere, before the reflection takes place. Therefore, greater frequencies tend to be reflected by higher layers, while lower frequencies by lower layers.

In frequencies above 100 MHz, the ionosphere is relatively of little importance. The present earth com-

munication systems using frequencies above 100 MHz are almost wholly limited to propagation in the troposphere.

2.3.3. PROPAGATION PARAMETERS

Any information-containing signal has a spectrum and a bandwidth associated to it.

Due to the fact that many propagation media do not allow propagation of all spectrum components of a signal in the same manner, the received signal is a distorted version of the transmitted signal.

The intensity of the distortion to which a signal having a certain bandwidth is subject, greatly depends on the path and type of the propagation medium: a signal transmitted via ionosphere is frequently subject to a greater distortion as compared to the same signal transmitted on a line-of-sight microwave path. Usually, the greater the spectrum bandwidth is, the greater the distortion to which the signal is subject. Due to the fact that distortion increases with the signal's bandwidth, it is convenient to know the "medium" has a bandwidth or a bandwidth limitation. However, such bandwidth definition is arbitrary.

A propagation medium can distort a signal in two ways: by changing the relative amplitude of the signal's spectrum components and by changing their relative phases.

It is pertinent to consider the physical characteristics of the propagation medium which causes amplitude and phase distortion in the signals, since the measures and calculations of such characteristics can directly and indirectly determine the bandwidth. The main physical characteristics that can distort a signal are the multipath propagations, and to a lesser extent the absorption and dispersion of the electromagnetic waves.

The effect caused by the multipath propagation bandwidth limitation may be described considering the propagation of a wave signal on two different fixed paths. In the receiving antenna output we will have the sum vector of the signals received through the two paths. If the frequency of the wave signal is varied, the relative phase of both multipath components will change, which will cause variation in the antenna's output in amplitude and phase, with respect to the frequency, in a periodic manner.

The magnitude of the amplitude and phase variation with frequency depends on the relative amplitude of the two multipath components, and the separation between successive peaks is inversely proportional to the differential propagation time. The bandwidth of a multipath medium is defined as the inverse of the differential propagation time between two multipath components, in seconds. Where three or more multipath components having significant intensities are propagated, the differential

propagation time is between that with longer path and that with shorter path.

Absorption of an electromagnetic wave results in attenuation or power loss and heating of the medium. Wave scatter can also produce a loss in the signal's power. Even if the wave scatter is not a power absorption in the true sense, it reduces the intensity of the signal received in the receiver, like an absorption.

A sample of a true absorption is the propagation of HF signals in region D of the ionosphere; a portion of the power will be lost in the heat transferred to the ionosphere. An example of wave scatter which causes apparent absorption is the wave scatter of a microwave signal due to raindrops.

If the absorption was independent from the frequency, no distortion would result in the received signal. However, absorption usually varies with frequency, and it is possible, in some cases, that the resulting frequency-depending attenuation causes amplitude distortion great enough to define a bandwidth for the medium. Nevertheless, in many cases other distortion sources predominate and the band limitation effects due to absorption are relatively small.

Dispersion is the variation of a wave's propagation speed with frequency, caused by the frequency dependence on the index of refraction of the propagation medium. An example of a dispersive propagation medium is the ionosphere. If a signal containing information is transmitted through a dispersive medium, the phase speed of the spectrum components will not be the same. This implies a phase distortion in the received signal. Therefore, the bandwidth due to the distortion can be defined in terms of bandwidth due to the phase.

2.4. ANTENNAE

It should be emphasized how important antennae are in the allocation and utilization of frequencies. Antennae can be the main economic as well as technical factor in projecting a radiocommunication system. For many types of service, the number of users which can be accommodated in a certain band allocation will be at least partially dependent on the characteristics of the antennae employed.

Antennae have two main functions in radiocommunication systems: they can control the direction and magnitude of the broadcasted radiofrequency power, and they can improve the relation signal/interference in the reception system by the angular discrimination between the desired and the interfering signals. The use of the gain characteristics of antennae can result in considerable reductions in the transmitter's power for a certain service level.

while simultaneously reducing interferences in other services.

The antenna gain is usually defined as the relation between the signal's power density produced in an angular direction and specified distance and the signal's power density which would be produced at a same distance by a standard reference antenna (usually a hypothetical isotropic broadcaster in free space). The antenna gain may be computed from its dimensions and physical forms or through experimental measures.

Where the aspects of frequency allocation and designation are considered, the directive antennae discrimination capacities should be taken into account; moreover, in many cases different polarizations may also be used for discriminating undesirable signals. Standards should be set for reducing the side lobes in order to assure the attainment of an optimum density without unforeseen interferences.

2.5. RADIOFREQUENCY NOISE

Both natural and man-made radiofrequency noises should be regarded as a factor in the spectrum utilization, due to their intimate relationship to reception in radiofrequency. Such noises, in the receiver's bandpass, independently of their origin, represent the inevitable limit from which the desired signal must be extracted.

Therefore, for a certain service requirement, the noise from the receiver will determine the total gain of the system necessary for any service level selection.

Below around 20 MHz, the limitation regarding the use of frequencies is usually the noise, which can be both natural and man-made. Man-made noise can be controlled in some cases, however, in many areas close to urban centers, frequently the atmospheric noise plus the man-made noise will be the limiting conditions, against which the desired signals from the systems will have to compete.

Atmospheric noises in the frequency region below 20 MHz can propagate in great distances, like radio waves.

Since there exists a great number of atmospheric disturbances which can occur all the time, the basic noise level is a composition of contributions from many disturbances. Local storms, with lightnings and thunders, can increase the basic noise and produce interferences in systems operating at frequencies in the order of several hundreds of MHz.

At around 20 MHz, the predominating natural noise has extraterrestrial origin, rather than atmospheric, the main noise sources being the solar and cosmic noises. As the frequency is risen, the thermal noise from the receiver's input terminals, produced by the electronic movement, becomes predominant as noise source.

Thermal and cosmic noises are wholly foreseeable, both regarding the mean value amplitude and the distribution in relation to such average. Atmospheric and man-made noises are less foreseeable in relation to the expected mean values and distributions around the average.

2.6. PROPAGATION OF SIGNALS IN FREQUENCIES BETWEEN 2 AND 30 MHz

Due to the great importance of this frequency band to radiocommunications, mainly in view of the technical simplicity and relatively low cost of the HF communication circuit and consequent large scale utilization of this portion of the spectrum for certain types of services, we will approach with some details the technical characteristics of this band's propagation, which, as a matter of fact, are very complicated.

2.6.1. RADIO PROPAGATION FORECAST

The availability and systematic application of radio propagation forecasts is essential in optimizing the circuit design and effectively using the spectrum in HF communication systems.

Most long-distance HF radiocommunications depend on the capacity of the ionosphere to return the radio signals to the earth. Therefore, it is vital to forecast ionization levels in the several ionospheric regions in forecasting the performance of any HF ionospheric wave circuit.

Since the maximum frequency able to return from the ionosphere usually establishes the upper limit of the useful HF band, knowledge of the ionization degree in the several regions is useful in estimating the probable propagation losses associated to the several propagation paths. The ionization degree in the ionospheric layer F_2 is usually the most important variable in estimating the performance of the HF circuit.

2.6.2. SELECTING OPTIMUM FREQUENCIES

The complexity of the propagation mechanism, the diversity of the service requirements and the spectrum overload flotation, render it impossible that any simple and clear criterion is used in the selection of optimum frequencies. The basic technical requirements of an appropriate relation signal/noise is frequently an useful criterion.

Usually, within the HF spectrum, all types of radio noise tend to decrease as the frequency is increased. During one day's hours, the HF power requirements are greater and the propagation loss tends to be greater in the lower frequencies of the HF spectrum.

Since the utilizable signal/noise relation usually increases with the frequency, it is a general rule for HF cir-

circuits with ionospheric propagation that the higher the frequency is, the better the signal/noise relations is, until the frequency reaches a point in which reflection in the ionosphere becomes improbable. Therefore, the first approximation to the optimum frequency in the absence of interferences can be made estimating the higher frequency displaying a consistent reflection probability in the ionosphere, with the required circuit reliability.

The geographical and time variation of the electronic density and of the associated critical frequencies for the several layers and the laws which rule transmission via these layers are sufficiently well established to allow general forecasts of such upper frequency limit.

Since a limited flexibility is observed in the selection of frequencies, and since the optimum frequency is based on the probable upper useful frequency limit, which is characterized by daily, seasonal and other variations, it is desirable to establish the probable useful frequency band.

Since the "FOT" (Optimum Work or Operation Frequency) is based on 90% of the ionosphere performance probability, it can be used as an estimate of the probable upper useful frequency limit for radio circuits requiring continuous service; the corresponding lower useful frequency limit can be estimated considering the probability that the available signal/noise relation is adequate. As the signal/noise relation decreases with the frequency lowering, there is usually a frequency below which the probability of an adequate signal/noise relation is not acceptable. Such probability is frequently established in 90%, and the corresponding frequency is known as LUF, that is, lower useful frequency.

2.6.3. FREQUENCY SELECTION FOR A CIRCUIT, IN THE ABSENCE OF OTHER INTERFERING CIRCUITS

The obtainment of the useful frequency band is basic for selecting frequencies, and it should be obtained for the representative months over the period of time in which the circuit being considered is required to operate. For a semi-permanent operation, daily variations of the useful frequency band for seasonal extremes, that is, June and December, and the solar activity extremes, that is, sunspots' numbers 10 and 130, are usually adequate.

The absolute continuity of any radio service is difficult in one single frequency, even if there is an unlimited availability of operation frequencies for HF ionospheric waves propagation.

The choice of frequencies must be based on the concept of the maximum possible continuity, and according to the radioelectric circuit continuity requirements, other additional frequencies should be selected in order that a flexible operation is possible. For certain types of service, up to 4 frequencies may have to be used in order that the continuity is maintained during the 24 hours of a day.

2.6.4. TIME DIVISION IN GEOGRAPHICALLY SEPARATED CIRCUITS

Where circuits are geographically separated, it is possible to develop plans considering solely the utilization of the frequencies on the individual circuits, without considering the interference potential.

2.6.5. DIVISION OF FREQUENCIES

The development of frequency division plans requires forecast of the MUF and of the available signals along the paths of desired and undesired signals. A powerful tool for the spectrum engineering is the availability of computer programs that can quickly make a required extensive analysis, and such programs should be able to develop systematic and effective frequency plans, specially where the operational experience is used to feedback the results obtained through the computer.

2.6.6. UTILIZATION OF WAVES IN THE FROM 2 TO 30 MHz BAND.

Presently, circuits in this band are used for:

- Telephone and telegraph channels, where the terrain conditions (islands, deserts, jungles) or the reduced traffic volume prevent or render antieconomic the installation of terrestrial or satellite microwave circuits.
- Long-distance connections, to ships and airplanes.
- Military or civil safety connections. If there aren't intermediate stations, the circuit cannot be interrupted due to an occasional or provoked failure, except by the terminal equipment.
- Diffusion of telegraph information by press agencies. One transmitter can cover a very extensive zone.
- Long-distance radio broadcasting or in zones in which medium waves noise is prohibitive (mainly in the tropical zone).

2.6.7. USING COMPUTERS TO FORECAST PROPAGATION

The fast growth of the use of propagation forecasts during the last decades to analyze the performance of HF radio circuits for several ionospheric conditions, several antennae and equipment combinations, change of the terminals' locations, interference effect, different seasons, sunspots' activity and several other reasons, resulted in a mechanization of propagation forecasts. Modern computers are well adapted for the task of absorbing the several input data, processing the data and automatically issuing printed tables and daily curves of the received signal intensity, MUF (maximum useful frequency), LUF (lowest useful frequency) and "FOT" (optimum transmission

frequency). Once the program is in operation, the production of solutions to the different situations is a mechanical and cheap routine operation.

2.7. PROPAGATION OF SIGNALS IN FREQUENCIES ABOVE 30 MHz

The most important frequency bands in telecommunications in our present days are those above 30 MHz, due to the great volume of information they are able to transmit. Therefore, considerations on their propagation characteristics are indicated herein.

2.7.1. PROPAGATION CHARACTERISTICS

The most important propagation characteristics which led to the potential use of VHF, UHF and upper frequencies (microwaves) are the following:

- atmospheric noise decreases with increase of the operation frequency and drops to a value below the thermal noise level.
- tropospheric propagation is not affected by the ionosphere; propagation takes place in the lower atmosphere (troposphere), which is more stable and is only affected by meteorological influences such as pressure, temperature, air humidity, turbulence and stratification of the atmosphere.
- propagation, as the frequency increases, draws close to a straight (optical) path with limited range, which under certain conditions allows the use of one same frequency in many locations which are not in radioelectric visibility one to the other.
- the available spectrum is around 1000 times greater than the HF one.
- the modulation bandwidth is around 1000 times greater as compared to the HF one, which renders possible to transmit wide band signals, such as TV and multichannel.
- the only limitation is the line-of-sight operation for very high frequencies (microwaves), the propagation being limited along the curved ground which limits the distance from 40 to 70 km, depending on the terrain topology. For VHF and UHF frequencies (approximately up to 1 GHz), there is no need of the line-of-sight condition, as diffraction over obstacles and the ground's curvature itself render feasible circuits in these frequencies.
The propagation mode through tropospheric diffraction predominates in lower frequencies, the hops being able to reach from 100 to 300 km. There is the possibility of using propagation through tropospheric wave scatter, which allows the mark of 1000 km or more, but the cost for implementing it is very high, and its utilization is restricted only to very special cases.
- One of the most important factors in the propagation of electromagnetic waves in these bands is the

gradient of the atmospheric index of refraction, which many times is translated by parameter K, which supplies the relation between the effective earth's radius and its real radius, in the propagation of radioelectric waves.

For higher frequencies, a limiting factor for the utilization is related to attenuation due to rain and atmospheric absorption, mainly in frequencies over 10 GHz.

2.7.2. INFLUENCE OF THE TERRAIN AND OF OBSTRUCTIONS IN TROPOSPHERIC PROPAGATIONS

The radioelectric beam in tropospheric propagations is influenced by the terrain characteristics and by obstacles between the transmitting and the receiving antennae. Such beam tends to follow a straight azimuth line, unless it is intercepted by obstacles along the path or close to it. Traversing through the atmosphere, the beam follows a slightly curved path in the vertical plan, that is, it is vertically refracted due to the variation with height in the dielectric constant of the atmosphere, in most cases slightly downwards, in such a way that the radioelectric horizon is effectively extended. The value of such refraction varies with time due to changes in the temperature, pressure and relative humidity, which control the dielectric constant.

Where there is an obstacle to the free passage of the wave front, in the tangency points over the obstacle the diffraction phenomenon takes place, and the energy is re-directioned through the geometric shadow formed by the energy source and the obstacle. The diffraction effect on the radio waves is more remarkable in lower frequencies, that is, greater wavelength.

Propagation loss due to diffraction mainly depends on the magnitude of the obstruction between transmitter and receiver, as well as on the wavelength, on the form and type of diffraction surface and on the rugosity of such surface. The characterization of the influence of the obstruction's form, type and rugosity should be made in relation to the wavelength, and a typical example of the frequency influence on this characterization is that a mountain can behave like a knife edge for VHF frequencies and like an obstacle with an approximately curved surface for SHF. A knife edge type obstacle tangent to the line-of-sight between the transmitter and the receiving antennae causes of a loss of approximately 6 dB, which is minimum for the tangency condition. On the other hand, in smooth surfaces or water, which resembles very much the flat ground, there result the maximum losses due to diffraction in the tangency condition, which get close to 20 dB. In the same tangency conditions, most obstacles cause propagation loss between such extreme limits.

Therefore, the presence of obstacles to the line-of-sight between antennae, such as hills, trees, buildings and even the earth's curvature, gives rise to a diminution in the received energy.

A beam of electromagnetic waves can be reflected by relatively smooth surfaces or water surfaces, just like a light beam is reflected by a mirror. Since the wavelength is much greater than the light waves, the smoothness criterion for a certain surface is different and depends on the frequency. Likewise, such criterion differs for very small incidence angles and for great angles.

The ratio between the intensities of the reflected and the incident waves is evaluated through a parameter called reflection coefficient, whose value depends on the type of ground and varies from 0 (null reflection effect) to 1 (total reflection condition). Where the reflection takes place, the incident wave front has its phase reversed due to the fact that the horizontal electric field and the vertical magnetic field annul themselves in the reflecting surface.

The radioelectric beam reflection may cause problems in the signal's reception, as the direct and reflected wave fronts may be out of phase, such out of phase condition varying according to the reflected wave path. Depending on such out of phase condition, there may result a very strong attenuation, or even cancelling of the received signal as a result of the two waves' composition.

2.7.3. FRESNEL ZONES

An important concept in analyzing the tropospheric propagation effects, particularly those related to diffraction, refraction and terrain and obstruction effects, is the *Fresnel zone*. The radius of the first Fresnel zone is a type of unit which serves to measure certain distance characteristics, such as gaps and obstructions in the path, in terms of their effect on the frequency in question, in lieu of the metric units.

Fresnel zones of upper orders are also important under certain conditions, such as in paths having highly reflecting characteristics.

2.7.4. USING COMPUTERS TO FORECAST PROPAGATION

Presently, there are several reliable theoretical models for forecasting radiopropagation, which are based on large proportions measuring programs for obtaining appropriate statistical samples for all the set of variables which influence the radiopropagation medium.

Such propagation forecast models are adequate, or rather, adapted, to be used in computer, and they greatly facilitate the engineering of radioelectric systems, particularly the frequency spectrum engineering.

Many of such models are based on the automatic recuperation and analysis of topographic and geographical data on the radioelectric paths. This is due to the fact that the propagation of terrestrial communications in frequencies above 30 MHz is greatly influenced by the topographic characteristics of the path's relief between antennae.

On item 4.4 we will approach in greater detail the models for gathering topographic data.

3. TECHNICAL ANALYSIS OF ELECTROMAGNETIC COMPATIBILITY

In order that the spectrum is effectively used, it is required that, in addition to a correct and reliable administration, technical processes are applied.

Such processes necessarily employ several types of analyses aimed at forecasting interference situations, through mathematical models representing the physical phenomena involved.

The following mathematical models are required:

- interfering transmitter
- desired transmitter (own link)
- transmitting and receiving antennae
- propagation characteristics
- interfered receiver
- noise analysis

to carry out such calculations.

The refinement degree of the physical phenomenon representation distinguishes one type of model from another.

Generally, the simplest representation used in cases where there is a great number of potential interactions is called selection or compilation model. Such model makes a conservative estimate of the physical factors, and it is used to exclude interactions displaying remote interference-producing possibilities. This model's advantages are the provision of minimum descriptions necessary to the equipment and the medium, and the simple and fast processing which results from the simplification of the input data. Its basic limitation is the pessimistic characterization of the evaluated situation.

More refined models with more precise representations are used to carry out more extensive analyses of the possible interfering pairs.

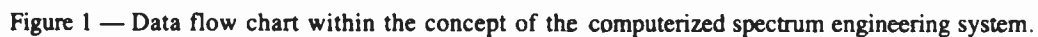
In addition to the cited forecast models, models which accomplish optimization of a situation on the standpoint of electromagnetic compatibility are used.

For such function, forecast models are used to evaluate the operation effects of an equipment or system in several frequencies and to select the minimum interference case as the best configuration (frequency designation).

An accurate representation of the equipment characteristics, localization parameters and terrain considerations requires an embracing data base. Relations between these mathematical models and the data base are illustrated in Figure 1.

Basically, the interference phenomena and mechanisms can be characterized through deterministic and probabilistic functions.

Whenever possible, the variableness of the equipment parameters and the statistical behavior of the propagation should be considered. Too simplified characterizations of the electromagnetic compatibility parameters may result in forecasts of the equipment performance which do not represent a true mean performance of a real operation.



Deterministic models display such failure and should be carefully used.

Models should be used which reflect the uncertainty and statistical nature of the electromagnetic compatibility analysis.

4. MATHEMATICAL MODELS

In order to accomplish the several functions of a Spectrum Engineering System, each task or problem must be analyzed on the standpoint of its particular objectives and requirements.

The use of a single generalized model which can be applied to any type of operation or situation, with embracing analysis characteristics, becomes counterproductive mainly in view of the fact that its effectiveness will surely result weak.

In a Spectrum Engineering System, the use of models having several complexity degrees in keeping with factors such as the required analysis level, type of service and the spectrum utilization degree, among others, yield the best effectiveness characteristics, on the standpoint of data processing.

We will display some of the main mathematical modes necessary to a spectrum engineering system, related to the problems of propagation and interference forecasts.

4.1. PROPAGATION FORECAST MODELS

Propagation considerations are basic for electromagnetic compatibility analyses within any interference forecast model.

A propagation forecast model aimed at such must have enough capacity to consider the several propagation modes. Depending on parameters such as frequency, polarization, length of the paths, effective heights of antennae, the radio waves energy may propagate from a transmitter antenna to a receiver (interfered) through several propagation modes.

Propagation mechanisms are influenced by variations in the geophysical and atmospheric parameters, each in a certain level. Attenuations in the propagation processes constitute one of the most important factors in analyzing electromagnetic compatibility, and they are usually estimated through statistical and empirical processes based on theoretical and practical considerations.

Propagation forecast models can be divided in two great groups, according to the characteristics of dominant propagation modes:

- Propagation forecast models for frequencies up to 30 MHz.
- Propagation forecast models for frequencies above 30 MHz.

Such division is justified by the need of knowing the topographic characteristics of the relief in the path between antennae in most cases of propagation forecast of terrestrial communications in frequencies above 30 MHz, which doesn't necessarily happen for frequencies under

this level, as up to approximately 30 MHz the predominant modes are usually independent from the topographic data on the path's relief, for they are mainly a function of atmospheric conditions, such as the ionospheric propagation, or of dielectric and soil conductivity conditions, in propagations of soil waves.

Therefore, an automatized propagation forecast system needs to have a system for recuperating topographic profiles for frequencies above 30 MHz.

4.2. INTERFERENCE FORECAST MODELS

Interference forecast models quantitatively determine the degree of interference for each interfering pair.

It is necessary to have a great number of fairly precise data for each receiver and each interfering source, and the propagation conditions, including atmospheric and terrain effects, need to be dealt with precision.

A general configuration of a model aimed at forecasting interferences is shown in figure 2. Basically, we have a signal, in baseband, being sent to a transmitter which, through a modulation and amplification process, is transformed in a radiofrequency (RF) signal.

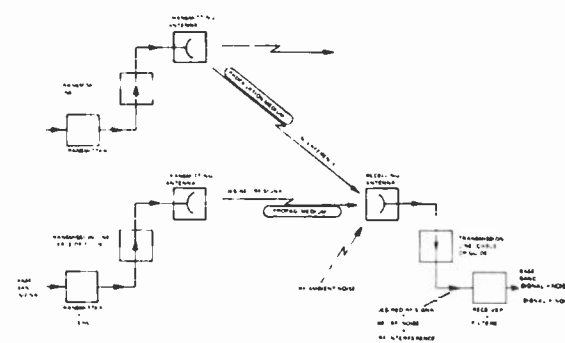


Figure 2 — Configuration of a receiver subject to ambient interferences and noises.

Such signal is sent to the broadcasting element (antenna) through a transmission line (cable, guide, etc.), usually also passing through RF filters and in some cases through branching systems. The signal which reaches the antenna, already somewhat attenuated, is broadcasted to space (free). The receiving antenna picks up an infinitesimal portion of the power emitted by the transmitting antenna, whose intensity is a function of the characteristics of the path's propagation medium between transmitter and receiver, and of the antennae characteristics. In the same way the antenna picks up the desired signal, it can pick up undesirable signals from a transmitter of another system, as well as natural or man-made atmospheric noises, such as RF radiations and spuriousness emitted by electric/electronic equipment, ignition noises, etc.

Propagation modes other than the main one of the signal emitted by the desired transmitter (considered system) may also be considered undesirable signals, such as multipath signals, reflected signals, signals resulting from wave scatter, etc. Such details must be considered on the standpoint of projecting the communication system in question itself. However, these secondary modes should also be analyzed as to their electromagnetic compatibility with other communication systems.

All signals received by the receiving antenna are sent to the receiving equipment through a transmission line, usually also passing through filters, and in some cases through branching systems. The receiver demodulates the desired signal, together with the undesirable signals, resulting in a signal which is not identical to the original one due to distortions and noises caused by interfering signals and the propagation medium characteristics, as well as the equipment characteristics.

The analysis of the noise level caused by interfering signals (not including ambient RF noises) from a certain transmitter in a specific receiver, may be subdivided in two case

- Receiver and transmitter are closely located, as in the case of antennae in the same tower or very close, or equipment in the same frame, among other cases.
- Receiver and transmitter are sufficiently far apart.

The first case differs from the second due to the fact that the effect of spurious frequencies and intermodulation products within the receiver's bandpass are significant, which usually doesn't happen if the equipments are far apart, due to the low power of these signals and to propagation loss caused by the medium.

Figure 3 displays a general block diagram of an interference forecast model, considering all useful frequency cy bands in radiocommunications. Notice there is a clear division in the frequency spectrum when the interference calculations are carried out. Such division is justified in view of the dominant propagation modes for the several frequencies.

Up to approximately 30 MHz, predominant modes are usually independent from topographic data on the path's relief, these being mainly a function of atmospheric conditions, such as in ionospheric propagation, or of the soil's dielectric conditions, in soil waves propagations. On the other hand, the dominant modes for frequencies above 30 MHz usually depend on topographic and atmospheric conditions, for terrestrial communications.

Noise generated by the composition of involved signals will depend on several parameters, such as the system's type of modulation/demodulation, types of interfering signals, receiver's bandpass, separation between carrier frequencies, bandwidth of the interfering signal, etc.

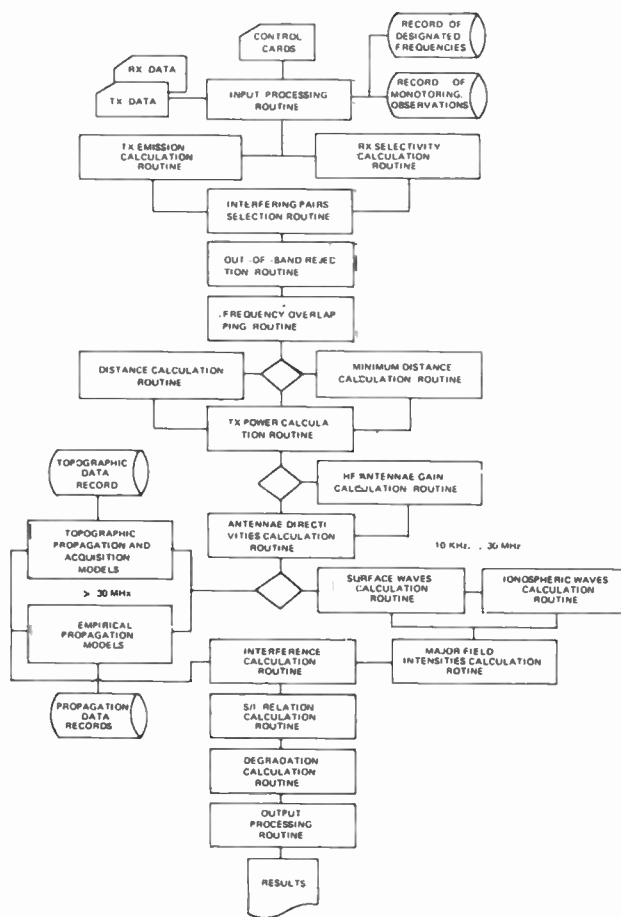


Figure 3 — Interference forecast model flow chat.

4.3. EQUIPMENT ANALYSIS MODELS

Equipment analysis models should synthesize characteristics related to the transmitting equipment transmission, selectivity, susceptibility and sensitivity of the receiving equipment and the broadcasting elements' (antennae) broadcast diagram.

Such models serve to provide necessary data for analyzing electromagnetic compatibility and for checking if the equipment characteristics are in tune with the required standards.

In order to accomplish such functions, these models require a description of critical parameters, regarding interferences, such as:

- Modulation system employed
- Emission of spuriousness by the transmitter
- Combinations of frequencies not allowed for the transceivers

- Emission bandwidth characteristics
- Selectivity, sensitivity and susceptibility characteristics of the receivers
- Noise characteristics of transmitters and receivers
- Characteristics of the filters
- Frequency stability of transmitters and receivers
- Antennae gain values and corresponding broadcast diagrams

4.4. TOPOGRAPHIC DATA-GATHERING MODELS

Topographic data-gathering models should allow reconstruction of the terrain's altitude profiles between two considered points, from a topographic data base stored in computer.

There are presently two known processes for storing topographic data in digital computers. Both use topographic charts as source of information on representative elevations in the relief, but the methods for gathering the charts' information and the way these information are stored completely different.

The first of these methods shall be called here storage *Matricial System*. This method is based on the experience described by R. Edwards and J. Durkin in "Computer Predictions of Service Area for VHF Mobile Radio Networks" (IEEE vol. 116, n. 9, 1969) and basically consists of taking from the topographic chart from a certain region the representative altitudes of square areas (small squares with 0.5 km in each side, according to a matricial scheme, which are recorded in computer-accessible files.

The choice of such intervals for registering altitudes is convenient, as it results from a reasonable engagement between the volume of stored data and the profiles' recuperation precision.

Interpretation of the level curves through the matricial system, in which every small square is represented by its significant elevation, depends of predetermined criteria. Figure 4 illustrates the storage method, in question.

It is possible to generate profiles of paths, from the topographic data base using the matricial system, providing only two terminal points of the path.

There are several interpolation methods, among which we can cite:

- Orthogonal Projection
- Square Interpolation

According to the orthogonal projection, each point of the path is generated by the orthogonal projection of the center of each small square intercepted in the path line.

Figure 5 illustrates such procedure, and it can be seen that the profile points do not have uniform separations.

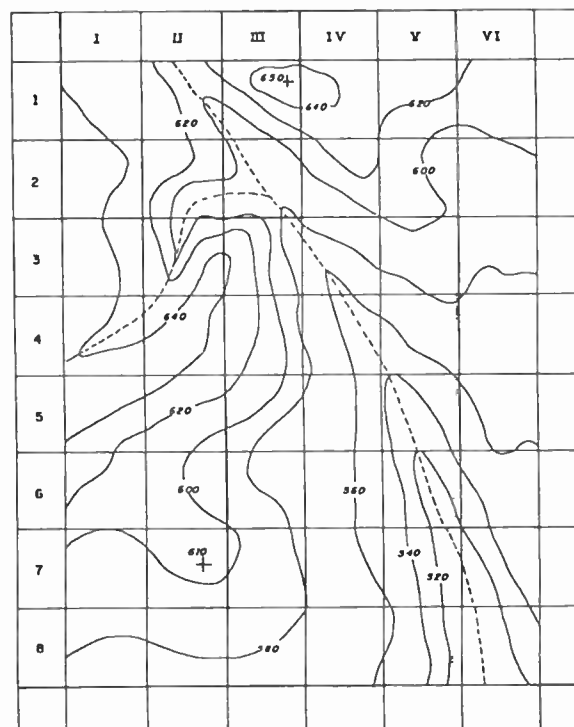


Figure 4 — Interpretation of the level curves through the matricial system, according to which each small square area is represented by its significant elevation.

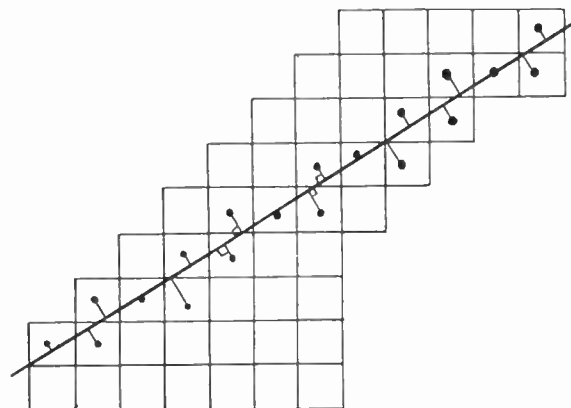


Figure 5 — Generation of profile through orthogonal projection (data stored in matricial system)

In the square interpolation method, separation between the profile points is uniform and preset, and the interpolation of a point's height is linear and obtained from the stored heights of the four squares which surround the point. Height of a certain point P, as can be seen in figure 6, is provided by:

$$h = (h_1 - h_2) \cdot x + h_1 + ((h_4 - h_3) \cdot x + h_3) \cdot y - ((h_2 - h_1) \cdot x + h_1) \cdot y$$

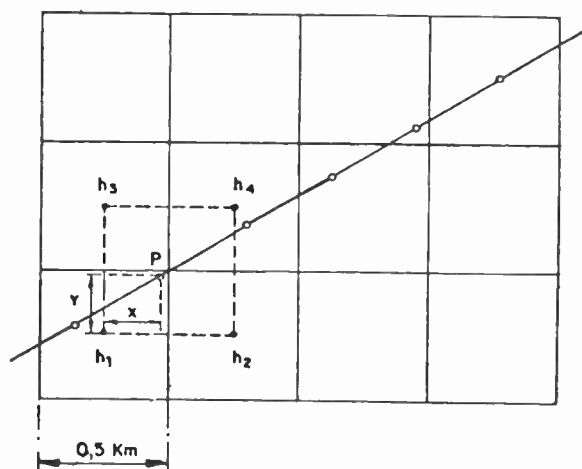


Figure 6 — Generation of profile through square interpolation (data stored in matricial system).

The second method for storing topographic data in digital computers is widely used by FCC and basically consists of storing the level curves themselves, in keeping with the metric coordinates, also including isolated elevations. This method shall be called herein *Level Curves Registration System*.

Transference of the topographic charts' data through level curves recording may be made through an automatic or semi-automatic digitalization system and a criterion of minimum interval of the metric coordinates must be established in keeping with the required forecast and of the volume of data to be stored.

Figure 7 illustrates the present storing method.

It is possible to generate profiles of paths, from the topographic data base using the level curves recording system, providing the two terminal points of the path, and elevations are obtained through the intersections between the path line and the stored level curves.

Figure 8 illustrates such procedure.

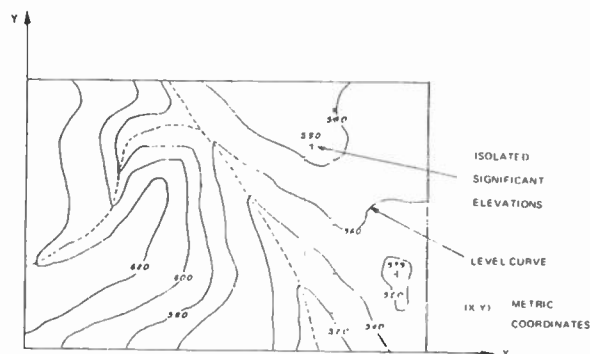


Figure 7 — Interpretations of the level curves through level curves registration, in keeping with the metric coordinates. Isolated elevations are also registered.

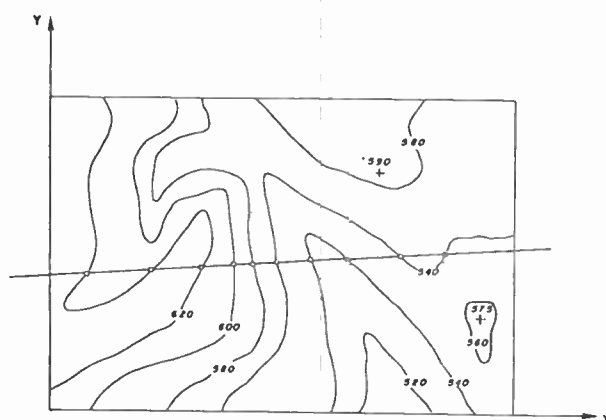


Figure 8 — Generation of profile through intersections with the level curves.

5. CONSIDERATIONS ON AN AUTOMATIZED DATA BASE IN A SPECTRUM MANAGEMENT SYSTEM

The spinal cord of a spectrum engineering system is its data base, which may include accessible data in computer, data in physical files, catalogs of manufactures and a library of reference documents.

For an effective spectrum engineering system, the automatized, in-computer data base represents one of the most important factors for optimizing the use of the radioelectric spectrum, due to the great volume of involved data.

We will approach the computerized data base conceptualization, including its creation, maintenance and op-

eration. Within this structure, specific project considerations on the data base specifications in a spectrum engineering system are discussed.

Within the present study we shall consider the configuration of a *centralized* information system, which should be the configuration for the first phase in implanting a spectrum management system at national level.

Configurations for the subsequent phases will depend on the implanted system's effectiveness, mainly in what regards its operational system.

Once the initial implanting phase is over, including efficiency tests, *there is a tendency* to decentralize the information system, and consequently the data base and its processing, as stored information increase and the spectrum control becomes increasingly embracing. Therefore, as there is an increasing possibility of enlargement of the data base capacity and a growing need of processing such data, whose time factor is also an important parameter, the distributed processing becomes an attractive technique. Within this line, a decentralized configuration should be implanted in the subsequent phases, and the maintenance and operation procedures must be consistent with such modification.

5.1. DATA BASE CONCEPT

The data base concept discussed herein below may be regarded as an initial effort to define the requirements of an integrated spectrum management system.

The term "data base" is generally accepted to denote a set of records, and therefore the term "data files" may be used as a substitute to "data base". However, the data base concept is somewhat more refined, since it includes aspects of interrelation between files, and these details are significant within the files' management context. An effective interrelation of the several files comprising the data base (that is, deriving benefits from the general character of data requirements from the several management and information processing functions), results in the definition of a data base, with a general character.

The methodology for establishing a general data base must be an utmost important area within the efforts for implanting an automatized spectrum management system.

5.2. DBMS — DATA BASE MANAGEMENT SYSTEM

The software allowing the creation and maintenance of files and access, recuperation and/or updating of such data is called DBMS — Data Base Management System.

The main role of the DBMS is to allow the user to deal with the data in abstract terms, rather than in the way the computer stores the data.

Within this line, the DBMS works as an interpreter for a high level language, allowing the user to specify what needs to be done with little or no attention, in detailing algorithms or representation of the data used by the computerized system.

5.3. DATA BASE PROJECT

A data base project deals with creating structures for supporting the data.

To determine the data needs of the information system is an activity independent from the data base project. Therefore, before a data base project is started, it is indispensable that all information on the system's needs are available. Such data needs may be formalized by establishing the contents, or even shape, of reports, access procedures, recuperation and updating, etc., with indications of frequency, volume and other relevant details.

In projecting a data base it is important to define and keep a distinction between the logical vision and the physical vision of the data control. The logical vision has the form of a data structure showing existing dependences and relationships between the different data elements. The physical vision or that of data implementation depends on the support supplied by the DBMS — Data Base Management System. This vision is formalized in many DBM's through a data-defining monitor called "schema", master record, dictionary or data base descriptor.

Therefore, in projecting a DBMS we are faced on the one hand with the application data needs, and on the other hand with the data-manipulating facilities provided by the DBMS. To conciliate both extremes constitutes one of the main tasks in such project. Hence, the result of such task will be strongly influenced by the knowledge of the designer on the application data needs and on the facilities offered by the DBMS software.

Mapping of the logical data base for the physical depends on the characteristics of the chosen DBMS, and it is also a very important aspect within the general project. Under certain circumstances, its importance becomes crucial, such as in response or input/output time minimizing operations. In this case, attempt-and-error processes cannot usually be allowed, as knowledge on the updating and recuperation processes and on the access methods will be directly reflected on the quality of the mapping process. Moreover, the basic data structures accepted by the DBMS, the number of records which can be interconnected, intra and inter relationships between records, number of allowed secondary indexes and the alternatives to the physically grouped data (using the DBTG-CODASYL terminology), can influence the logical project.

Basically, a Data Base project is composed of two main processes:

- Logical Project
- Mapping of the resulting structure in a structure supported by the DBMS (logical mapping for the physical).

In the logical project, the data base is first conceived as a structure displaying the relations between the different data elements. Once such structure is ready, individual data elements are related between them and grouped in files. The structure resulting from the individual files and from the corresponding interconnections between files depends on the DBMS.

The logical mapping for the physical is highly dependent on the DBMS characteristics, and therefore the choice of an appropriate DBMS is a very important task.

In order to analyze the DBMS characteristics, it is essential to characterize the type of "Data Model" used in its data logical structure.

Data Model is defined as the class of data logical structure which is available to the user by a computer system or language, aimed at data-processing applications.

There are three great groups of data models:

- Hierarchical
- Network
- Relational

See <Ullmann>, that describes in "Principles of Database Systems" each of these data models in detail.

It is necessary to have a set of procedures for evaluating a data model, so as to render possible an evaluation of alternative models within the specific context of the set of applications.

Two types of criteria are commonly used:

- *Use Criterion*, which allows an evaluation of the facility degree provided by the model; and
- *Implementation Criterion*, which measures the implementability of the model and resulting implementation efficiency.

In short, it is necessary to appropriately choose the DBMS for a set of applications. In order to analyze the DBMS characteristics, it is essential to analyze the type of *data model* used by the DBMS and to evaluate its applicability for the set of functions required by the database.

See <Mcgee>, who displays an interesting criterion for evaluating the data models in "On user Criteria for Data Model Evaluation"

5.4. INFORMATION CONTAINED IN THE DATA BASE

The information necessary to a frequency spectrum management system, at national level, contained in an

automatized data base, may be basically divided in five different file groups:

- System General Technical Data
- Administrative Data
- Equipment Characteristics Data
- Planning Parameters Data
- Topographic Data

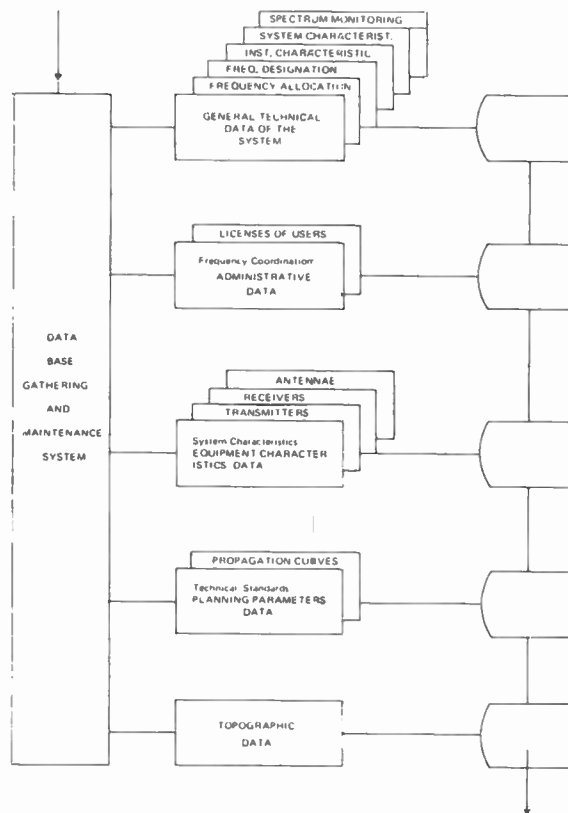


Figure 9 — Data base concept.

The *System General Technical Data Files* consist of records related to the operation characteristics and location of the communication and electronic equipment.

Its main utility is to identify equipment in a certain "electromagnetic environment" which represents potential interference sources for a certain receiver being considered, or that is susceptible to interferences, due to a certain proposed transmitter being considered. Such information are used to assist compatibility projects in the areas of frequency designation and location selection plannings.

Samples of information types which should be recorded are the following:

- Frequency Allocation
- Installation and system characteristics:
- equipment location: coordinates and elevation of the location

- antenna height
- transmitter power
- emission bandwidth
- receiver sensitivity and susceptibility
- designated frequencies
- organization to which it belongs, etc.

— Monitorization Data (Radio Monitoring)

These referenced information must be stored, if possible, permanently on-line in the computer's processing unit. This allows immediate access to the database of the "electromagnetic environment" from remote input/output terminals, and contributes to the multiprogramming efficiency, where many programs access the database.

Administrative Data Files are composed of all data describing users, licenses, requirements, including coordination data.

Equipment Characteristics Data Files consist of information related to the rated technical characteristics of the communication and electric/electronic equipment, that is, they include all types of equipment having minimum performance standards for an effective use of the spectrum.

Such data are basically divided as follows:

- System Characteristics
- Transmitters
- Receivers
- Antennae
- Other Electric/Electronic Equipment which influence or are influenced by the electromagnetic environment.

Planning Parameters Data Files are formed by data related to problems of electromagnetic compatibility and frequency allocation within the spectrum.

Such files contain national, international and even military resolutions, regulations and recommendations related to the use of the spectrum frequency, as well as propagation curves of radioelectric waves obtained through statistical and/or empirical measures aimed at serving as a basic tool for characterizing propagation modes which influence the "electromagnetic compatibility" environment.

Topographic Data Files contain topographic data digitalized in an accessible manner for the data computer processing.

They are used for determining the line-of-sight conditions between antennae and as data input for the propagation loss calculation models which depend on the path profiles knowledge.

5.5. CREATION, MAINTENANCE AND OPERATION OF A DATA BASE

The required capacity of a general data base for a spectrum management system must be considered in three basic levels:

- a) Creation of the data base
- b) Maintenance of the data base
- c) Operation of the data base

The *data base creation function* basically involves generation of the automatized data base. Before formatizing the data files and associate records, some factors must be determined, such as:

- Which information or data items must exist in the data base
- Which methods must be used regarding access to the data
- Precision and Exactitude Level of numerical data to be stored
- The collection of data to be recorded, filed, processed and accessed
- Provision of facilities for data introduction
- Facilities for storage in magnetic tapes and direct access storing (disks)

The *data base maintenance function* comprises to a great extent the function of data base management cited before and principally involves the functions of adding new records or files to the data base, elimination of life records and changes of data fields. Records condensation, that is, to rewrite tapes and disks containing many erased records, is a sample of a typical data base maintenance function.

The data updating and recuperating services, that is, the methods for accessing the data, are part of such function, even though the maintenance function in itself does not get involved with data processing or with creating new data.

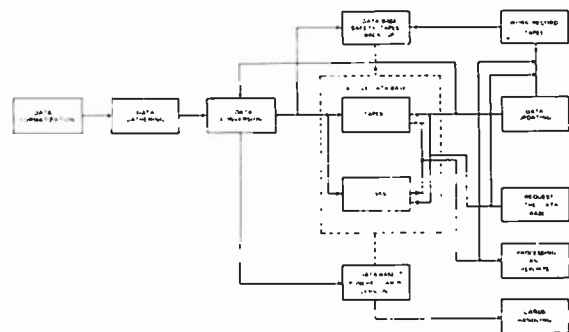


Figure 10 — Creation, maintenance and operation of the data base.

The *data base operation* comprises updating of information (data input), solicitation of information to the data base, data processing and generation of reports, and it is a type of activity which involves the interrelation man/machine and uses the data base information.

Figure 10 displays the functional flow chart of elements composing the three above-considered levels. Such flow chart is an initial attempt to interrelate the several aspects of an automatized data base for a *centralized information system*. In addition to this, it anticipates means for a logical discussion of the several elements which must be considered *during the evolution of the manual process for automatizing the general data base*.

Each of the elements displayed in figure 10 are described herein below.

It should be noticed that the main functions displayed are those directly involved with the data base creation, maintenance and operation. The data-processing and reports generating functions are not specifically considered, even though their existence as functions is implicit when the spectrum management system structure is considered altogether.

5.5.1. DATA FORMATIZATION

The data formatization function is mainly associated to the data definition, structuring of files and records, definition of access to the information and generally to all procedures related to the creation of the several files and tables composing the data base.

It is necessary to emphasize that the data formatization function is carried out before gathering and compiling the data. In other words, the file project must be made before the real data are gathered, provided determinations such as items of required data, effective access keys and the general character of the data elements are defined. Once files are structured and the required tables specified, the gathering and preparation of the required data becomes almost a routine activity.

5.5.2. DATA GATHERING

As mentioned before, once the data base structure is defined, the gathering of required data is a simple task.

Existing data, related to frequency designations already effected, must be revised regarding the totality of contained information and data which need to be included in the automatized data base. Such revision must include revision of several forms, pertinent data elements and which of them should be coded.

Mapping must be considered as a supplementary information to aid the visualization.

5.5.3. DATA CONVERSION

Once formats are defined, that is, the structure of the several data base elements, and the data to be formatized

are gathered, the proceeding task *during the automatized data base capacity creation* is to convert existing data in a way they can be automatically processed and manipulated.

Punched cards, punched tapes, magnetic storing devices, or even the operational system editor, may be used for this intermediate operation.

An implicit characteristic of the data-converting process is the development of an effective coding process. Coding of data items should keep a relation to the corresponding items of non coded original data. What is aimed is that there is reached an abstraction minimization, as abstraction is usually inherent to coding schemes, and codes should be as intelligible as possible, in order that efficient mnemonic words are used to the utmost. The code needs to be developed for all possible inputs of new requirement forms, as well as supplementary forms, in order that they can be readily introduced in the data base.

Forms of requirements should be projected so that requirers are compelled to carry out a substantial portion of the coding (that is, multiple choice responses, in which each of them is coded). However, a significant portion of the requirement form should be directly coded by the operator, for which he will use a code table. The technical revisers will check all the requirements, including supplementary forms and documentation. Some items may be coded by the revisers, but this step should be minimized if most information items are filled by the requirer in coded form.

The comments above on the requirement information coding imply the use of detachable requirement forms or the use of intermediate coding tables. The main consideration during the process of data conversion is to render it the most direct possible up to the computerized system introduction operation. This requires the development of a well planned and easy-to-read conversion table to be used by operators, as an effective coding table reduces the amount of operation mistakes.

A great portion of the automatized data base should be based on already existing data, and additional information should be required from now-existing users of radioelectric systems.

Therefore, the data base generation requires an initial coding effort, which implies the need for additional intermediate coding tables that can be similar to the new requirement forms. The use of intermediate coding tables can be an efficiency test for the new requirement form, providing necessary data for possible modifications. The use of an intermediate coding table, even though it is undesirable as a permanent step within the automatized system, represents a transition phase between the existing system and the new operational system. Once the main data base capacity is established, this transition step can be eliminated.

5.5.4. PUNCHED CARDS VERSION OF THE DATA BASE (optional)

In the process of data conversion, punched cards representing a formatted version of the data base may be used. Such card deck serves for a dual aim, if kept in updated conditions. It provides additional safety capacity (back-up) to the data base information, in case of any eventual loss of the magnetic facilities (tapes and disks) available to the computer, and provides additional manipulation and processing facilities.

5.5.5. DATA BASE SAFETY TAPES (BACK-UP)

During the phase of the data base creation, the data base main safety capacity must be developed. Such main safety capacity should be in the same form of a version residing in the data base, on tape, that is, all information correctly formatted constituting the data base (files, tables, etc.) should be kept in a separate set of safety tapes. After the initial generation, these tapes must be updated by the work tape, which leaves recorded all updating information, as well as any input/output activity (such as issuance of reports).

5.5.6. ACTIVE DATA BASE

The active data base is constituted by the version residing in the tape and disk data, as shown in figure 10.

The active data base contains the same information of the safety tape (back-up) versions and of the punched cards (if adopted) of the data base.

Selection of which datum should be stored in disk or tape directly depends on factor such as the frequency of use of the particular information items, nature of the information to be stored (that is, sequentially or randomly ordered input data), the most advantageous access techniques for each application, the updating frequency of each record or file, and the type of processing required.

Information items such as lists of used frequencies and important statistical data are samples of data types that can be stored in tape, while antennae broadcast diagrams, signal/noise tables, among others, represent the data types which need to be stored in disk.

5.5.7. DATA UPDATING

Data updating, for the initial (centralized) configuration, is completely off-line. The regional centers send updating information to the central data-processing center by mail, telephone, telex, facsimile, etc., and the updating of information is carried out locally. All updates are introduced in the system through reading of punched cards or magnetic storage devices, or through keyboard devices, such as video/teletype terminals.

In any of the updating modes, punched cards may be created to keep an updated version in punched cards of the data base. However, in some cases, this can be inconvenient, due to the great physical volume occupied by the cards.

All updates must be recorded in the work/record tape system, which precedes the updates in the data base safety tapes.

5.5.8. WORK AND RECORD TAPES

The work and record tape is used to record all updates, requests, output of data and results of the system's diagnoses. The record of requests and requirements for information can be projected to have the function of a safety record. Names and codes of requirers may be recorded together with the accessed information. This provides a record for future reference on the information items which were actually accessed, who required same and when they were required.

The work/record tape is an integrating portion of the system's safety capacity. It is periodically used to transfer the last updates to the safety tapes. Such procedure provides a reliable capacity for updating the data base, since at any time the updating information that is placed in the system is recorded in the work/record tape or in the system's safety tape.

5.5.9 REQUESTING INFORMATION TO THE DATA BASE IN A CENTRALIZED SYSTEM

Whereas the requesting of information to the data base is separately shown in figure 10, it may effectively apply the same input devices of the system used in the data base updating.

Requesting of information for the *initial configuration (centralized system)* may be made off-line, that is, information requirements are received in the computation center through the same means the updating information are transmitted (i.e. mail, telephone, telex, facsimile, etc.).

The keyboard/video devices appropriately carry out the functions of requesting information from the data base, making it possible for the system's operators to interpret responses before the preparation of printed outputs, and also to examine the input data before actually accessing the required data.

The function of requesting information from the data base can include a safety checking capacity, which limits access to the data base only to authorized operators. Authorization levels may also be supplied, according to which only specific personnel levels (such as managers) or designated individuals are allowed to access a certain

type of information (i.g. secret data with a list of pending requests).

As shown in figure 10, all requests to the active data base must be recorded in the work/record system, in the form of a historical record of data requests.

5.5.10. PROCESSING AND REPORTS

The present function mainly deals with the interface between the central processing facilities (operational system) and the software of the data base processing and management.

It is through this function that the data base is served and all of the system's outputs, that is, intermediate results, reports, calculations and answers to requests, are developed. Keyboard/video devices can be advantageously used to monitor certain output functions, to specify format variations of the report and to check the grounds of results and conclusions.

Figure 10 indicates the existence of the data base/operational system interface. This is a very complex area deserving a high degree of consideration during the data base management software project phase.

Factors such as the development of the system's directorate, development of the files' specifications, selection of the data-accessing methods, definition of "interruptions" and the system's priorities, control system logic, etc., must be deeply considered during the development of an efficient capacity for the automatized data base.

Generally, specialized DBMS's — data base management systems — require that particular components of the data base software are developed, which must be compatible with the operational system that controls the central processing facilities operation.

Before efforts are directed towards projecting the data base management system, which is usually expensive and takes time, it is a good procedure to check the commercially available DBMS's able to meet, with some modifications, the required needs of a frequency spectrum management system.

5.6. FINAL CONSIDERATIONS ON THE DATA BASE PROJECT

It is difficult to completely detail the data base in order to gather all national needs or specify one sole embracing criterion for such detailing.

This is mainly due to the close relationship between the data base and the spectrum engineering processes' elements.

Detailing of the data base project must be somewhat flexible, until a balance is reached among the individual responsibilities of frequency selection functions, reduction of interferences and the engineering planning, together with their mutual responsibilities of helping one the other; and similarly until a balance is reached among analysis, measurement, data and standards.

To help one understand the complexity of the problem of defining the problem's detailing, we can say that:

- The analytical techniques adopted will require certain input data.
- Consequently, certain measures and other data-gathering activities are necessary.
- If the latter cannot be provided, the analytical techniques cannot be used.
- But until the analysis is defined, the data base detailing cannot be carried out.

In short, until the total detailing of the spectrum engineering system is attained, objectives to be gathered in the data base detailing remain pending.

6. RADIO MONITORING

The implantation of the Radio Monitoring National Network can be considered a reality in Brazil, and its introduction will allow monitoring of the spectrum and accomplishment of several spectrum engineering functions.

Article "Radio Monitoring", of J. V. Pareto Neto, published by *Telebras Review*, year IV, n. 1, Jan/Mar, 1980, displays in detail the capacities of the Monitoring system being implanted by the Ministry of Communications.

7. PILOT PROJECT

The detailing and implementation of a spectrum engineering system should be associated to an experimental work of a pilot project.

The geographical area chosen for the pilot project must allow inclusion of a wide range of interactions between the systems using the spectrum.

Such area must include urban areas with great concentration of spectrum use, separated by low utilization areas. Data should be obtained on the utilized frequencies and on the extension of the non utilized spectrum.

The pilot project should experimentally process hypothetical applications of authorizations to operate in the area.

Concepts and procedures should be tested as to eventual modifications and new developments.

8. RECOMMENDATIONS FOR IMPLANTING A SPECTRUM ENGINEERING SYSTEM

The setting of a spectrum engineering system involves an experimental work stage, in addition to the detailing and integration of all the project's elements and of the implementation altogether.

a) Pilot Project

To experimentally operate the frequency selection for a certain region, in order to determine its particularities and develop information for the project's detailing and implementation. The pilot installation should be regarded as the prototype of the operational system.

b) Analytical Capacities

To introduce the spectrum engineering analytical capacities, aiming at solving problems at national level.

c) Spectrum Monitoring

To introduce the spectrum monitoring capacities as a support to accomplish the measures on utilizations, and prevention and identification of interferences.

d) Data Base

To introduce the Data Base capacities, by standardizing the terms, detailing and implementing the automatized data base and establishing a coordinated data-gathering activity. The parts considered necessary to the analytical work should be rendered operational.

e) Standards

To revise the existing standards and develop and establish new standards, in keeping with the needs. Legally compulsory standards, during the fabrication phase, are necessary to rule the receiver's susceptibility and-undesirable radiations, for many classes of devices and equipment.

Major knowledge on the man-made radio noise and its effects can greatly help the spectrum engineering, mainly in what regards the following:

- To promote development of a consensus regarding parameters to be measured for a reliable and utilizable description of undesirable radiations.
- To coordinate the gathering of data on undesirable radiations, resulting from man's action (man-made radio noise).

- To study the behavior of systems subject to ambient noise.
- To develop formulations aimed at forecasting undesirable radiations in future times or in locations in which the data of measures in noise environments are not available.

9. SUGGESTIONS FOR THE TECHNICAL DETAILING IN IMPLEMENTING A SPECTRUM ENGINEERING SYSTEM

The implementation of a spectrum engineering system must be carried out according to priorities of the several activities which compose it.

Therefore, it is suggested that the project is divided in two parts, which are not chronologically isolated, with overlapping of some activities which belong to each of these parts, in common periods of time.

The first part of the project would consist of the following activities:

- Development of all the administrative system composed of automatized data base and management programs related to such administrative data base.
- Development of methodologies, mathematical models and electromagnetic compatibility analysis programs.
- Development of frequency designation models and models for analysing projects.
- Definition of technical and administrative procedures for gathering data.
- Preparation of manuals.
- Training courses on matters related to the first part of the project.

The second part would consist of the following activities:

- Refinement of methodologies, mathematical models and electromagnetic compatibility analysis programs, considering the aspects of propagation and influence of the topographic characteristics for frequencies above 30 MHz.
- Development of mathematical models and propagation forecast programs for the electromagnetic waves.
- Development of a system for gathering topographic data, composed of storing and data recuperation programs, and of a data base of the topographic characteristics.
- Development of rules and standards for the characteristics of the system, equipment and operation, as well as the development of a data base of equipment standards.

- Development of technical and administrative procedures for using the monitoring results, as well as the creation of a data base for supplying subsidies for the planning and solution to interferences.
- Development of the technical bases for the engineering planning.
- To organize the formation of a technical file.
- Development of procedures and criteria for allocating and designating frequencies.
- Development and implantation of a pilot project for testing and introducing eventual modifications and improvements to the spectrum engineering system.
- To carry out studies on the equipment characteristics and on RF modulation details and ambient noise, aiming at optimizing the spectrum use.
- Preparation of manuals.
- Training courses on the matters related to this second part of the project.

10. CONCLUSIONS

There are no technical barriers to developing and implanting a spectrum engineering system, whose capacities are technically essential for an effective spectrum management.

The two determinant factors which practically constitute the prerequisites to start the development aimed at implementing a spectrum engineering system are the following:

- a) Sure knowledge on the radioelectric waves' propagation and transmission techniques, as well as on data file management.
- b) Availability of a computerized system for introducing an automatized data base.

as (a) constitutes the basis for developing powerful techniques for constructing electromagnetic compatibility mathematical models, and (b) is indispensable for processing the great volume of data involved in a spectrum engineering system.

11. THANKS

Thanks, in memoriam, to my eternal master Prof. Arnel Picquenard, for his encouragement, support and assistance to my technical and professional formation, without which it wouldn't be possible for me to be contributing now with the present and modest research work.

12. BIBLIOGRAPHY

1. Picquenard, A. — "Radio Wave Propagation"; Philips Technical Library, Macmillan Press.
2. Picquenard, A. — "Telecommunications Complements"; Cia. Editora Nacional; 1976.
3. ITT — "Reference Data for Radio Engineers"; sixth edition, 1975.
4. GTE Lenkurt Incorporated — "Engineering Considerations for Microwave Communications System", 1972.
5. Hamsher, D. H. — "Communication System Engineering Handbook", McGraw-Hill, 1967.
6. Shmeling, Dietrich — "An Application of Electronic Data Processing as an Aid for the Radio Frequency Management", Seminar on Frequency Management and the Use of the Radio Frequency Spectrum; International Telecommunication Union, Document n. 28/74-E, Sept. 1974.
7. Computer Sciences Corporation — "Frequency Assignment Techniques for Microwave Systems. Phase II", NTIS U.S. Department of Commerce, Feb. 1972.
8. JTAC — Joint Technical Advisory Committee — "Radio Spectrum Utilization"; IEEE, 1964.
9. Harada, Wilson I. — "Frequency Spectrum Planning and Management", Telecommunications Technical Informative — PROMON NEWS, n.° 5, July, 1979.
10. Dadson, C.C. — "Radio Network and Radio Link Surveys Derived by Computer from a Terrain Data Base" — AGARD Conference on Terrain Profiles and Contours in E.M. Propagation, Preprint n.° 269, Sept. 1979.
11. Ministry of Communications — "Frequency Administration System" — Synthetical Study, n.° 001/78 — STP/SG — "Proposal for Implanting a Frequency Administration System for Brazil"; Planning and Technology Bureau, General Secretariat, Ministry of Communications, December, 1978.
12. JTAC — Joint Technical Advisory Committee — "Spectrum Engineering — A Key to Progress", IEEE, 1968.
13. Jansky, Donald M. — "Spectrum Management Techniques" — Multi-Volume EMC Encyclopedia Series vol. II, Don White Consultants, Inc. 1977.
14. Davis, E.D. and P. G. Tremper — "A Terrain Elevation Retrieval Program" — FCC — Federal Communications Commission, June, 1966.
15. Causebrook, J.H. — "Computer Prediction of UHF Broadcast Service Areas", BBC — The British Broadcasting Corporation; June, 1974.
16. Causebrook, J.H. — "Tropospheric Radio Wave Propagation over Irregular Terrain: The Computation of Field Strength for UHF Broadcasting"; BBC — The British Broadcasting Corporation, 1971.
17. Causebrook, J.H. and R.W. King — "Computer Programs for UHF Co-channel Interference Prediction Using a Terrain Data Bank", BBC — The British Broadcasting Corporation; Feb. 1974.
18. Kinase, A. — "Ground Wave Propagation in the VHF, UHF and SHF Bands" — NHK — Japan

- Broadcasting Corporation; 1976.
19. Izyumov, N. and D. Linde — "Fundamentals of Radio"; MIR Publishers, Moscow, 1976.
 20. Silva, G. e O. Barradas — "Radio Visibility Systems", Livros Técnicos e Científicos Editora, Embratel, 1977.
 21. Pareto Neto, J. V. — "Radio Monitoring"; Telebras Review, year IV, n. 1, Jan/Mar, 1980.
 22. Harada, Wilson I. — "Model of a Frequency Spectrum Engineering System at National Level", Telebras Review, year V, N. 4, Dec, 1981.
 23. Wiederhold, G. — "Data Base Design"; MacGraw-Hill Kogakusha, 1977.
 24. Molina, F. W. — "A Practical Data Base Design Method"; Data Base, pp. 3-11, summer 1979.
 25. McGee, W. C. — "On User Criteria for Data Model Evaluation"; ACM — Transactions on Database Systems", Vol. 1, N. 4, Dec. 1976, pp. 370 — 387.
 26. Ullmann, J. D. — "Principles of Database Systems"; Computer Science Press, 1980.
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OBJECTIVE EMC CRITERIA FOR RADIO SYSTEMS : DO THEY EXIST?

Complete presentation of the entire family of EMC criteria for radio systems is attempted. The level-spacing rules for signals and distance-spacing rules for stations are discussed. The conventional approach /in CCIR documents/ as well as advanced analyses, elaborated in the USA are outlined. The methods and the terms seem to be noncompatible with each other.

Some methods are regarded as "objectively" formulated. In this respect essential difficulties are emphasized. The inherent obstacle lies in the man-machine interaction at the user's side. Ultimately, information transfer to humans has to be assessed subjectively. Subjective performance scoring is the very basis for the EMC criteria.

The objective and subjective aspects of the EMC criteria for radio systems are presented, as dependent on the

1. INTRODUCTION : THE EMC CRITERIA

The electromagnetic compatibility of radio systems can be interpreted as the state of undisturbed coexistence and proper functioning of equipment, in a given environment. It follows that some measures of radio equipment degradation due to interference are needed. It follows also that quantitative bounds between the state of compatibility and the opposite state of non-compatibility have to be set up.

These bounds are termed the EMC criteria /for radio systems/. In general, criteria are expressed quantitatively in terms of some pertinent electromagnetic space variables: geometric coordinates, time, frequency and signal levels. EMC criteria are indispensable for radio systems engineering. They are also of importance for equipment engineering, spectrum management and standardization.

This paper is aimed at completely presenting the whole family of EMC criteria, partly in a novel form. The objectiveness, i.e. the objective measurability of the criteria will be scrutinized, with reference to the CCIR Report 525 /on protection ratios/ and the Report 526 /on performance measures/.

The author tried to select more difficult and less elaborated problems in the delineated area. Therefore, point-to-area nondirectional radio systems are primarily considered rather than point-to-point directional ones. Major attention is paid to radio systems transmitting analogue information rather than to systems with digi-

tal information. With analog information, many pertinent EMC criteria seem to be objective. It will be shown that the appearances are somewhat deceptive.

2. SYSTEM-ORIENTED STATION-SPACING CRITERIA

With unguided transmission in point-to-area systems, the intentional signal transfer is always accompanied by unintentional interfering action. Although space-frequency slots are utilized to separate various radio links, conflicts do occur due to the reuse of frequency channels and to the spurious spill out of the slot.

Evidently, the interference of co-channel signals constitutes the worst case in EMC analysis of radio systems. The pertinent compatibility criterion is based upon two spatial ranges of a radio station. The service zone, with its service radius d_s , determines the area of correct perception of the transmitted signals. The radius d_s is defined for a given transmitter with respect to a given receiver, with an underlying measure for "correct performance" and with a predetermined probability of exceeding the performance bound.

On the other side, the interference zone /with its radius d_i / is understood as the area ^{beyond} which the interference I is not perceptible even with the weakest /minimum usable/ desired signal S . Similar measures of performance and probability have to be introduced in this case, for the three objects /i.e. two transmitters and one receiver/involved.

Now, the basic system-oriented criterion of co-channel compatibility for a set of radio stations reads: the service zones should not coincide with the interference zones. For any pair of desired/interfering transmitters /see Fig. 1/, the criterion is expressed

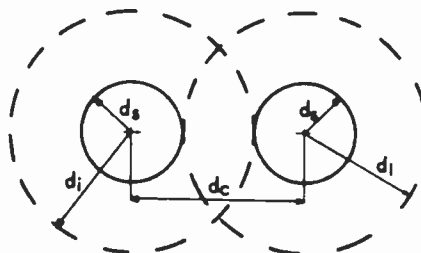


Fig. 1. Two closely spaced co-channel stations. The coordination distance depends on the action radii of the stations.

as a one-dimensional station-spacing bound:

$$d_c \geq d_s + d_i \quad / 1 /$$

where d_c is the coordination distance of co-channel transmitters.

Of course, co-site operation of co-channel transmitters is not admissible. Apart from this, the criterion /1/ is quite general, and allows for arbitrary modulations of two transmitters.^{x/}

For radio systems spread over a territory, the station-spacing criterion /1/ is natural and consistent. It is nominally measurable insofar as the action radii of radio transmitters can be assessed by field-strength measurements. Note, however, that two threshold values have to be predetermined:

- the minimum usable signal strength $S_{\min}$ for the desired signal to be perceptible, and
- the minimum signal-to-cochannel-interference S/I ratio, for the interference to be negligible.

In other words, the system-oriented station-spacing criteria are not autonomous, because they rely upon other criteria defined by signal levels at the receiver input /resp. at the receiving antenna/.

In the EMC literature, the receiver-oriented criteria are regarded as fundamental. In the CCIR - documents, e.g. [1,2,3,4], the $(S/I)_{\min}$ "protection ratios" are emphasized, while the station-spacing rules are disregarded. The same applies to the U.S.-borne literature, e.g. [5,6,7], where the term "performance threshold" is used instead.

3. RECEIVER-ORIENTED LEVEL-SPACING CRITERIA

At the receiver input, the desired signal has to dominate the environmental noise, the receiver noise /virtually transferred to the receiver input/ and interfering signals.

The processing of noise in an analogue radio receiver in the "weak-noise, strong-signal" condition can be summarized as follows. Noise power is linearly and additively transferred from input to output terminals of the receiver. The receiver as a whole can be regarded as a two-port "transformer of the S/N ratio". This model, see Fig. 2, is found implicit in the CCIR Recommendation 331 [8], and has been studied by this author in [9].

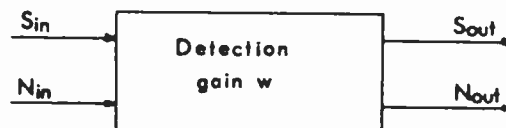


Fig. 2. An analogue radio receiver, processing strong signal and weak noise, can be regarded as the "transformer of SNR".

x/ The interference-radius concept can be generalized in the frequency domain. The idea is explained in a paper by this author, submitted to the EMC'81 Symposium in Zürich.

Denoting the detection gain by w , we arrive at the relation between two signal-to-noise level spacings:

$$(S/N)_{out} = (S/N)_{in} + w \quad / 2 /$$

with median decibel values throughout. The output S/N level spacing is a practical measure for the "noise-only" case. With constant N_{in} and fixed modulation parameters - the S_{min} , responsible for the service radius, depends on the minimum-acceptable $(S/N)_{out}$. The levels and the level spacings here are objectively measurable, and are rather accurately related to subjective performance scoring [3]. Thus, our set of criteria with respect to noise becomes extended, but measurable throughout. These criteria are sufficient for assessing the receiver sensitivity and the station service range.

The simple model of Fig. 2 does not hold for the processing of typical interfering signals in an analogue radio receiver. As a rule, the level spacing $(S/I)_{in}$ is objectively measurable and serves well for defining the "protection ratio" interference criterion. However, interfering signals produce various additive and non-additive effects /like crosstalk, distortion, masking, etc./ at the receiver output. Therefore, in many cases expressing $(S/I)_{out}$ in terms of power levels can be meaningless. The simple level-spacing relation $(S/N)_{in} \Leftrightarrow (S/N)_{out}$ has usually no counterpart with interfering signals.

It follows that special output performance measures, see later §4, must be employed in the protection-ratio methodology. Nevertheless, the $(S/I)_{in}$ level spacing is commonly used as the main criterion of compatibility with respect to co-channel interfering signals, provided the signal level overcomes the noise level.

Thanks to an enormous effort of the world radio-engineering community, the matrixed tables of RF co-channel protection-ratio values have been compiled and published [3,5]. Rows and columns denote the desired/interfering classes of emission /with subclasses added if necessary/. The averaged values of $(S/I)_{min}$ are accompanied by more or less precise description of the performance level, i.e. output-quality degradation due to interference. These levels range from MINIT /minimum interference threshold/ to IUQ /just usable quality/.

Summing up, the receiver input level-spacing criteria with respect to noise appear to be much more objectively founded than those pertaining to the signal interference.

Let us now mention that the simple input-level-spacing approach can be refined in two directions. First, the probability of exceeding a given protection-ratio value can be calculated, taking into account the random variability of propagation losses.

Moreover, spurious properties of radio transmitters and receivers can be allowed for. Then, multiple undesired reception modes are investigated with respect to resulting co-channel S/I ratios at the detector input, so that potentially harmful cases can be extracted and analyzed.

Both directions of the advanced EMC analysis are well represented /with different terminology/ in U.S. literature sponsored by the IEEE, ECAC and the EMC-Institute. Our intention here is to emphasize the very roots of the protection-ratio criteria as depending on the system performance at the user's side.

4. USER-ORIENTED OUTPUT PERFORMANCE CRITERIA

Output terminals of radio systems transmitting analogue information are usually equipped with transducers acting on human operators or users. The ultimate information transfer through human senses into brain is, so far, mathematically untractable. Therefore, special measures of information intelligibility /like articulation score AS and articulation index AI in voice communication/ have been established in order to assess the system performance, compare [4].

Output performance estimates, as affected by noise and interference, result from subjective statistical scoring by "typical observers". Efforts to replace humans by complex machines when detecting the perceptibility of interference or determining the quality impairment cannot be regarded as successful, see [1]. In consequence, different performance levels or impairment grades are strongly subjective as well as all output performance measures and criteria for analogue systems. The same applies to digital systems /PCM, DM/ for digital transmission of analogue primary signals.

As the only exception, the case of interfering noise-like signals resembles the simple "noise-only" case in an analogue system /considered in §3/. In this instance, EMC can be approximately analyzed with objectively measurable output S/N level spacing. It follows that simple semi-objective criteria are sufficient for determining the protection ratio in this case, i.e. for analyzing the compatibility with respect to noise-like signals.

Contrarily, the analysis of interference caused by typical analogue signals in radio systems has to be based upon subjective performance measures. This can be done in two ways. First, the protection-ratios for analogue radio systems, disturbed by any /analogue or digital/ interference, can be determined with a fixed value of output performance criterion /e.g. 50% AS [5] or 0,7 AI [3] for voice communication, or the minimum interference threshold MINIT for sound broadcasting, see [4] /.

Secondly, subjective performance criteria can be - in some degree - replaced by simplified objective tests and specifications.

This is the basic idea of measuring the receiver selectivity or, for instance, susceptibility to intermodulation. However, a reference to the subjectively assessed output performance /like AI/ is always needed to verify the procedures and the numeric criteria.

Note that a radically different situation is encountered in digital systems for text /or alphanumeric data/ transmission. The system output delivers the final product, not necessarily "consumed" by humans. Then, simple unambiguous measures of correctness /e.g. the character error rates/ do exist and serve as the objective reference [3,7].

The S/N and S/I level-spacing criteria for digital systems can be evaluated objectively for EMC analysis and prediction. Then the main task of the system specialist is to determine the random variability of system parameters; and - next - to calculate the probability of meeting /i.e. exceeding/ the 10^{-n} output error rate, where n depends on the system objectives and goals.

5. CONCLUSION: THE FAMILY OF EMC CRITERIA

Electromagnetic compatibility of radio systems depends strongly on the subjective properties of human users. Therefore, EMC measures, criteria and specifications are /or have to be/ based upon subjective scoring of system's output performance. The only exception pertains to digital systems transmitting coded primary information /texts or digital data/.

It follows that only in the latter case strictly objective criteria can be formulated and used for EMC analysis and prediction. In all other cases /i.e. with analogue or digital transmission of analogue information/ all EMC criteria are directly or indirectly subjective. The output performance criteria rely directly upon subjective performance scoring. The receiver input S/I protection ratios and the station-spacing criteria for radio systems are closely related to subjective performance criteria.

Let us now visualize the entire family of EMC criteria for radio systems /Fig. 3/. Left side of the figure shows three types

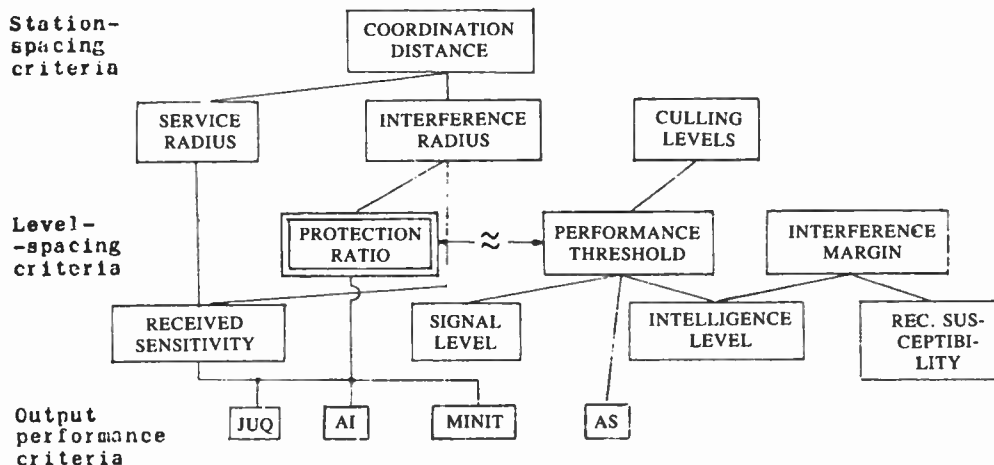


Fig. 3. Three types of the EMC criteria for radio systems. Some signal and performance measures are also shown.

of criteria, considered in §2, §3 and §4 of this paper. Some additional measures /parameters/ used in defining and evaluating of the criteria are also shown. The right side of Fig. 3 is concerned with the U.S.-borne methodology of EMC analysis, which is slightly more detailed and utilizes differently named terms.

It is hoped that the diagram in Fig. 3, as well as the considerations in this paper might aid in classifying and better understanding the EMC criteria and their non-objective character.

6. REFERENCES

- 1 C.C.I.R. Recommendation 240: Signal-interference Protection Ratios. Vol. III, Geneva 1979.
- 2 C.C.I.R. Report 358: Signal-to-interference Protection Ratios... Required in the Mobile Services. Vol. VIII, Geneva 1979.
- 3 C.C.I.R. Report 525: Provisional Signal-to-interference Protection Ratios Required for Spectrum Utilization Investigations. Vol. I, Geneva 1979.
- 4 C.C.I.R. Report 526: Measures of Voice Transmission Performance Applicable for Electromagnetic Compatibility Analysis. Vol. I, Geneva 1979.
- 5 D.H.J. White: Electromagnetic Compatibility Prediction and Analysis Techniques /Vol. V/. Germantown /Md/, 1972, EMI.
- 6 ECAC Communications/Electronics Receiver Performance Degradation Handbook. Springfield /Va/, 1975, NTIS.
- 7 W.G.Duff. A Handbook on Mobile Communications. Germantown /Md/, 1976, EMI.
- 8 C.C.I.R. Recommendation 331: Noise and Sensitivity of Receivers. Vol. I, Geneva 1979.
- 9 W.Hotkiewicz /Ed/: Kompatybilność elektromagnetyczna w radio-technice. Warszawa 1978, WKiŁ.

MEASURES OF VOICE TRANSMISSION PERFORMANCE APPLICABLE FOR ELECTROMAGNETIC COMPATIBILITY ANALYSIS

1. General

This Report discusses the measurement of baseband output signals (desired and undesired) to evaluate performance degradation of voice-modulated radio systems. Such measures are important as a means of quantitative assessment of interference effects in spectrum utilization and may be used in presenting "signal to interference" protection ratios as in Report 525. Objective measures are valuable for computing interference effects as discussed in Report 520.

The "complete" mathematical modelling of a system's performance is the objective of a prediction analysis. However, there does not exist one mathematical operation for analyzing all types of system performance and the best that can be accomplished is to use the measures that are most appropriate to a particular system (i.e., mean-square measures, probability measures, etc.). The basic difficulty is to determine what exact type of evaluation should be associated with interference degradation. Although considerable research has been conducted on performance degradation evaluation, the desired outputs for receiving systems still reduce to a few basic types. In particular, for voice systems. Articulation Score (the percentage of words correctly received) is still used as the main intelligibility standard. For digital systems, the probability of detection and probability of false alarm are desired. For analogue signals, the mean-square error (or the r.m.s. error) is usually desired.

The following discussion will examine the performance measures of articulation score, articulation index. CORODIM and minimum interference thresholds for voice systems.

2. Articulation score

The basic measure of the intelligibility of a voice system is in terms of the percentage of words correctly understood over a channel perturbed by interference. This intelligibility indication has been designated as an articulation score (AS) and its measurement is usually conducted with specific types of words or syllables as well as specific system parameters [Robertson, 1962]. In an attempt to define the main voice parameters that are involved, experiments have been conducted by varying (at audio frequencies) the word content, bandwidth, audio (S/N) ratio and the types of talkers and listeners that are involved. Through these experiments, articulation scores have been obtained as functions of the above variables and, as one would expect, the scores increased with increasing bandwidth, number of syllables in the words, speaker-listener familiarity and audio (S/N) ratio.

If the receiving system is subjected to a range of distortion or masking conditions, the articulation score may then be determined as a function of the interfering condition. Fig. 1 presents typical articulation score curves for different phonetically balanced (PB) word groupings in which the interference was white noise of various bandwidths [Robertson, 1962]. White noise, which contains a continuous uniform spectrum, is one of the most effective maskers of speech and is often used in speech intelligibility studies as a standard or reference interference.

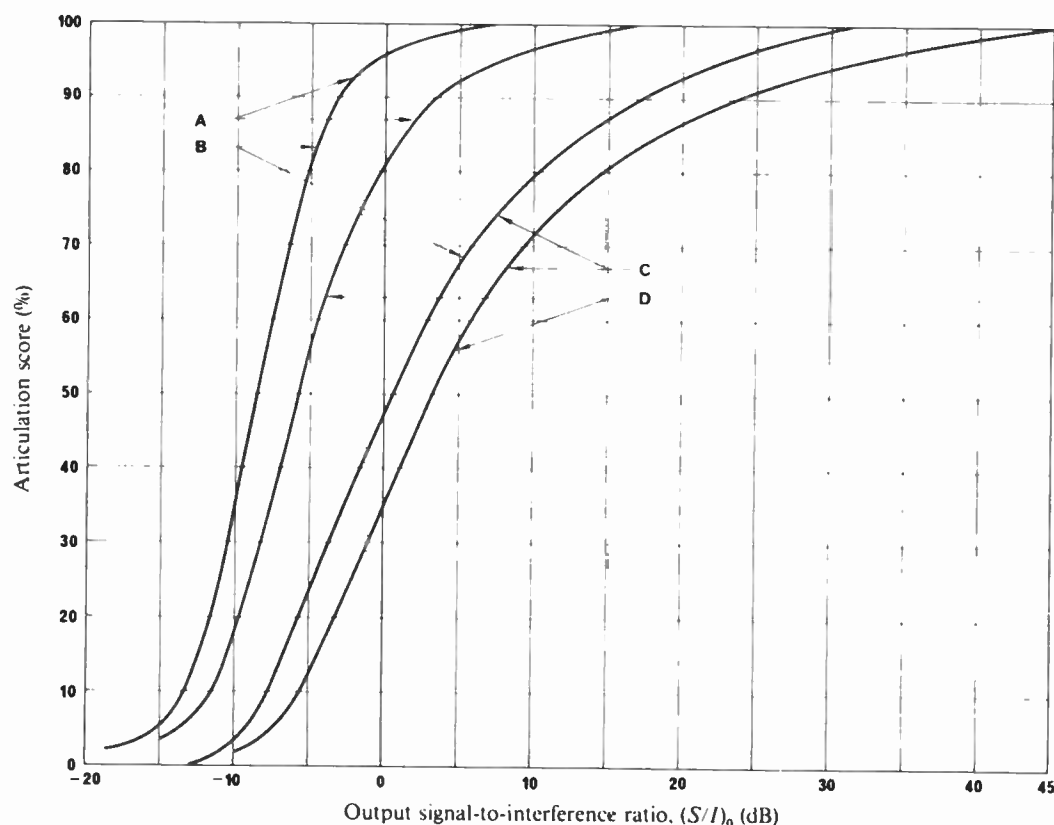


FIGURE 1 — Articulation score as a function of noise interference

- A: phonetically balanced word groupings: 50
- B: white-noise bandwidth ≥ 6 kHz
- C: phonetically balanced word groupings: 1000
- D: white-noise bandwidth ≈ 3 kHz

The articulation testing procedure is not simple nor has it always been standardized. Because it deals with the performance of human beings, the tests can yield variable results in individual cases when proper statistical safeguards are not taken. It is generally necessary to use a number of listeners so as to obtain statistically meaningful results. Proper conduct of the test is tedious and time consuming. The situation is aggravated by the necessity for training the listeners to an efficiency level where the improvement resulting from repeated exposure to most word lists no longer occurs. The test procedures, the material used, and the techniques employed to measure the average power of the desired and undesired signals vary among investigators.

In spite of such shortcomings, the tests provide the most valid objective method available for evaluating the intelligibility of speech communication components or systems. When the articulation score tests are carefully organized, the scores are repeatable 68% of the time within a 2 dB data spread.

The articulation score test is generally used as the basic standard of intelligibility. However, degradation measurements involving a large number of parameter variations, signal-to-noise, undesired signal pulse width, undesired signal pulse rate, etc., can be required for an interference investigation. Because of the time required to run articulation score tests with these parameter variations, it is desired to use an automated measure. A number of techniques that can be automated will be subsequently discussed.

3. Articulation index

The best predictor of voice intelligibility for a channel interfered with by noise and/or interference is the percentage of words which are correctly perceived by a group of trained listeners (the articulation score testing procedure). The previous discussion delineated the difficulties of making AS tests. In order to be able to circumvent these difficulties, the Articulation Index (AI) procedure was developed and validated for white noise interference. In order to validate the AI procedure for different types of receivers interfered with by various types of undesired signals, calibration curves relating AI to simultaneously measured AS scores were examined. Thompson [1966 and 1967] discusses this problem and shows the possible variation of AI versus AS with the AI measured by means of the Voice Intelligibility Analysis Set (VIAS) procedure for non-pulsed interfering signals. Hatch, *et al.*, [1970] discussed the same problem for pulsed signals interfering with AM receivers. These reports indicate that, for the continuous modulation and pulsed interference cases, the relationship between AS and AI was not constant.

Experience has shown that the smallest value of AI which consistently provides correct information transfer in the presence of normal language configuration is 0.7 on a scale ranging from 0 to 1, and the lowest acceptable value of AI for a useful link is 0.3 [Kryter and Licklider, 1963]. For the narrow-band AM, FM and SSB interference cases, the Thompson reports show that the range of variation in the AS scores for the typical AI criteria of 0.7 and 0.3 are 8% and 26% respectively. The AI criterion of 0.7, therefore, results in a reasonably constant standard in terms of AS intelligibility scores. The AI criterion of 0.3, however, can result in values of AS between 11% and 37% for the cases of AM, FM and SSB modulation with the same types of interference. Therefore, the type of desired modulation and interference would have to be specified in order to accurately determine a lower acceptability threshold.

For the pulsed interference cases, the AS score is approximately independent of AI score [Hatch, *et al.*, 1970] because of the large amount of redundancy in a voice signal and the low duty cycle of the pulsed interference. AS scores typically vary between about 98% and 95% for AI scores from 0.7 to 0.3, respectively. Because of the large variation in AI scores for a relatively small change in AS scores, an AI value of 0.7 was chosen to describe the lower threshold for pulsed interference [Hatch, *et al.*, 1970].

There are a number of approaches that provide a measure of the effects of undesired signals on speech communications systems by calculation and/or instrumentation of a criterion measure in each of a number of bands in the speech frequency spectrum. The articulation index (AI) approach is relatively well-known. Others are the formant intelligibility and pattern correspondence index (PCI) approaches.

All these methods operate on the short-term power spectrum to obtain a performance measure of speech. Basically, the procedures stem from the original work of French and Steinberg that led to the concept of articulation index (AI) [French and Steinberg, 1947]. The results of their work, essentially, determined that one can divide the speech spectrum into n unequal contiguous bands which contribute equally to intelligibility (in terms of AS). The method ideally assumes there are negligible effects on intelligibility due to the speech sounds from one band masking, or in some way affecting, sound components of another band. Effects of noise and other factors (interference, distortion) prevent these bands from making their full contribution to intelligibility. The intensity of speech varies according to the band. For these and other reasons, a weighting factor must be included for each band in recognition of the fact that some bands do not make the maximum possible contribution to speech intelligibility. The weighting factors vary for each band according to the ratio of the speech energy (in that band) to the hearing threshold. When the speech energy level in the band is 30 dB or more above the threshold level, it contributes its maximum value and hence has a unit weighting factor. When the speech energy level is between 0

and 30 dB above the threshold, the band's contribution is proportional to its energy level, in decibels. When the energy level is below the threshold, there is no contribution to intelligibility and the weighting factor vanishes. These weighting factors are additive and the sum can be used with empirical curves to determine the corresponding articulation score.

The French and Steinberg method is, however, still fairly complex and simpler methods have been developed. Another procedure, the tonal method, asserts that the intelligibility of speech depends, not on the absolute magnitude of speech and undesired signal intensities, but rather on the amount by which the speech exceeds the auditory threshold level for a particular type of noise. This perception level is determined in each of twenty equally contributing bands covering 100 to 10 000 Hz for standardized speech and for particular undesired signals. The tonal method, "formant intelligibility" [Tkachenko, 1955] has the property of additivity, such that the overall intelligibility is the sum of the contributions from each band.

The formant intelligibility process is readily automated by feeding pure tones from an artificial voice source, one at a time, to each of the n channels. Listeners then measure the excess noise in each band by attenuating the standard test signal until it is barely audible. The formant intelligibility can then be related to syllabic intelligibility by empirically obtained curves. The importance of this method is that it eliminates most of the variabilities associated with the transmission process and eliminates the articulation scoring procedure. It does not, however, eliminate the listener as the final subjective evaluator.

Other methods have been developed which measure the effects of the undesired signals without subjective listener evaluation. Two of these have led to the development of testing machines based upon the assumption that speech intelligibility resides principally in the short term spectrum [Licklider *et al.*, 1959; Thompson, 1967].

One machine measures a number called the pattern correspondence index (PCI) [Licklider *et al.*, 1959]. This number is an index of the correlation between a speech spectrum without interference and the same speech pattern with interference. The PCI is actually obtained by taking the average spectral difference between recorded sentences without interference and the transmitted sentences with interference. The PCI, theoretically, has a monotonic relationship to articulation score and should be calibrated for white noise interference. It is postulated that the curve for white noise is universally applicable as a function of signal-to-noise, independent of the type of interference. If curves of articulation score as a function of noise are available for the particular undesired-signal case being investigated, a direct translation between PCI and AS can be made. This machine uses an autocorrelation measure of the desired signal and the corrupt output. Therefore, except for possible mechanical deficiencies, this approach is adequate or inadequate depending on the effectiveness of the autocorrelation measure for the particular interference being considered.

The other machine, produced to measure voice intelligibility mechanically, is called the Voice Intelligibility Analysis Set (VIAS) [Thompson, 1967; Fitts, 1963]. This device also operates on the principle, previously described, of dividing the spectrum into a number (fourteen) of unequal continuous bandwidths and measuring the desired-to-undesired signal ratio relative to the hearing threshold. The width of each band is selected such that all bands contribute equally to intelligibility. The sum of the contributions from each band is then averaged over all fourteen bands to produce the composite articulation index. The fourteen VIAS frequency bands are shown in Fig. 2 and the calculation of the articulation index is depicted graphically in Fig. 3. To perform this basic calculation, a synthetic desired speech signal, which consists of a triangle-modulated 950 Hz tone, is transmitted over the test channel and is then measured by the recording portion of the device, in order to determine representative speech levels in the 14 bands. The average power (over a period of 17 s) of the undesired signal in the 14 bands is then measured and from knowledge of the average desired signal in that band, the desired-to-undesired signal ratio is computed. The articulation index is then computed by summing the contribution from each of the 14 bands. VIAS incorporates empirically-derived correction factors to account for the upward spread of masking. This is the phenomenon in which interference at a low frequency masks a higher frequency portion of the voice spectrum. A correction must also be inserted manually for the receiver's frequency characteristics, which are determined by measurement of the system. Thompson [1967] discusses this correction factor in detail. The important difference between the articulation index machines and the tonal method is the simplification to one test signal and the elimination of the subjective evaluation. The VIAS method implies that interfering effects are independent and, consequently, additive. This last statement is especially critical since the use of a number based on this technique, even for the simplest use (i.e., that of system comparison and not performance measurement), requires validation for situations in which the undesired signals (interference) are not additive.

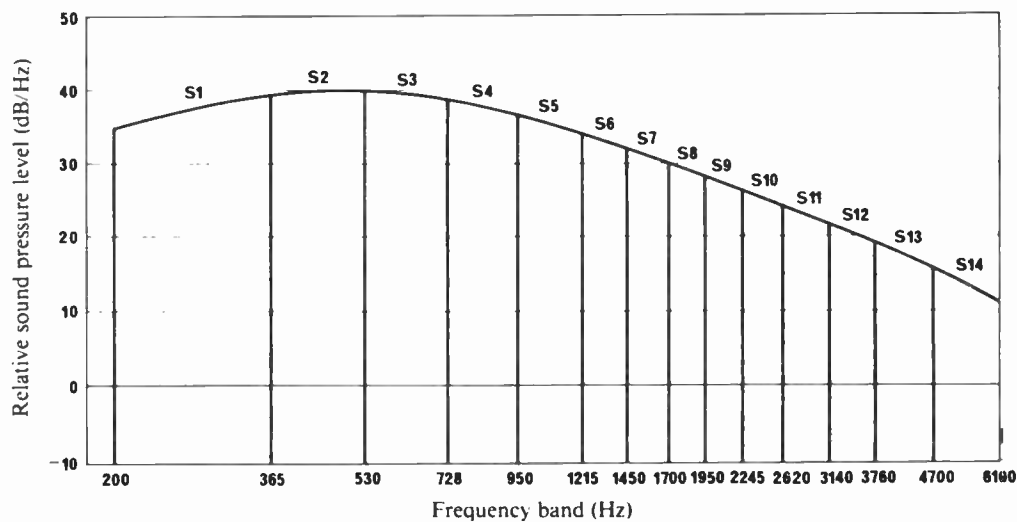


FIGURE 2 — Long term speech spectrum and associated AI bands

Note. — The curve represents the voice spectrum, while the S values represent the voice power in each AI band.

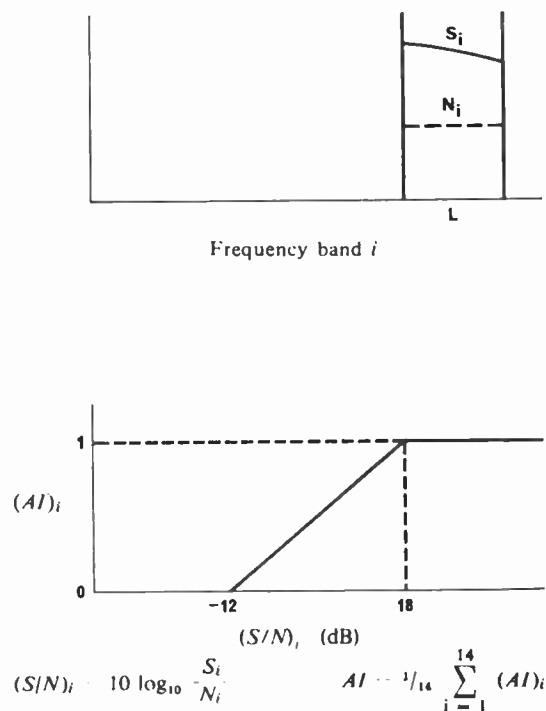


FIGURE 3

Theoretical calculation of articulation index score

S : Desired signal N : Noise

Another device that automatically calculates the articulation index, in a slightly different manner, is the Speech Communications Index Meter (SCIM) [Hudson and Limburg, 1964]. The basic difference between this device and VIAS is the manner in which the synthetic voice signal is generated. In the SCIM machine, a noise spectrum is transmitted that has been frequency-filtered or shaped to correspond to the average voice spectrum. This signal is then filtered into nine frequency bands and used to compute the desired-to-undesired signal ratios. Ideally, therefore, this system has an advantage over VIAS in that the actual synthetic signal power in band n is used rather than an extrapolation of that signal. The SCIM machine also takes into account the upward spread of the masking effect.

The latest version of the automated articulation index calculator is the PSI/COMP machine. The performance of this machine should be very similar to the SCIM machine, since it employs the same basic signal processing.

The American National Standards Institute (ANSI) has specified a procedure for calculating AI [ANSI, 1969]. The major difference in this procedure and the previous machine scoring procedures is that the 20 band method of calculating AI has been used.

Another concept, called CORODIM (Correlation of the Recognition of Degradation with Intelligibility Measurements), has also been developed [Strohmeyer *et al.*, 1967]. This technique is similar to the previous methods in that the baseband power spectrum is again used as a basic measure. It differs from other automatic intelligibility measuring techniques in that it transmits a test signal composed of speech-like sounds representative of phonemic consonants. The degradation manifests itself as an "effective noise spectrum" which is measured and matched to one of a library of reference noise spectra. For each reference spectrum, data are stored relating phonemic recognition probability to speech-to-noise ratio. Thus, by means of the spectrum matching operation and a measurement of signal-to-noise ratio, each component sound of the test signal is assigned a probability of recognition. These values are weighted by phoneme probability of occurrence factors, summed and normalized to obtain a score representative of word intelligibility based on either initial or final consonant recognition. CORODIM evaluates scores for both the initial and final consonants and takes their product for the overall word intelligibility score.

The scores obtainable for CORODIM are directly comparable to listener panels [Strohmeyer *et al.*, 1967]. If sufficient audio spectra have been pretested, the AS results from CORODIM should also be generally applicable for other (but not necessarily all) interfering signals. This technique, therefore, has an important theoretical advantage over all previous automated scoring techniques.

CORODIM has potential use in future voice degradation problems. In particular, it is only necessary to couple the CORODIM process with the simulated receiver output described in Report 520 to obtain simulated articulation scores.

4. Minimum interference thresholds

The degradation threshold, or minimum interference threshold (MINIT), although not a performance threshold measure, is useful in assessing the effects of interference for voice transmissions. It is the level at which the interference is first detected in the audio output. Since this level is obtained through a subjective evaluation, there is an inherent variability due to the human observer and also one due to the manner in which the threshold is defined to the observer. In particular, the threshold level can be determined by decreasing or increasing the interference level relative to a fixed desired signal level. In the first case, the test begins with very noticeable interference and stops when the interference is just perceptible. In the second case, the interference is increased until the subject records that the interference was first heard. The first method is more repeatable than the second, although care must be taken to ensure that the level recorded is indeed the last level that can be heard. This is easily implemented by allowing the subject to adjust the interference level above and below the threshold level to definitely determine that the interference was or was not heard.

The test can also be made without the presence of a desired signal. This type of test would be used for high fidelity or television sound systems where the presence of interference during the time the desired signal intelligence is absent may be unacceptable. A lower threshold interference level would be required for this case than if the desired signal were present, since the desired signal aids in masking the presence of the interference.

The validity of this type of measurement is shown by [Egan, 1944]. Two separate listening crews were used to determine the threshold of perceptibility (MINIT) for speech masked by noise. One crew contained three experienced listeners and the other contained eight inexperienced listeners. The signal (speech)-to-noise ratio (S/N) was then adjusted by each listener until he obtained the threshold of perceptibility. With the exception of one individual in the crew of eight, the maximum variation in the S/N ratio required by each listener was 3 dB. The average difference in S/N between the two crews was less than 1 dB.

The MINIT can be obtained from an objective procedure by measuring the interference level which produces approximately a 1 dB change in the desired signal-to-interference plus noise ratio. This has been documented in the literature as a "Just Noticeable Difference" [Miller, 1947]. The procedure can also be automated by taking the simulated receiver output described in Report 520 and obtaining the input level of interference which corresponds to a 1 dB change in the simulated output desired-to-undesired signal ratio.

Measurements have shown that the MINIT is a function of the interference-to-noise ratio. For a specified signal-to-noise ratio, the MINIT therefore also corresponds to a signal-to-interference ratio. In the linear portion of the receiver, a change in the desired signal level results in a corresponding change in the signal-to-noise and linearly changes the signal-to-interference although the interference-to-noise remains constant.

The MINIT is a threshold that can be used as the boundary between a region of negligible interference and a region of permissible interference and can be used in frequency coordination problems (see [CCIR, 1974-78]).

5. Speech quality

The concept of speech quality encompasses the total auditory impression of speech on a listener. In addition to intelligibility, speech quality includes factors such as loudness, naturalness and clarity, speaker identifiability, timbre and rhythmic character, systematic amplitude or time distortions, and many others. Fidelity of speech is usually measured by subjective methods. Subjective methods as opposed to objective methods are most often used when intelligibility in terms of articulation score is almost 100%. A Special Committee [IEEE, 1969] was organized in 1963 to study and to recommend a practice for *subjective* speech quality measurements. After six years of study, the committee concluded that a single method should not be recommended. However, they did narrow their selection to three *subjective* methods: the Isopreference Method, the Relative Preference Method, and the Category Judgement Method. The three methods all require a trained listening group, who must compare and choose between a test signal and a reference signal. These methods are difficult to implement because of the number of people employed and the amount of time needed to administer a test.

6. Psophometer method

The disturbing effects of additive noise and/or interference on a voice signal have also been evaluated by the psophometer method [CCITT, 1980; Belger and von Rautenfeld, 1965]. A psophometer is a power meter which contains a baseband filter with a frequency response that simulates the typical frequency response of an electro-acoustic transducer (such as an earphone or a loud speaker) and that of human ear. When the disturbing effects of additive noise and/or interfering signals are a major problem of voice quality degradation, hearing tests for assessment of subjective preference quality can be substituted by measurements of the ratio of voice signal power to psophometrically weighted noise and/or interference power. In order to effectively use this method for the general spectrum utilization problem, it is, however, necessary to subjectively evaluate various power ratio criteria for different types of demodulated baseband AM, FM, SSB, Pulsed, etc. interfering signals – that is, as one example, it is necessary to determine subjectively what psophometrically weighted output signal-to-interference ratio corresponds to “good commercial quality” for FM interference being demodulated by a FM receiver with a desired FM signal present. This type of evaluation has only been accomplished for white Gaussian noise.

7. Conclusions

Several measures of baseband signals (desired and undesired) are described which permit evaluation of voice transmission degradation due to interference and/or noise. Those most easily computerized are the articulation index and the MINIT methods. These methods have been used to calculate voice degradation in the output of the Receiver Performance Model described in Report 520 and documented [ECAC, 1975].

REFERENCES

- ANSI [1969] Methods for calculation of articulation index. ANSI S3.5-1969. American National Standards Institute, New York.
- BELGER, E. and VON RAUTENFELD, F. [1965] The objective measurement of the RF wanted-to-interfering signal ratio in amplitude-modulation sound broadcasting. *EBU Rev.*, **90**, Part A, 57-64.
- CCITT [1980] Psophometers (Apparatus for the objective measurement of circuit noise). Recommendation P.53, CCITT Yellow Book, Vol. V.
- ECAC [August, 1975] Communications/electronics receiver performance degradation handbook. The spectrum management support division, Office of Telecommunications, US Department of Commerce and the Electromagnetic Compatibility Analysis Center (ECAC), ESD-TR-75-013, NTIS, AD-A016400. (Available from the US Department of Commerce, National Technical Information Service, Springfield, Va., USA.)
- EGAN, J. [November, 1944] Articulation testing methods II. OSRD Report No. 3802, Research on Sound Control, Psycho-Acoustic Laboratory. Harvard University, Cambridge, Massachusetts.
- FITTS, R. [August, 1963] Electronic evaluation of voice communications systems. RADC-TDR-63-355 National Technical Information Service (NTIS), US Dept. of Commerce, Washington.
- FRENCH, N. and STEINBERG, J. [1947] Factors governing the intelligibility of speech sounds. *J. Acous. Soc. of Amer.*, Vol. 19, 90-119.
- HATCH, W., HINKLE, R. and MAYHER, R. [1970] Analysis of pulsed interference to amplitude modulated receiver. IEEE International Electromagnetic Compatibility Symposium Record, Philadelphia, Pennsylvania.

- HUDSON, C. and LIMBURG, W. [November, 1964] Loss of system effectiveness due to electromagnetic interference. Tenth Tri-Service Conference on Electromagnetic Compatibility, Chicago, Illinois; National Technical Information Service (NTIS), US Dept. of Commerce, Washington.
- IEEE [September, 1969] Special Committee, *IEEE Trans. Audio and Electroacoustics*, Vol. Au-17, 3.
- KRYTER, K. D. and LICKLIDER, J. C. R. [1963] *Human Engineering Guide to Equipment Design*. (Edited by Morgan, Cook, Chapanis and Lund), McGraw-Hill Book Company, Inc., New York, NY.
- LICKLIDER, J. C. R., BISBERG, A. and SCHWARZLANDER, H. [1959] An electronic device to measure the intelligibility of speech. Proceedings of The National Electronic Conference, 15.
- MILLER, G. A. [1947] Sensitivity to changes in the intensity of white noise and its relation to masking and loudness. *J. Acous. Soc. of Amer.*, Vol. 19, 609.
- ROBERTSON, D. [April, 1962] A comparison of the procedures and results of intelligibility tests for a number of interference conditions. ECAC Technical Memorandum No. X003-10; National Technical Information Service (NTIS), US Dept. of Commerce, Washington.
- STROHMEYER, G., RICHARDS, J. and SCHULTZ, J. [August, 1967] Voice quality determination study. RADC-TR-67-319. National Technical Information Service (NTIS), US Dept. of Commerce, Washington.
- THOMPSON, A. [April, 1966] Articulation Index as a predictor of communication link performance in a RFI environment. 1966 IEEE Region Six Conference Record, Tucson, Arizona.
- THOMPSON, A. [November, 1967] The application of the voice interference analysis system to the prediction of voice intelligibility. Part 1, Bell Report No. A70009-280; National Technical Information Service (NTIS), US Dept. of Commerce, Washington.
- TKACHENKO, A. [January-June, 1955] Tonal method for determining the intelligibility of speech transmitted by communications channels. *Soviet Phys. - Acoustics*, Vol. 1, 2.

CCIR Documents

PPI INTERFERENCE PREDICTION

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Abstract

The interference prediction model is a major tool in the effort to obtain electromagnetic compatibility in the crowded radio frequency spectrum. Work has progressed in the prediction modeling of the transmitter, antenna, propagation, and receiver, but additional expressions for the degrading effect of interference upon information output to the operator are required to complete the analysis. The paper introduces an analytical approach to obtaining a quantitative prediction of the interference degradation to a radar PPI display. Determining the signal output from the receiving system due to environment has been accomplished by various approaches and is reported on elsewhere. For the purposes of this investigation, a description of the receiver output in terms of the pulse density distribution by received power level is assumed. The task remaining and the subject of the study performed, is the relationship between the pulse signal distribution input to the display and the resulting interference to the PPI.

Background

Ranging and direction information obtained from a radar system is utilized directly, or after more or less complex processing, in a multitude of read-out devices. One of the earliest and still the most widely employed of these devices is the Plan Position Indicator (PPI). The wide application of the PPI as a radar output device warrants detailed analysis of its response as an element in the overall system subject to interfering signals. The other elements of the overall interference model, the transmitter, transmitting and receiving antennas, propagation path and receiver have been analyzed and described in terms of mathematical and statistical expressions. The parameters involved in these expressions, voltage, power, frequency, phase, and numbers of pulses, are for the most part measurable with available instrumentation. On the other hand, the PPI furnishes to the operator numerous bits of information (range, angle, and intensity) of thousands of desired and undesired effects, each bit not individually measurable by the human operator at the high information rate of which they are received. The decision as to the presence of one or more de-

sired signals cannot be made by analyzing the absolute value of the thousands of parameters involved, with the near simultaneous influx of data. Therefore an expression that combines the effect of amplitude, and density of the PPI input signals is required to determine the PPI response to that signal environment in terms of the degradation of the desired information output. This expression, when combined with the signal transfer description of the rest of the interference system, provides a model for prediction of PPI interference.

Application of PPI Interference Prediction

A quantitative classification of interference on a radar PPI scope is useful in describing the level of interference effecting a radar system. Such a classification is applicable in assessing the effect of interference on an existing installation, aiding in the determination of remedial action required for interference problems, and in describing the interference likely to result from a hypothesized combination of equipment characteristics and operational environment conditions.

The Air Defense Command has standardized on a five level classification of interference on manually operated equipments in its specification for interference reporting.¹ These five levels, illustrated in Figure 1, range from Condition 1 having little or no interfering pulses on the scope to Condition 5 which has heavy interference clutter over most of the scope face. The five scope conditions of this classification were used as the scope interference categories for the prediction model.

The classification of interference by scope condition is useful primarily for systems with operators observing the scope. The prediction technique was developed from data obtained from radars with normal receiver characteristics. The method is equally applicable to more sophisticated receiver systems by application of the receiver transfer characteristics to the signal at the receiver terminals to determine the signal characteristics to be processed according to the scope condition prediction model.

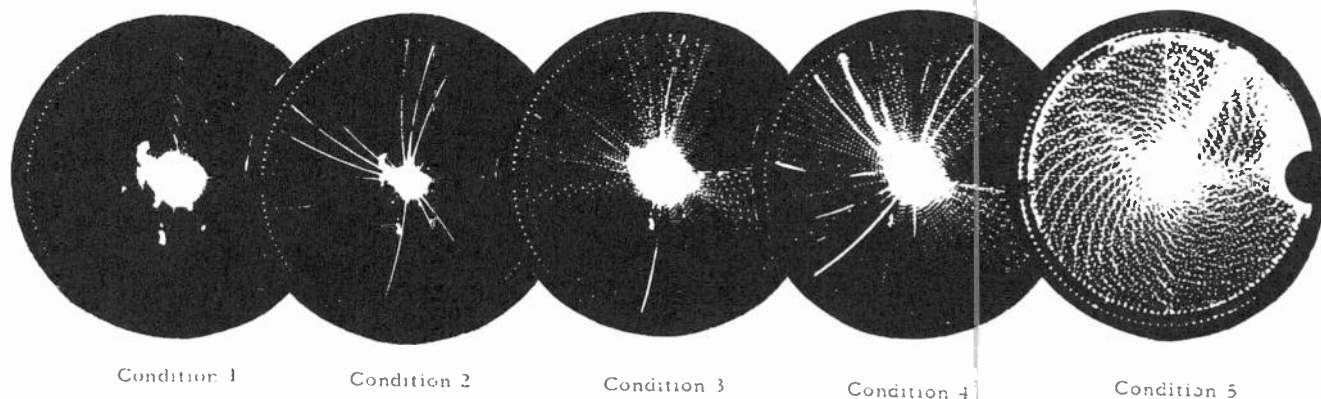


Figure 1. PPI Display Condition Classification.

Basis for Correlation of Pulse Amplitude Distributions with Scope Interference Conditions

The interference level of a PPI scope display with a given interfering signal input is to some extent a subjective determination varying among observers. The hypothesis, that the effect both in degradation of operator performance and in degradation of target detection range will be a function of the proportion of the scope cluttered and the luminance* of the cluttered areas, can be accepted as qualitatively correct. Operator fatigue and confusion can be readily associated with these factors. The probability that a target return at a given signal level will be hidden by interference clutter on the scope is directly related to area extent of the clutter and to its luminance. A target falling in an area of the scope having interference clutter will not be detectable until it is brighter than its background, thereby degrading detection capability directly in relationship to clutter brightness. The probability of a target appearing in an interference clutter area on the scope

is equal to area extent of clutter/area of PPI display and the degradation effect increases as the probability of the target being in the cluttered area.

Having related interfering signal display to its effect on the PPI scope interference condition, it is then necessary to relate the pulse amplitude distribution data for the interfering signal to the display parameters. The result is the direct correlation of interfering signal with the scope interference condition it produces. The quantitative correlation of these parameters develops as follows:

Scope Interference Level varies as Interference Clutter Area.

Scope Interference Level varies as Clutter Brightness.

Scope Interference Level varies as Clutter Area X Clutter Brightness.

But,

Clutter Area X Clutter Brightness = Clutter Intensity**

*Where luminance is defined as intensity per unit area and is sometimes termed brightness.

**Intensity is the photometric term for total light output from a source and can be interpreted as the product of luminance and area, although the inverse relationship $\text{luminance} = (\text{intensity})/(\text{unit area of source})$ is usually defined.

RADIODETERMINATION SPECTRUM UTILIZATION/CONSERVATION

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ABSTRACT

Several frequency bands allocated for radiodetermination services have been identified both within the United States by the National Telecommunications and Information Administration (NTIA) and the Federal Communications Commission (FCC) and internationally by the World Administrative Radio Conference (WARC) as being potentially congested. Frequency bands which have been designated as potentially congested bands include: 1215-1400 MHz, 2700-2900 MHz and 9300-9500 MHz [1-3]. The Department of Commerce, (NTIA) recognizes the wide applications and various functions of radio determination service, and the requirement for electromagnetic spectrum support. Pursuant with this requirement, NTIA has established procedures and regulations to promote more efficient utilization/conservation of the spectrum allocated for radio determination services. Government standards related to new radar procurements of federal systems are given in the Radar Spectrum Engineering Criteria (RSEC) [4].

This paper summarizes an investigation conducted by NTIA in cooperation with the Department of Transportation, Federal Aviation Administration (FAA) to assure that future spectrum requirements for Aeronautical Radionavigation Services in the 2700-2900 MHz band can be satisfied. An extensive measurement, model validation, receiver simulation and analytical investigation was undertaken to assess the degree of band congestion in the 2700-2900 MHz band. The investigation showed that new transmitter output tubes and waveguide filter devices, along with radar receiver signal processing techniques will result in more efficient use of the spectrum. These radar spectrum utilization/conservation techniques will provide a means of satisfying future spectrum requirements of this nation.

INTRODUCTION

The 2700-2900 MHz band is allocated on a primary basis for aeronautical radionavigation and meteorological aids, and on a secondary basis for radiolocation. During the period of August 1971 through April 1973, the IRAC had under study the accommodation of FAA, Department of Defense

(DoD) and Department of Commerce (DoC) radar operations in the 2700 to 2900 MHz band. Concern regarding spectrum congestion in the 2700-2900 MHz band was raised because FAA and Military requirements called for the addition of numerous Air Traffic Control (ATC) radars, and the continued presence of USAF air defense radars that function as part of a joint DoD/FAA surveillance system. In addition to the increased number of radars expected in the band by 1981, the FAA and Military have introduced a frequency diversity capability in their air traffic control radar systems, thus adding a new dimension to the existing EMC problems. The IRAC, being aware of the potential congestion in the band, tasked NTIA to investigate the accommodation of planned deployments in eight designated congested areas within CONUS.

The 2700-2900 MHz Spectrum Resource Assessment was conducted in two phases: Phase I included an extensive measurement program in the Los Angeles and San Francisco areas during the period of May through November 1975 utilizing the facilities of the Radio Spectrum Measurement System (RSMS) van. The measurement program involved measuring radar emission spectra, antenna radiation patterns, propagation loss, as well as video tape recordings of the radar PPI displays during various operational conditions. Findings from the Phase I investigation are given in Reference 2. Phase II included an investigation into the signal processing properties of the radar receivers and post processors presently operating and planned for the band. The investigation included measurements, receiver simulation, and analytical analyses of the radar receiver signal processing to assess the capability of obtaining more efficient utilization/conservation of the band. Findings from the Phase II investigation are given in Reference 5.

The following is a discussion of the findings of the Phase I and Phase II investigations that relate to more efficient utilization/conservation of the 2700-2900 MHz band.

EMISSION SPECTRUM

One of the major factors contributing to

SAMPLE CALCULATION

PHOTO #34 FOR AN/TPS-15 PPI RANGE = 160 NM PRF = 380
SINGLE PULSE MDS = -88 DBM

Measured Data

"N" Computation

(A)	(B)	(C)	(D)	(Q _i)	(P _i)	(N _i)
Pulse Power Level (dbm)	Pulses/Scan Exceeding (A)	Pulse Power Level Category A _n -A _{n+1} (dbm)	Midpoint of Power Level Cat. $\frac{A_n + A_{n+1}}{2}$ (dbm)	Pulses in Category (B) _n (B) _{n+1}	Power Level Above Threshold (D) MDS Max 20 (db)	(Q _i)(P _i) x 10 ⁻⁴
(1) -85	47415					
(2) -75	9753	-85 to -75	80	37662	8	30.13
(3) -70	8291	75 to -70	-72.5	1462	15.5	2.26
(4) -63	6661	-70 to -63	-66	1630	20.0	3.26
(5) -57	655	-63 to -57	-60	6006	20.0	12.01
(6) -51	90	-57 to -51	-54	565	20.0	1.12
(7) -45	60	-51 to -45	-48	30	20.0	.06
(8) -39	11	-45 to -39	-42	49	20.0	.10
(9) -33	0	-39 to -33	-36	11	20.0	.02

$$N = \sum N_i = \sum Q_i P_i \times 10^{-4} = 48.96$$

Since $N > 25.3$, Scope Condition 5 would be the interference condition resulting from this pulse signal distribution.

Table 1

this case is the minimum peak power required for a single pulse to be detected on the PPI. The MDS for a single pulse was determined experimentally to be 12 db above the conventional MDS which is determined for a synchronized pulse train. This determination is in agreement with the work of Marcum and Swerling⁴ where the probability of detection is related to the number of pulses integrated on the detection device.

A further consideration in the computation of the quantity "N" is the transfer function of the receiver. The radar receivers in the normal mode of operation typically have a 15 to 20 db linear response range above which saturation occurs with no further increase in video pulse amplitude. Including this in the expression for PPI interference the equation becomes:

$$N = \sum Q_i (P_i - P_{MDS}) \times 10^{-4}$$

where,

Q_i = number of pulses/scan at power level P_i .

P_i = power level category of interfering pulse signals expressed in dbm.

P_{MDS} = single pulse threshold of victim PPI.

$(P_i - P_{MDS})$ has maximum value of receiver dynamic range.

Table 1 shows a sample calculation of "N".

3. The "N" numbers computed for each photograph were grouped according to the classification of scope condition assigned to the photograph and the mean and standard deviation of "N" for each condition calculated. Based upon the distributions of "N" in each condition category the limits of "N" corresponding to each scope condition were determined to minimize the probability of misclassification based upon the available sample of photographs and measured pulse distribution data. Figure 2 shows the distributions of "N" and the category limits derived for the test sample.

The categories of "N" arrived at with the test sample are representative of what might be termed a normal duty ratio of scope display time to total time. Interfering signals are re-

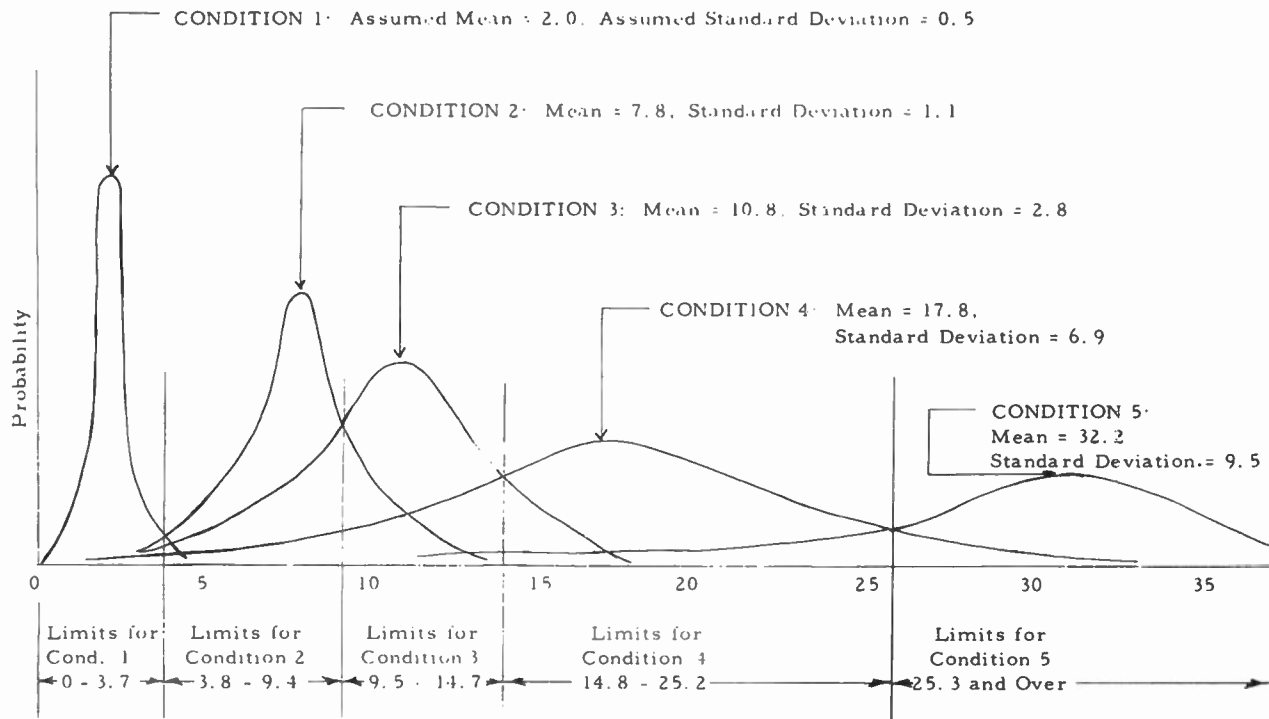


Figure 2.

ceived continuously while signals are displayed on the scope only during the range sweep. For a radar with a 160 nautical mile (NM) display range each range sweep is 160 NM x 12.4 μ sec/NM = 1985 μ sec. At a pulse repetition rate of 400 the duty ratio of the display would be 400 x 1985 μ sec/sec or 0.8, indicating that the scope is being painted 80% of the time. Since this factor applied to all scope settings employed the "N" number categories are representative for a display duty ratio of 0.8. In applying the analysis to other scopes, which do not employ this more less typical 80% display time ratio, the numbers would have to be adjusted accordingly. This would apply to scopes capable of display of an expanded range sweep or of switching of display range with no change of PRF.

4. The interference condition classification of individual photos by appearance was then compared with the condition classification by "N" number categories. The two classifications were found to agree in 64% of the cases and in no case to differ by more than one category. Figure 3 is a histogram showing the conformance of the two classifications of the test samples.

Conclusions and Recommendations

The limited test sample of PPI photographs and pulse amplitude distribution measurements available for this study indicated a definite correlation of the quantitative relationship of pulse signal distribution and interference condition. A further evaluation with laboratory simulation would provide more precise data than could be obtained under field conditions and permit optimization of the PPI interference model. Laboratory evaluation would also permit addition of target simulation for extension of the model to prediction of detection range degradation. The effect of interference on degradation of operator efficiency could also be determined and both factors in performance degradation could be directly related to scope condition.

PPI interference predictions were also made based upon a predicted pulse signal distribution for the radar environment prevailing at the time the photographs were made. The correlation realized for these predictions approached that obtained for the measured signal conditions. Figure 4 indicates the agreement realized in PPI interference prediction for predicted signal distributions.

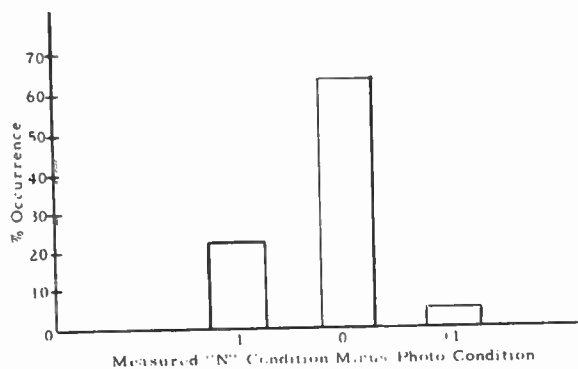


Figure 3

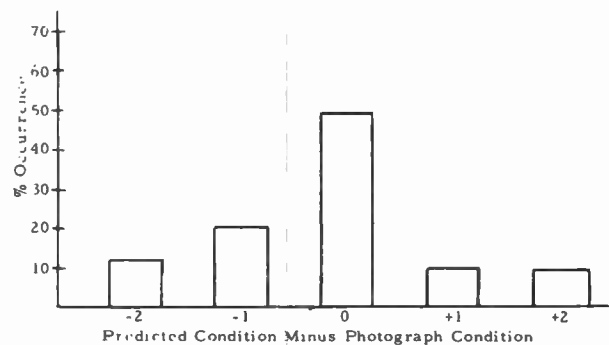


Figure 4

References

1. Radio Communications System Operation - Air Defense Command Instructions Pertaining to Radar Interference - AFM 100/24 ADC Suppl. 2.
2. Factors Influencing Target Detectability on CRT Screens, J. W. Ogland, IRE Transactions Aeronautical and Navigational Electronics, December, 1958.
3. ECAC-TDR-64-2, The San Diego Problem - Phase II L-Band Radar Interference Prediction Model Validation, January, 1964.
4. Studies of Target Detection by Pulsed Radar, Marcum and Swerling, IRE Transactions PGIT, Vol. 17-6, April 1960, No. 2.

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This paper summarizes an investigation conducted by NTIA in cooperation with the Department of Transportation, Federal Aviation Administration (FAA) to assure that future spectrum requirements for Aeronautical Radionavigation Services in the 2700-2900 MHz band can be satisfied. An extensive measurement, model validation, receiver simulation and analytical investigation was undertaken to assess the degree of band congestion in the 2700-2900 MHz band. The investigation showed that new transmitter output tubes and waveguide filter devices, along with radar receiver signal processing techniques will result in more efficient use of the spectrum. These radar spectrum utilization/conservation techniques will provide a means of satisfying future spectrum requirements of this nation.

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The following is a discussion of the findings of the Phase I and Phase II investigations that relate to more efficient utilization/conservation of the 2700-2900 MHz band.

EMISSION SPECTRUM

One of the major factors contributing to

inefficient utilization of the radio determination spectrum was the high transmitter emission spectrum skirts caused by frequency instability and spurious modes of the transmitter output tube devices. High transmitter emission spectrum skirts increase the frequency separation required for compatible operation between radars. The enforcement of the RSEC standards, and changes in hardware and transmitter frequency stability requirements have resulted in significant reductions of the transmitter emission spectrum skirts.

Figure 1 shows a measured emission spectrum of an ASR-7 radar using a magnetron transmitter output tube. The magnetron has an asymmetric emission spectrum due to the frequency pulling during the rise and fall time of the transmitted pulse. Figure 2 shows a measured emission spectrum of an AN/GPN-20 radar. The AN/GPN-20 has the same pulse width (.83 sec), as the ASR-7 radar, and uses the same magnetron tube (8789) as the ASR-7 radar. However, a waveguide diplex filter is used for frequency diversity operations and compliance with the RSEC. A comparison of Figures 1 and 2 shows that the use of a waveguide diplex filter greatly reduces the emission spectrum skirt levels.

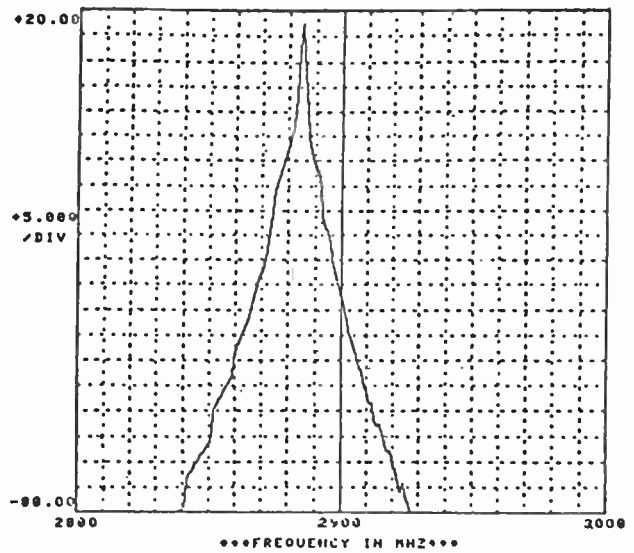


Figure 2. Measured AN/GPN-20 Emission Spectrum (8789 Magnetron with Waveguide Diplex Filter)

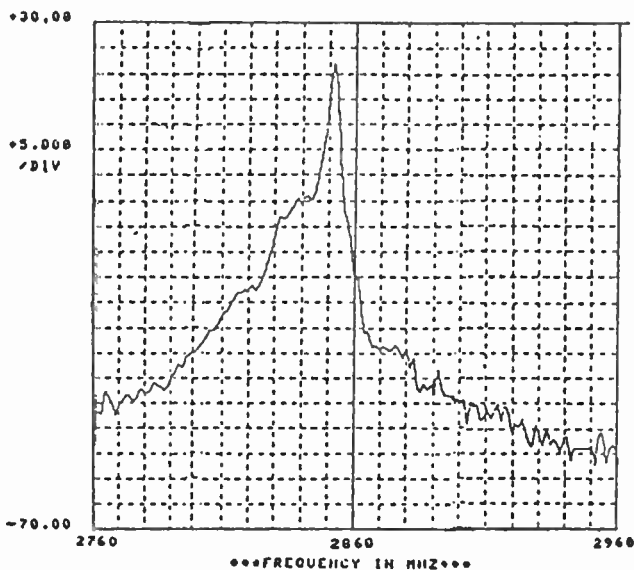


Figure 1. Measured ASR-7 Emission Spectrum (8789 Magnetron)

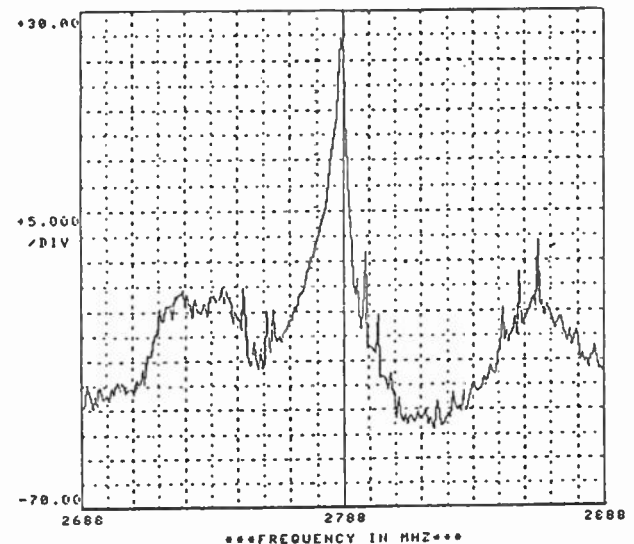


Figure 3. Measured AN/FPS-90 Emission Spectrum (VMS-1143 Coaxial Magnetron)

Also in recent years, some types of radar equipment have been modified to use coaxial magnetrons, and some new radars use klystron output tubes. Figure 3 shows a measured emission spectrum of an AN/FPS-90 radar with a coaxial magnetron. The coaxial magnetron emission spectrum has a sharp falloff around the fundamental frequency. However, the emission spectrum comes back up on the lower and upper

sides of the fundamental due to undesired modes. These undesirable coaxial magnetron modes are caused by improper rise and fall time of the modulating pulse, and inadequate mode suppression in the coaxial magnetron tube. Figure 4 shows a measured emission spectrum of an ASR-8 radar which uses a klystron. The emission spectrum is measured with the radar operating in the frequency diversity mode (both channels operating

simultaneously). The emission spectrum of the klystron has very sharp skirts. In summary, new radars in the past three years in the 2700-2900 MHz band have a significantly cleaner emission spectrum permitting more efficient utilization/conservation of the band.

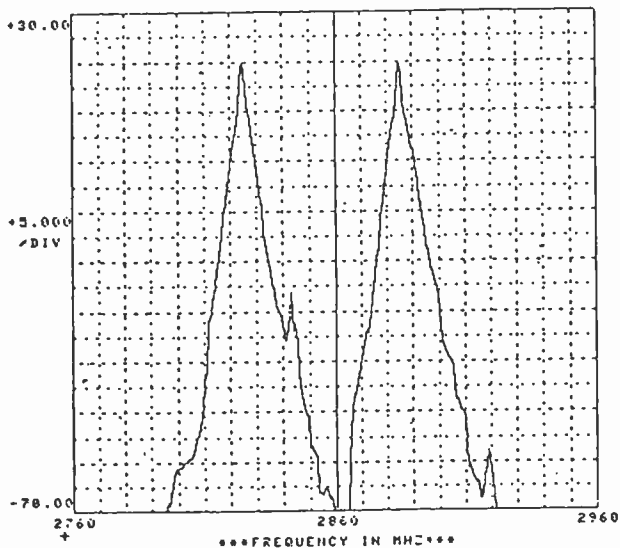


Figure 4. Measured ASR-8 Emission Spectrum (VA-87E Klystron with Waveguide Duplex Filter)

SIGNAL PROCESSING

Signal processing techniques in low duty cycle radars have long been recognized as a method of obtaining more efficient utilization of the spectrum. The RSEC recognizes the use of video integrators, correlators, and PRF and pulse width discriminators as methods of suppressing interference. However, it does not require the incorporation of such devices in new radar procurements. A detailed investigation [5] was undertaken to study the interference suppression capability of the video integrators presently used in radars in the 2700-2900 MHz band, and the Automated Radar Terminal System (ARTS-IIIA) planned for use by the FAA on Airport Surveillance Radars (ASR's).

Video Integrators

Video integrators are generally used in radars for two reasons: 1) To enhance weak desired targets for PPI display, 2) to suppress asynchronous pulsed interference. The principle of the radar video integrator is that radar signal returns from a point target consists of a series of pulses generated as the radar antenna beam scans past the target, all the pulses from the target will occur in the same range bins in successive radar periods. It is this series of

pulses from a target which falls in the same range bin that permits integration of the target returns to enhance the weak signals. The number of pulse returns from a target depends upon the radar antenna beamwidth, the rate of antenna rotation, the radar pulse repetition frequency (PRF), and the target characteristics. The number of pulse returns for radars in the 2700 to 2900 MHz band is between 12 to 20. The integrator will suppress asynchronous interference since the interfering pulses will not be separated in time by the radar period, and thus will not occur in the same range bin in successive periods (asynchronous with the system). Therefore, the asynchronous interference will not add-up, and can be suppressed.

All Radars in the 2700 to 2900 MHz band employ post detection or noncoherent integrators. The types of post detection integrator employed in radars in the 2700 to 2900 MHz band can be categorized either as a feedback integrator or a binary integrator. Radars employing feedback integrators may be of analog (delay line) or digital (shift register) type. Only digital binary integrators are presently used in this band.

Measurements, receiver simulation, and analytical analysis were undertaken to investigate the transfer properties of the video integrators. The transfer properties of noise, desired signal and asynchronous interference were investigated as well as the trade-offs in the desired signal performance when suppressing asynchronous pulsed interference. When a video integrator is used to suppress asynchronous interference, there are trade-offs in target azimuth shift, angular resolution and target sensitivity. Both the normal and Moving Target Indicator (MTI) radar channel transfer properties were simulated and investigated. The MTI Channel is the most difficult channel to suppress interference due to the signal transfer properties of the MTI cancellers which generate several synchronous pulses for each interference pulse.

Figure 5 shows a simulated oscilloscope display for an MTI channel nonintegrated target return pulse train for target azimuth shift and angular resolution reference. The desired Signal-to-Noise Ratio (SNR) is equal to 20 dB. Figure 6 shows a simulated MTI channel nonintegrated radar output for three interference sources (ASR-5, Interference-to-Noise Ratio (INR) = 10 dB; ASR-8, INR = 15 dB; and an AN/FPS-90, INR = 20 dB;), and a desired target with a SNR of 20 dB.

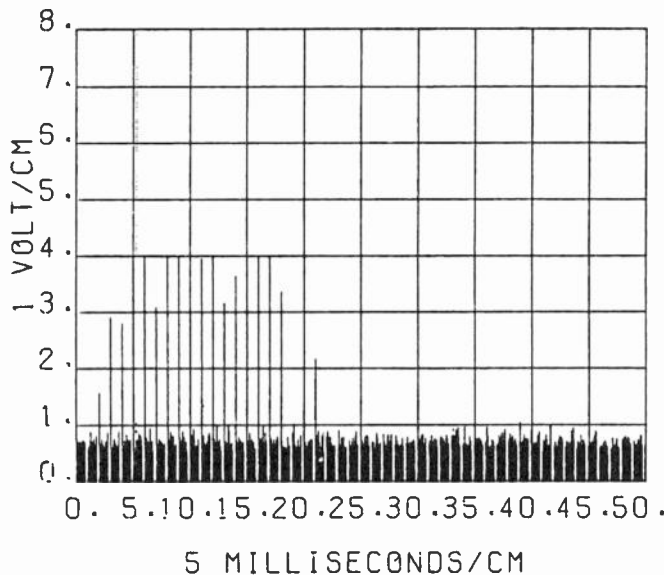


Figure 5. Simulated MTI Channel (Mode 1 & 2 CASC) Nonintegrated Target Return Pulse Train for a SNR = 20dB

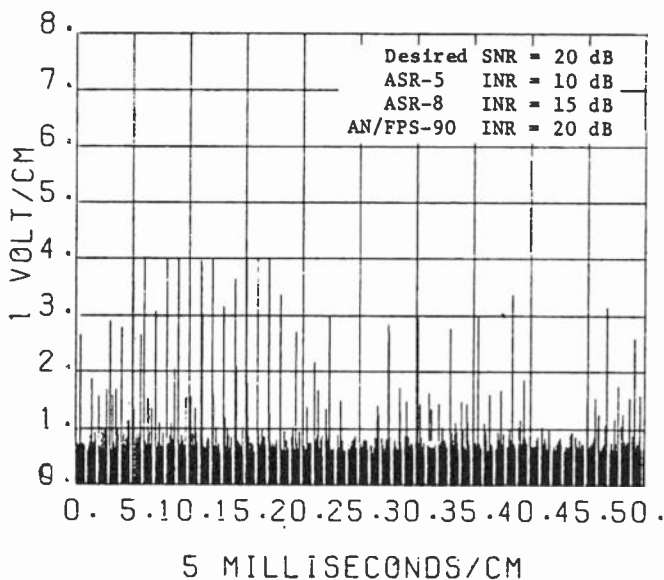


Figure 6. Simulated MTI Channel (Mode 1 & 2 CASC) Nonintegrated Radar Output with Interference

Feedback Integrator

Figure 7 shows a block diagram of a typical feedback integrator. The signal-to-noise ratio enhancement (SNR) factor for the integrator feedback loop for the normal channel can be expressed by:

$$SNR_E = 20 \log \left[\left(\frac{1-K}{1-K^2} \right) (1-K^2)^{\frac{1}{2}} \right] \quad (1)$$

Where:

K = Feedback loop constant

N = Number of pulses integrated

It should be noted that Equation 1 is only a first order approximation of the actual signal-to-noise ratio enhancement of a feedback integrator since it assumes a zero mean noise amplitude distribution, and a constant desired signal level. For the MTI channel, the signal-to-noise ratio enhancement given by Equation 1 should be reduced by 1.0 dB for a single stage canceller and 1.8 dB for a double stage MTI canceller due to the correlation of noise by the MTI cancellers [6].

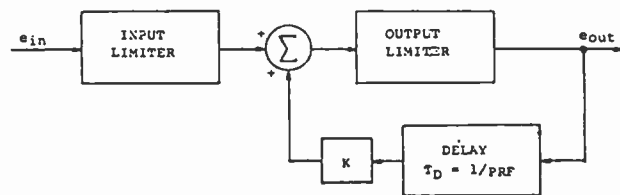


Figure 7. Feedback Integrator Block Diagram

Proper adjustment of the input limiter of a feedback integrator will suppress asynchronous interference. However, if the input limiter is not adjusted properly on the feedback integrator, asynchronous interference can be enhanced by the feedback integrator rather than suppressed. Figure 8 shows a simulated radar feedback integrator output for the input limiter set at 0.34 volts for the same interference condition shown in Figure 6. The interference has been suppressed by the feedback integrator. Also, a comparison of Figure 8 with Figure 5 shows that the number of pulses above 1.0 volts (peak noise level) increases when the feedback integrator is used. This increase in number of pulses results in an effective target azimuth shift and a decrease in angular resolution. (The property of the radar to distinguish between two targets.) In summary, the feedback integrator causes a target azimuth shift of approximately 0.90 degrees, and an angular resolution loss of approximately 1.2 to 1.5 degrees relative to a nonintegrated target return pulse train. Measurements have shown when the feedback integrator is used to suppress asynchronous interference, there is also an approximate one dB loss in desired target Minimum Discernable Signal (MDS) level.

Binary Integrator

Figure 9 shows a block diagram of the binary integrator used in the AN/GPN-12 and the ASR-7 radars. The binary integrator consists of a threshold detector or comparator, binary counter (adder/subtractor circuit), a five bit shift

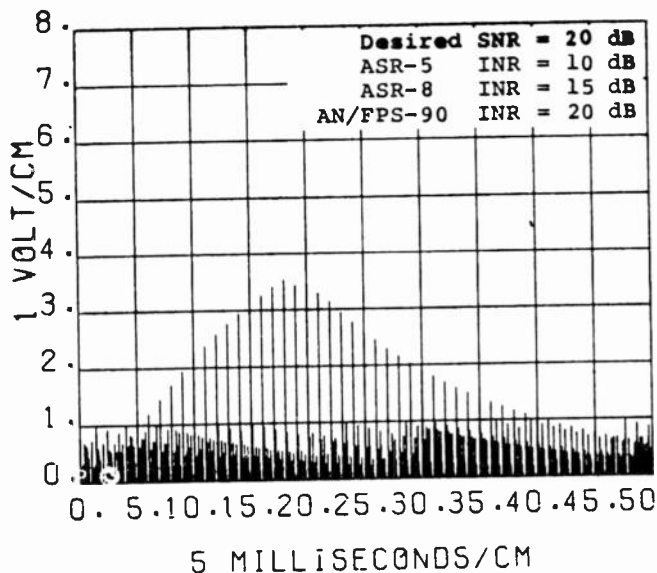


Figure 8. Simulated MTI Channel (Mode 1 & 2 CASC) Radar Feedback Integrator Output with Interference for the Input Limiter Set At 0.34 Volts

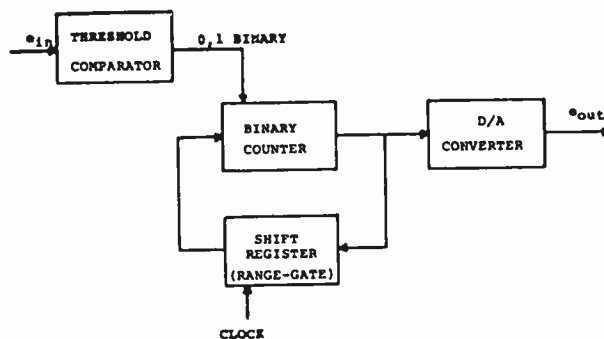


Figure 9. ASR-7 (AN/GPN-12) Binary Integrator Block Diagram

register memory, and a digital-to-analog (D/A) converter. Each PRF period is divided into range bins of .625 sec. If a pulse of a target return pulse train exceeds the comparator threshold level, the enhancer stores a one level digital signal in the shift register memory for that range bin. If the successive pulses of the target return pulse train continue above the comparator threshold in the given range bin, the binary counter will add one level to the stored digital signal in the shift register memory in each PRF period until a maximum integrator level of 31 is reached. If in any PRF period the signal fails to exceed the comparator threshold, the binary counter subtracts one from the stored integrator state in the given range bin until a digital signal level of zero is reached. The

subtraction provides the target return pulse train signal decay required after the antenna beam has passed the target, and also enables the suppression of asynchronous interfering signals. The voltage amplitude at the enhancer D/A converter output is determined by the binary counter level (0 to 31) for the particular range bin times .125 volts. Therefore, for a binary counter level of 31, the maximum enhancer output voltage would be 3.875 volts (31 x .125). The binary integrator can also be programmed for a particular hit/miss characteristic curve so that the integrator level can change several levels for each hit/miss.

It is shown in Reference 5 that the probability of a desired target return pulse train of 20 pulses causing the binary integrator to be in state E can be determined by using a one-dimensional random walk with reflecting barriers model where levels 0 and 31 are the reflecting barriers. Since the noise is continually summed in the binary integrator, the number of steps in the random walk is infinite. A one-dimensional random walk with reflecting barriers model for an infinite number of steps is identical to a truncated single channel queue model. Thus the probability of noise causing the integrator to be in state E can be modeled by a truncated single channel queue.

An investigation of the binary integrator showed that the binary integrator will also suppress asynchronous interference. The capability of the binary integrator to suppress asynchronous interference is a function of the threshold comparator level and hit/miss characteristic curve of the binary integrator. Figure 10 shows a simulated radar binary

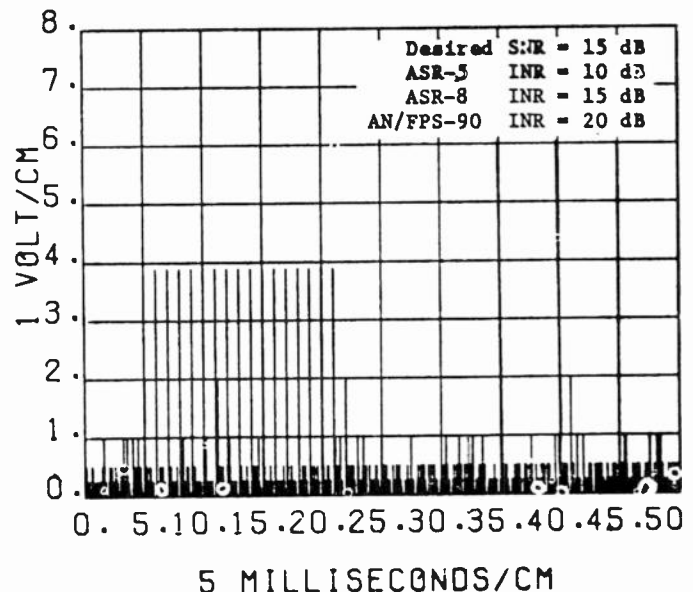


Figure 10. Simulated MTI Channel (Mode 1 & 2 CASC) Radar Binary Integrator output with Interference

integrator output for the hit/miss characteristic curve used by the FAA in the ASR-7 radar for the same interference condition shown in Figure 6. The interference has been suppressed by the binary integrator. The binary integrator causes a target azimuth shift of approximately .179 degrees. The use of the binary integrator results in no loss in angular resolution, and less than one dB in MDS. In summary, the FAA modified binary integrator used in the ASR-7 has the capability of suppressing asynchronous pulsed interference with very little trade-offs in target azimuth shift and desired target MDS level, and no loss of target angular resolution.

ARTS-IIIA

The Automated Radar Terminal System (ARTS) III processor presently employed at terminal radar control facilities utilizes flight plan information from Air Route Traffic Control Centers (ARTCC) and Air Traffic Control Beacon Interrogator (ATCBI) video. In addition to providing target reports on transponder aircraft, alphanumeric data blocks available for display are continually associated with the appropriate aircraft targets by a tracking program. The primary radar video is not presently processed by the present ARTS-III system, but the ARTS-III enhancement, referred to as the ARTS-IIIA, will process the video target information from both the primary Airport Surveillance Radars (ASRs in the 2700-2900 MHz band) and the Air Traffic Control Radar Beacon System (ATCRBS at 1030 MHz and 1090 MHz). The ARTS-IIIA is a post processor connected at the output of the radars, and consists of a Radar Data Acquisition Subsystem (RDAS), Beacon Data Acquisition Subsystem (BDAS), and a Common Processor Subsystem (CPS). Primary radar information is processed by the RDAS to produce radar reports and weather map data, and the Beacon information is processed by the BDAS to produce beacon reports. The CPS correlates radar and beacon reports and transmits target and weather reports.

Since the RDAS processes the 2700-2900 MHz primary radar signal, a detailed investigation of the capability of the ARTS-IIIA RDAS to suppress asynchronous interference was also conducted [5]. The ARTS-IIIA is currently scheduled to be operationally deployed at 60 airports throughout

the United States. This is a substantial deployment since it involves over 25 percent of the FAA Radar equipped airports in the U.S. The first ARTS-IIIA operational deployment is scheduled for July 1979 at Minneapolis, Minnesota. The deployment at each of the remaining 59 locations is scheduled at 2-month intervals after this initial date.

The ARTS-IIIA RDAS uses a rank order detection process, hit processor, and target detection algorithm software (See Figure 11). Analysis of the RDAS signal processing showed that asynchronous radar interference will not significantly increase the probability of false alarm, or significantly reduce the probability of target detection (less than 2% reduction). Also it was shown that asynchronous pulsed interference will not have any secondary effects on automatic video channel selection (Normal or MTI channel), or the variable MTI channel threshold of the ARTS-IIIA.

CONCLUSIONS

As a result of the detailed investigation into radar transmitter emission spectrums and receiver signal processing of radars in the 2700-2900 MHz band, it was concluded that:

1. The use of klystrons and duplex filters in the waveguide will result in lower transmitter emission spectrum skirts which allows more efficient spectrum utilization.
2. All pulsed radars which have a low duty cycle permit the use of signal processing techniques in the radars and postprocessors to obtain more efficient spectrum utilization.
3. The use of integrators (enhancers) and other digital signal processing techniques along with the trend of displaying synthetic video on the Plan Position Indicator (PPI) display provides the capability of suppressing asynchronous interference at levels of 50 dB above the receiver noise level, while also permitting the enhancement of weak desired targets that are below the radar receiver system noise level.

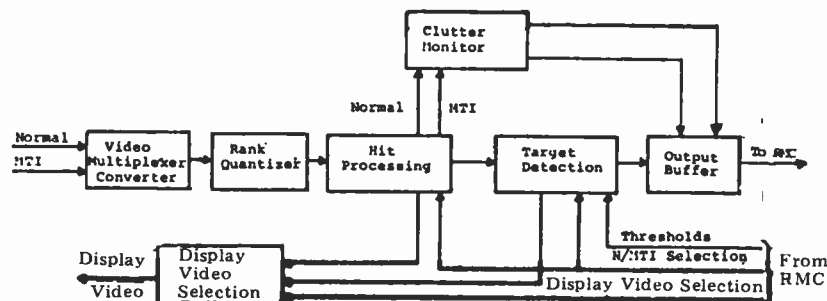


Figure 11. Block Diagram of ARTS-IIIA Radar Extractor

4. With properly designed signal processing techniques, the suppression of asynchronous interference in low duty cycle radars will have minimal effects on target azimuth shift, angular resolution and desired signal sensitivity.

REFERENCES

1. Maiuzzo, Michael A. (July, 1972), "Analysis of Factors Affecting Electromagnetic Compatibility of Radars Operating in the 2700 to 2900 MHz Band", FAA-RD-71-91.
2. Hinkle, R., R. Pratt and R. Matheson (August, 1976), "Spectrum Resource Assessment in the 2.7 to 2.9 GHz Band, Phase II: Measurement and Model Validation (Report No. 1), "OT Report 76-97.

3. Technical Basis for the World Administrative Radio Conference 1979, ITU, CCIR, Geneva 1978, Par. 4.3.5.2 and 4.6.1.4.

4. Manual of Regulations and Procedures for Federal Radio Frequency Management, U.S. Department of Commerce, National Telecommunications and Information Administration, Revised.

5. Hinkle, R., R. Pratt and J. Levy (May 1979) "Spectrum Resource Assessment in the 2.7 to 2.9 GHz Band, Phase II: Radar Signal Processing (Report No. 2), "NTIA Report."

6. Trunk, G. V. (April, 1977) "MTI Noise Integration Loss" NRL Report 8132.

Modulation Methods and Channel Separation in the Land Mobile Service

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Abstract—The following fundamental technical questions concerning the use of the spectrum allocated to the land mobile radio service are discussed. 1) Is it technically feasible to increase the number of assignable channels within the allocated spectrum space? 2) Are other modulation methods more or less suitable for providing more channels? The primary resource material used to answer these questions is the response of the Land Mobile Section, Industrial Electronic Division, Electronic Industries Association [49]. Only the frequency spacing question is treated in this paper.

I. INTRODUCTION

THERE HAS BEEN a continuing effort to seek ways to increase the number of assignable channels in the land mobile radio service within presently allocated spectrum space. The following analysis has considered this problem with 1) present technical standards and 2) new technical standards for narrower-bandwidth systems. Man-made noise (notably, internal combustion engine electrical system noise), transmitter noise, and the greater number and strength of intermodulation products impose important and limiting boundary conditions. Transmitter noise becomes a limiting technical-economic factor in adjacent-channel spacing, irrespective of modulation bandwidth.

As bandwidth is reduced, the effects of man-made noise degrade system performance. When transmitter power or the number of transmitters is increased to overcome the effects of noise, the number or strength of intermodulation products increase. These factors lead to greater numbers of interference cases, hence greater probability of missed calls. Missed calls lead to a greater number of transmissions for a given communication function, hence poorer spectrum utilization.

II. DEFINITIONS OF TERMS AND ABBREVIATIONS

DSBAMRC	double sideband amplitude modulation reduced carrier
Frequency Modulation Index (FMI)	$M_f = \frac{\text{frequency deviation}}{\text{audio modulating frequency}}$
NBFM	narrow-band frequency modulation; ± 5 -kHz deviation, 13-kHz receiver bandwidth
SBFM	single-band frequency modulation; ± 2.5 -kHz deviation, 6-kHz receiver bandwidth

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SINAD	$\frac{\text{signal} + \text{noise} + \text{distortion}}{\text{noise} + \text{distortion}}$
SSB	single-sideband amplitude modulation
SSBFM	single-sideband frequency modulation
VOSIM	voice simulator
WBFM	wide-band frequency modulation; ± 15 -kHz deviation, 30-kHz receiver bandwidth
Present Technical Standards	frequency stability ± 0.0005 percent channel spacing 20 kHz (25.01–49.6 MHz) 30 kHz (150.8–173.4 MHz) 50 kHz (450–466.475 MHz) frequency deviation ± 5 kHz (all except 450 MHz) ± 15 kHz (450 MHz).

III. TECHNICAL EVALUATION OF CHANNEL ASSIGNMENTS

A. With Present Technical Standards (see Section II)

13-kHz receiver bandwidth
 ± 5 -kHz deviation (except 450 MHz)
 ± 15 -kHz deviation (450 MHz)
+5-PPM frequency stability.

1) *Optimum Channel Spacing*: Channel spacing is determined by a knowledge of

- bandwidth required to transmit the desired intelligence;
- mechanisms that produce interference;
- extent to which environmental conditions prevent the communication function from being performed.

In this discussion, transmitted bandwidth is not the limiting factor and need not be discussed.

Interference is caused whenever the transmitted frequency spectrum intercepts the receiver selectivity curve. Fig. 1 illustrates the conditions under which this can occur, namely, interception by 1) transmitted carrier, 2) modulation sidebands, and 3) transmitted noise.

Beginning with the cochannel condition (transmitted carrier tuned to the receiver resonant frequency), it is the carrier that first penetrates the receiver selectivity. Only space (geographical) attenuation will prevent interference in this case.

As the frequency separation is increased to the point where two systems can just operate in the same geographical area, it will be the modulation sidebands that

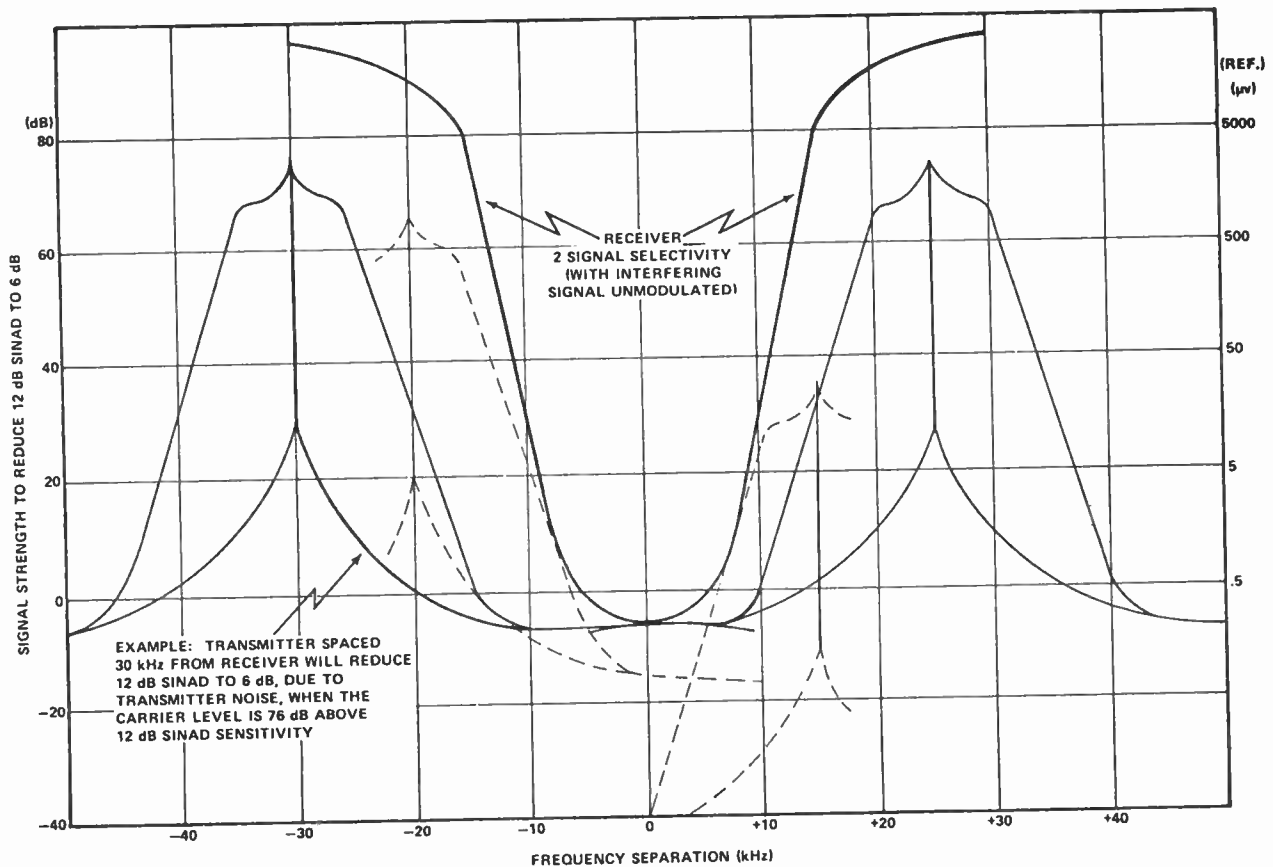


Fig. 1. Interference protection versus frequency separation.

will penetrate the receiver selectivity when interference is experienced. In FM systems using ± 5 -kHz deviation, the slope of the modulation side bands with voice modulation is about 6 dB/kHz. This is to say that any increase in receiver selectivity slope beyond 6 dB/kHz will not prevent modulation-sideband interference.

At still greater frequency separation, it is the transmitter noise which will intercept the receiver selectivity to cause interference. At frequencies very close to the carrier, the noise level is about 45 dB below the carrier level and attenuates to about 80 dB at frequencies 15 kHz removed from the carrier. Modern technology is unable to further attenuate this close-in transmitted noise spectrum.

In Fig. 1 the receiver selectivity is plotted to show the level of undesired signal at the antenna terminals that is required to reduce a desired-signal 12-dB SINAD (readable signal) to 6 dB (very-hard-to-read signal) when the undesired signal is unmodulated. For example, an undesired, on-frequency signal of $\frac{1}{4}$ μ V will degrade the 12-dB SINAD to 6 dB. At 15-kHz off-frequency, about 5000 μ V of undesired signal will cause the same degradation. Also, the transmitted spectrum is represented on the same sheet. It is measured by 1) applying a 12-dB SINAD signal to a receiver designed to receive the transmitted bandwidth, and 2) at some given frequency separation between transmitter and receiver, measure the attenuation between the interfering transmitter and the receiver receiving the desired 12-dB SINAD signal, that reduces the 12-dB SINAD signal to 6 dB.

Now by superimposing the worst condition of transmitter carrier, modulation sidebands or transmitter noise at any given frequency separation (sliding the transmitter curves horizontally and vertically to make them intersect the receiver curve), the level of undesired signal level to produce 6-dB degradation in a 12-dB SINAD can be determined. The undesired signal level can then be translated into equivalent transmitter power output radiated over some distance. When this is done the curves of Fig. 2 result. They show the average ranges at which interference will occur as a function of channel separation.

The interfering transmitter, in these cases, is VOSIM modulated. The industry experience shows that tone modulation does not allow prediction of field interference that is actually encountered. VOSIM modulation simulates the human-voice frequency spectrum and varies the level at a syllabic rate. The Appendix analyzes the sideband distribution from a theoretical point of view.

Knowing the mechanisms and the ranges at which they produce interference, the question can be asked; "What is the optimum channel spacing in the Land Mobile Service?" Another way of asking the question is "For what spacings do the problems increase more rapidly?" Examination of the curves of Fig. 2 shows that at less than 25-kHz spacing, the curve is very steep. Even frequency errors of 2×0.0005 percent (transmitter + receiver) cause drastic changes in the ranges at which interference will occur. This factor would lead to widely changing and unpredictable performance in systems designed for spacings at less than 20-25

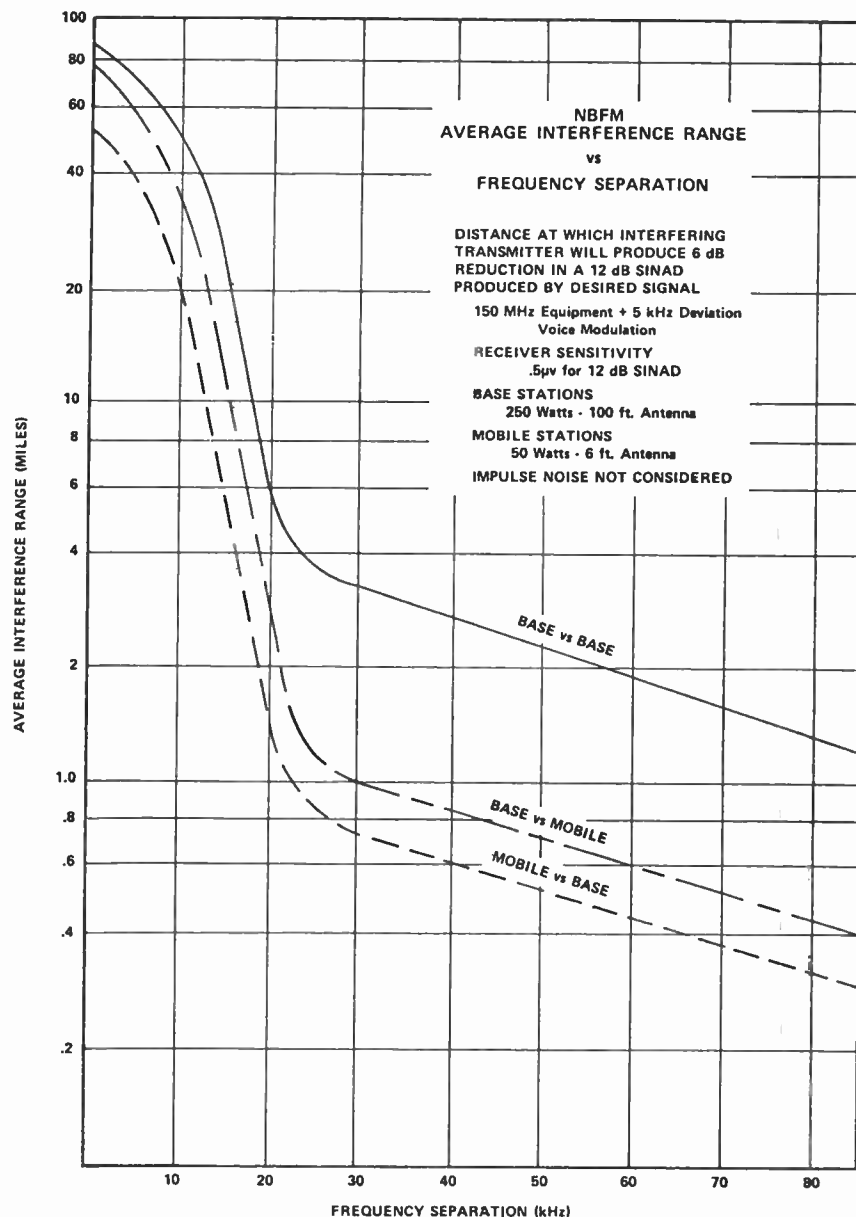


Fig. 2.

kHz. The conclusion must be that about 25-kHz spacing is minimum when the only considerations are the effects of transmitter radiations intercepting receiver selectivity. Additional degradation due to ambient noise is a natural consequence of narrower bandwidth.

It is important to note that the curves of Fig. 2 are limited by transmitter-carrier power output on the one hand and transmitter noise on the other. The solution for interference in either case is distance. There is no known practical method of reducing transmitter noise. The advent of semiconductors makes "staying even" a challenging task.

The channel spacings of 20 kHz (25.01–49.6 MHz) and 30 kHz (150.8–173.4 MHz), therefore, represent compromises to the 25-kHz spacing discussed previously. At the time they were implemented, the licensee's burden was eased in splitting from the previous 40- and 60-kHz

spacings. In the low band (25.01–49.6 MHz), the state of the art concerning frequency stability produces less absolute frequency error than in the high band (150.8–173.4 MHz), meaning that 20-kHz spacing is a reasonable compromise at the lower frequencies.

2) *Use of Tertiary Frequencies*: The foregoing represents the EIA Land Mobile Section's reasoning when it supported the commission's move to use tertiary (15-kHz spacing) frequencies in the 150-MHz band (docket 13930). This is the summary of the filing: "Interference on tertiary frequencies can be less than for cochannel operation provided there is proper geographical spacing. Their use represents a lesser-of-evils temporary answer to the congestion problem."

In some cases the tertiary interference is more bothersome than cochannel interference. For example, the tertiary channel's receiver squelch may not open when an un-

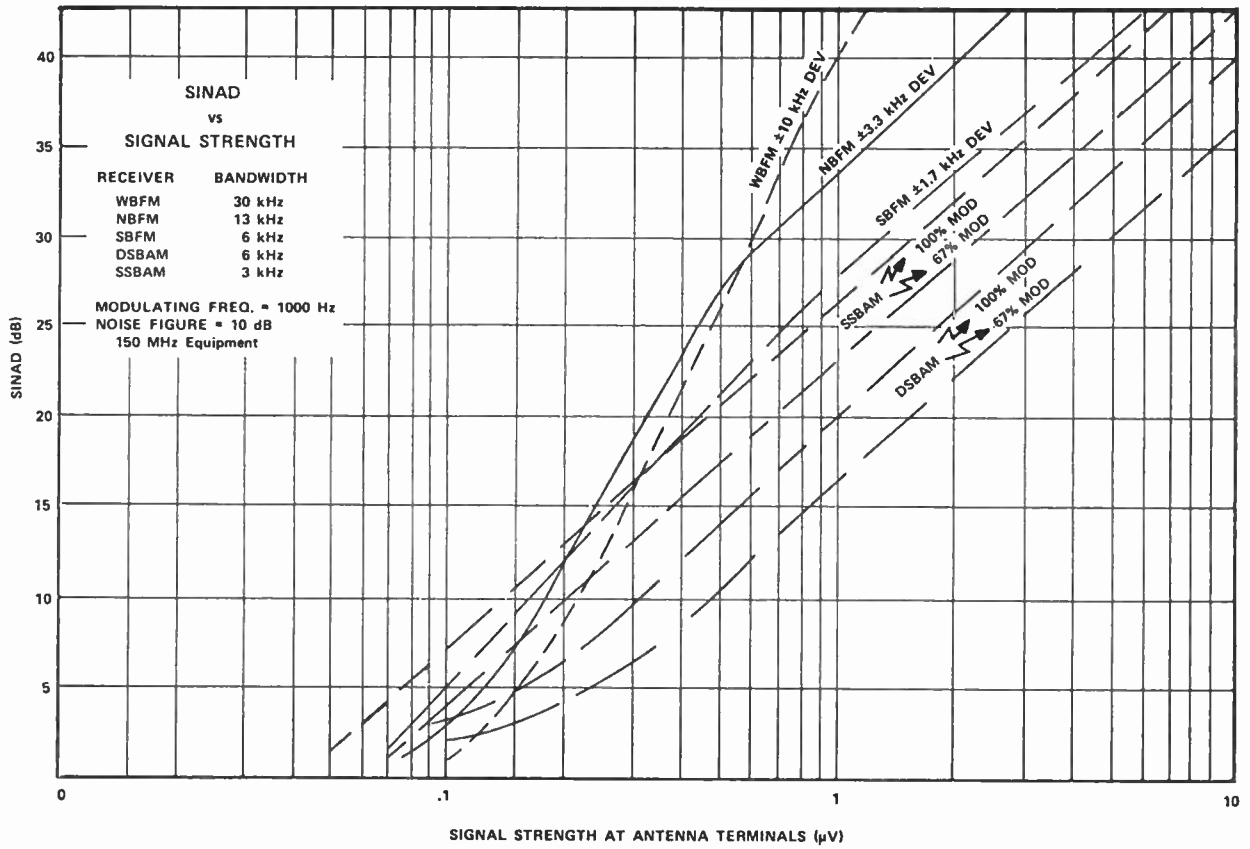


Fig. 3.

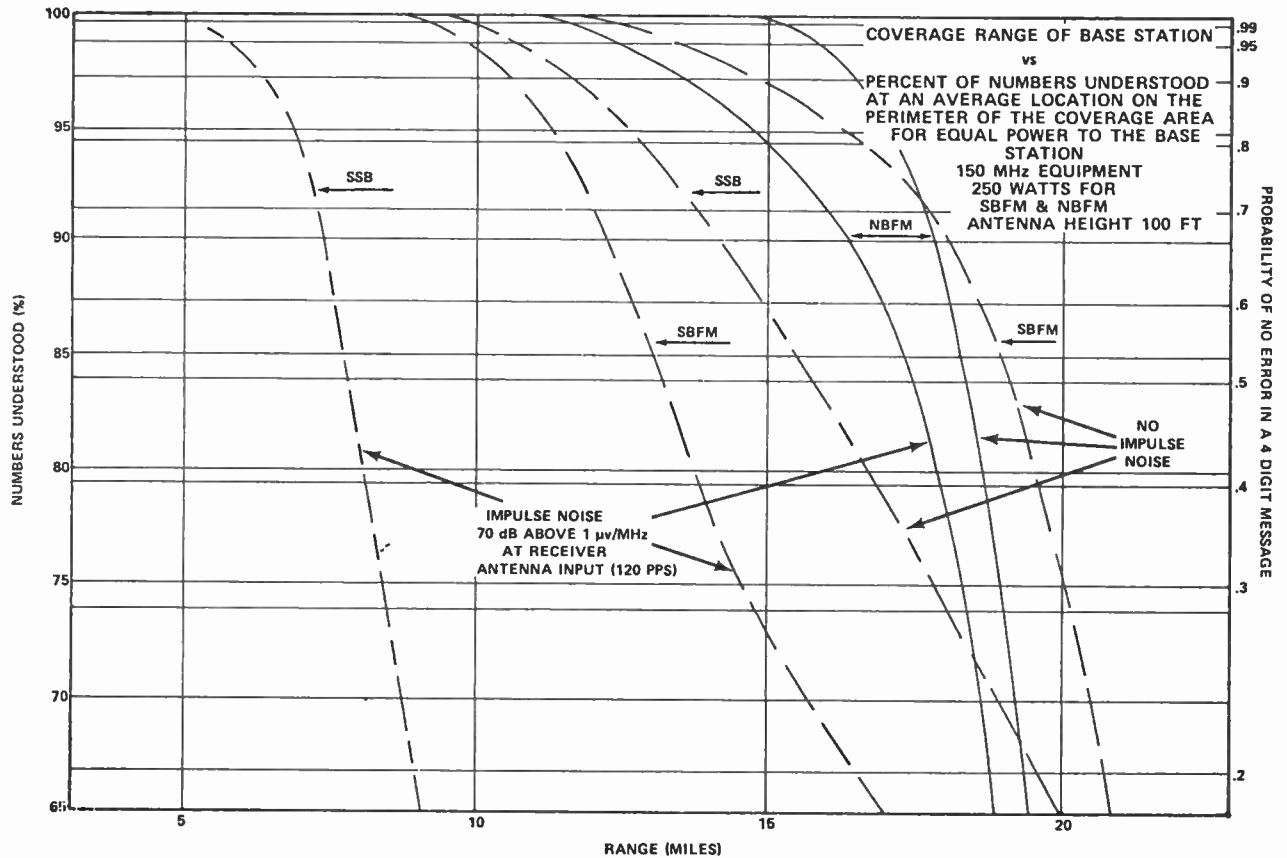


Fig. 4.

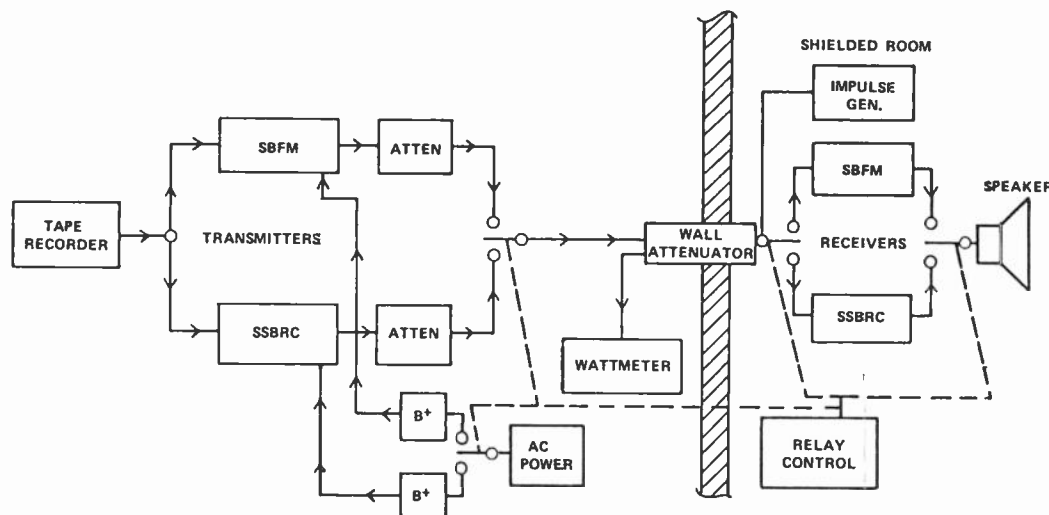


Fig. 5. Setup for comparative listening tests.

desired, 15-kHz-away transmitter is on. But when the desired transmitter is on, the interfering transmitter will then be heard, a phenomenon which precludes the ability to monitor the channel for interference-free moments.

Inasmuch as using tertiary assignments will increase the number of users and the fact that these users are now only 15 kHz away and not 30 kHz, we can positively predict an increase in desensitization occurrences. Unfortunately, desensitization manifests itself by causing a receiver to be insensitive to its desired "on-channel" signals while the audio output remains quiet. In other words, calls are missed and the user never knows it at the time it happens. It is, therefore, possible to test a tertiary assignment by listening in on the tertiary frequency, hear nothing and feel that the channel is clear, while in actuality the receiver could be desensitized part or even most of the time.

B. With Narrow-Bandwidth Technical Standards (AM and FM) (see Section II)

Sliver-band frequency modulation (SBFM): 6-kHz receiver bandwidth, ± 2.5 -kHz deviation.

Single-sideband amplitude modulation (SSB): 3-kHz receiver bandwidth up to 100-percent modulation.

1) *Single-Signal Performance*: Fig. 3 shows the detected SINAD for FM and AM 150-MHz systems normalized for receivers having equivalent noise figures. It is important to realize that the data for these curves has been taken with a) single-frequency signals (no interference), and b) low ambient noise (no degradation due to impulse noise).

The conclusions are as follows:

1) at very low signal strengths, AM produces greater SINADs than does FM, but with very weak signals, the quality of service is so low that there is no real net advantage;

2) at very low signal strengths, the narrower the bandwidth, the greater the SINAD (when there is no impulse noise to cause degradation);

3) at strong signal strengths, FM produces greater SINADs than does AM;

4) at stronger signal strengths, the wider the bandwidth, the greater the SINAD;

5) the maximum communication range occurs with weak signals where SSB shows superiority; but, again, the quality of service may be so poor as to show no real gain; also, impulse noise is not included;

6) the maximum intelligibility occurs with strong signals where WBFM shows superiority;

7) the FM improvement over AM systems reduces rapidly as the FMI decreases, meaning that the FM improvement factor is not realized if low modulation indexes are used.

Whereas AM and narrow bandwidth appear to be superior on the one hand, FM and wider bandwidth are superior on the other. An operational test gives another point of reference. Fig. 4 is a plot of number recognition versus range for NBFM, SBFM, and SSB. Fig. 5 illustrates the controlled conditions under which this test was made.

The conclusions are as follows:

1) NBFM and SBFM outperform SSB until the signal strength becomes so weak as to yield unacceptable service in any condition;

2) the improvement in SINAD for FM and wider bandwidth at strong signals contributes little to intelligibility.

So far, therefore, the overall conclusions must be that in low-noise strong-signal areas, the three systems will each give reasonable service with narrow-band FM and sliver-band FM having the edge. However, when impulse noise is introduced, SSB covers less than half the range (1/4 the area) that can be covered by the equivalent-power NBFM system, meaning that more SSB transmitters or higher power transmitters would be required to cover the equivalent NBFM area. Similarly, SBFM shows some advantage over NBFM in the absence of impulse noise. With impulse noise for 80-percent readability, SBFM covers about 60 percent of the area that can be covered by the equivalent NBFM system.

At this point, it might seem appropriate for someone to suggest that high-cost ignition-noise blankers be installed

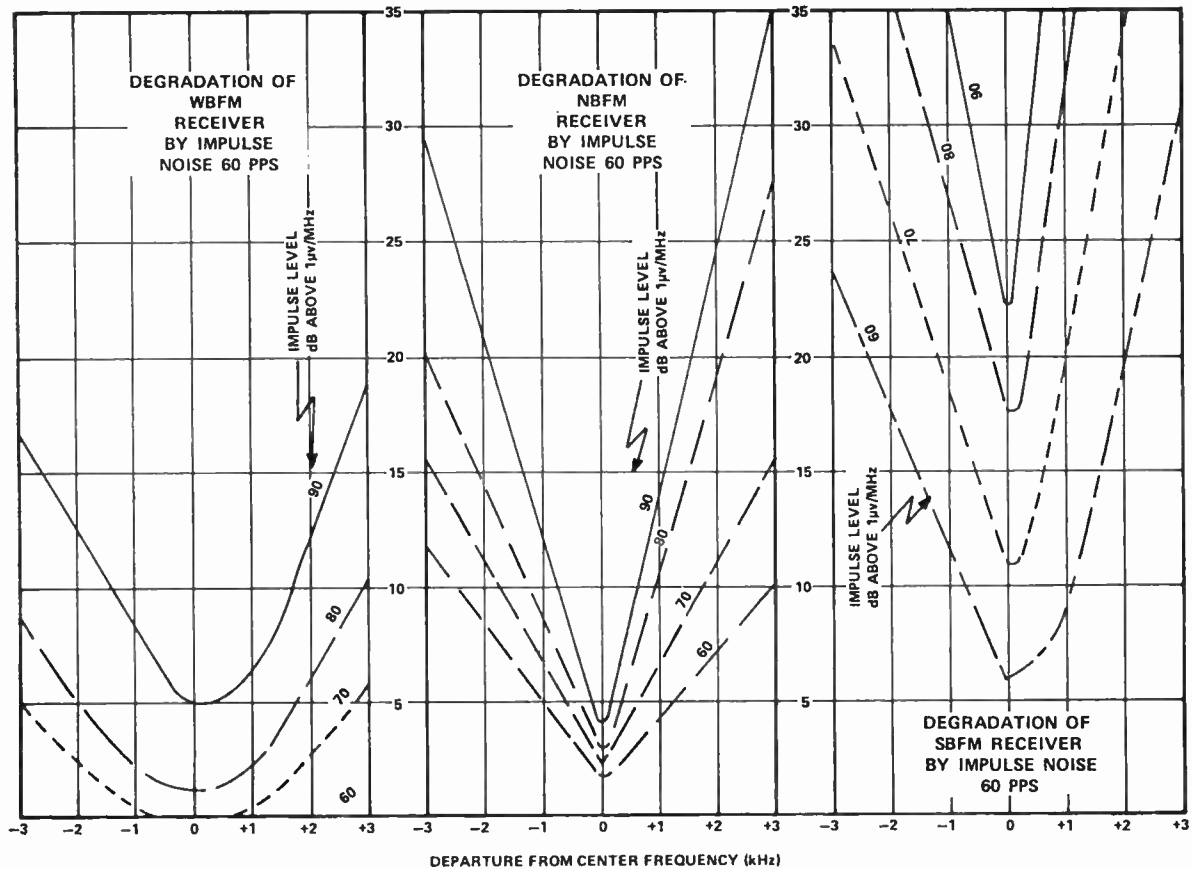


Fig. 6.

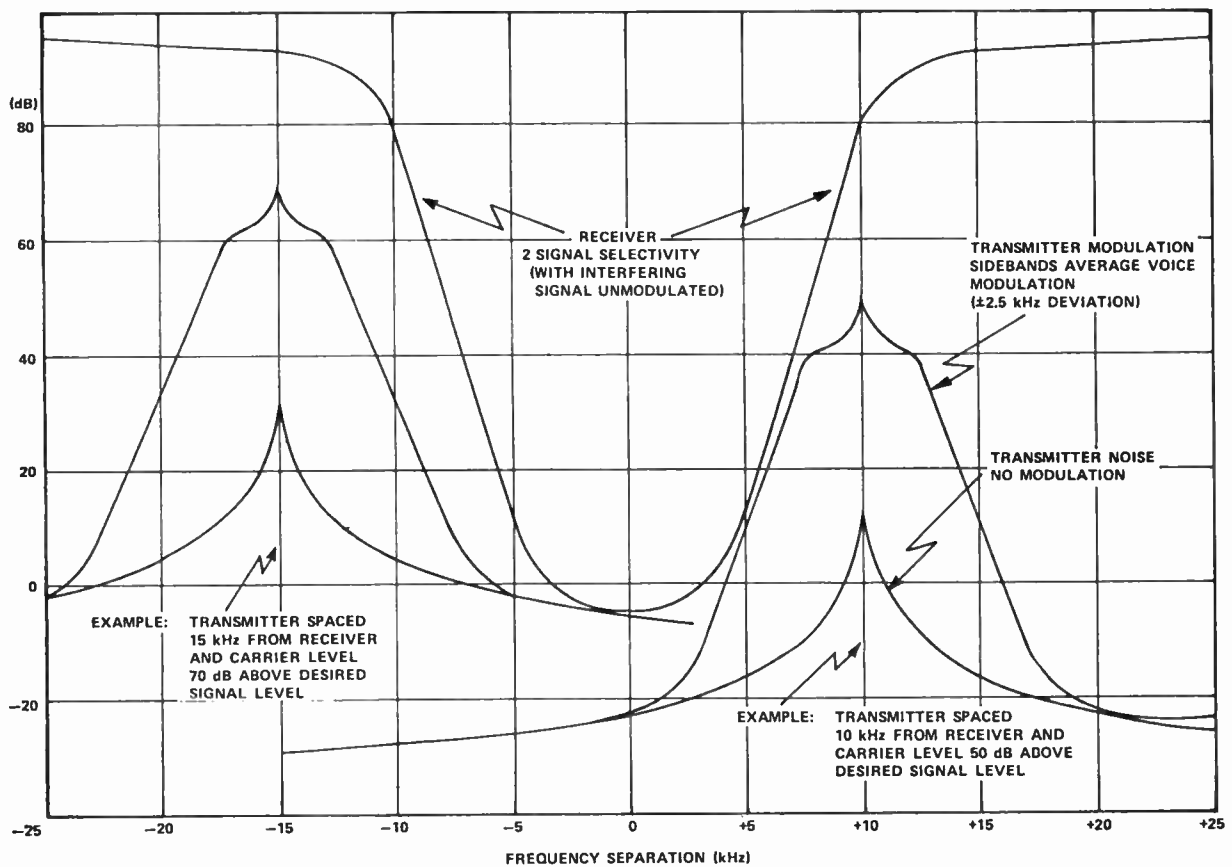


Fig. 7. Interference protection versus frequency separation.

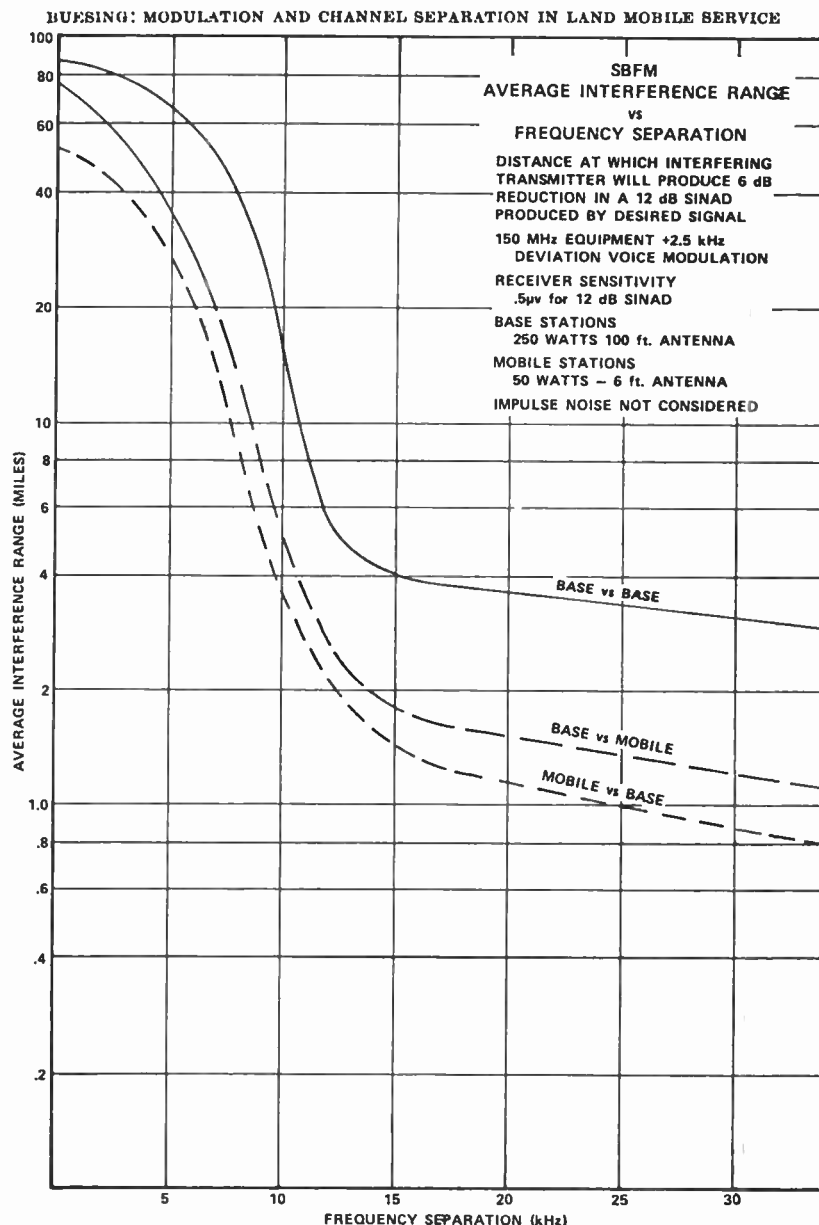


Fig. 8.

in all receivers to reduce the impulse noise degradation. It goes without saying that SSB receivers would require noise blankers as standard equipment. However, reduced receiver bandwidth increases the pulse stretching as the impulse traverses the receiver selectivity. High-performance noise blankers that will "saye the day" have not yet been designed. In addition it is important to realize that noise blankers do not blank all kinds of noise. The Appendix treats high-repetition-rate situations.

Fig. 6 illustrates the severity of the impulse noise problem. The comparison is made between WBFM, NBFM, and SBFM. An example is illustrated in Table I for a noise level 70 dB above 1 μ V/MHz at 150 MHz.

As a reference, consider the 3-5-dB degradation of NBFM versus WBFM. This is the magnitude of the problem that leads to the need for ignition noise blankers, precisely phase-tuned receiver selectivity elements, and

TABLE I

Systems Compared		Frequency Error (kHz)	Relative Degradation of A Compared to B (dB)
A	B		
NBFM	vs WBFM	0	3
NBFM	vs WBFM	$2 \times 5 \text{ PPM} = 1.5$	5
SBFM	vs NBFM	$2 \times 5 \text{ PPM} = 1.5$	19.5
SBFM	vs WBFM	$2 \times 5 \text{ PPM} = 1.5$	25
SBFM	vs NBFM	0	8

teams of manufacturer's engineers going into the field to work on area-coverage complaints during the change from WBFM to NBFM technical standards. Impulse noise, therefore, becomes the limiting factor in preventing a move to narrower-bandwidth technical standards.

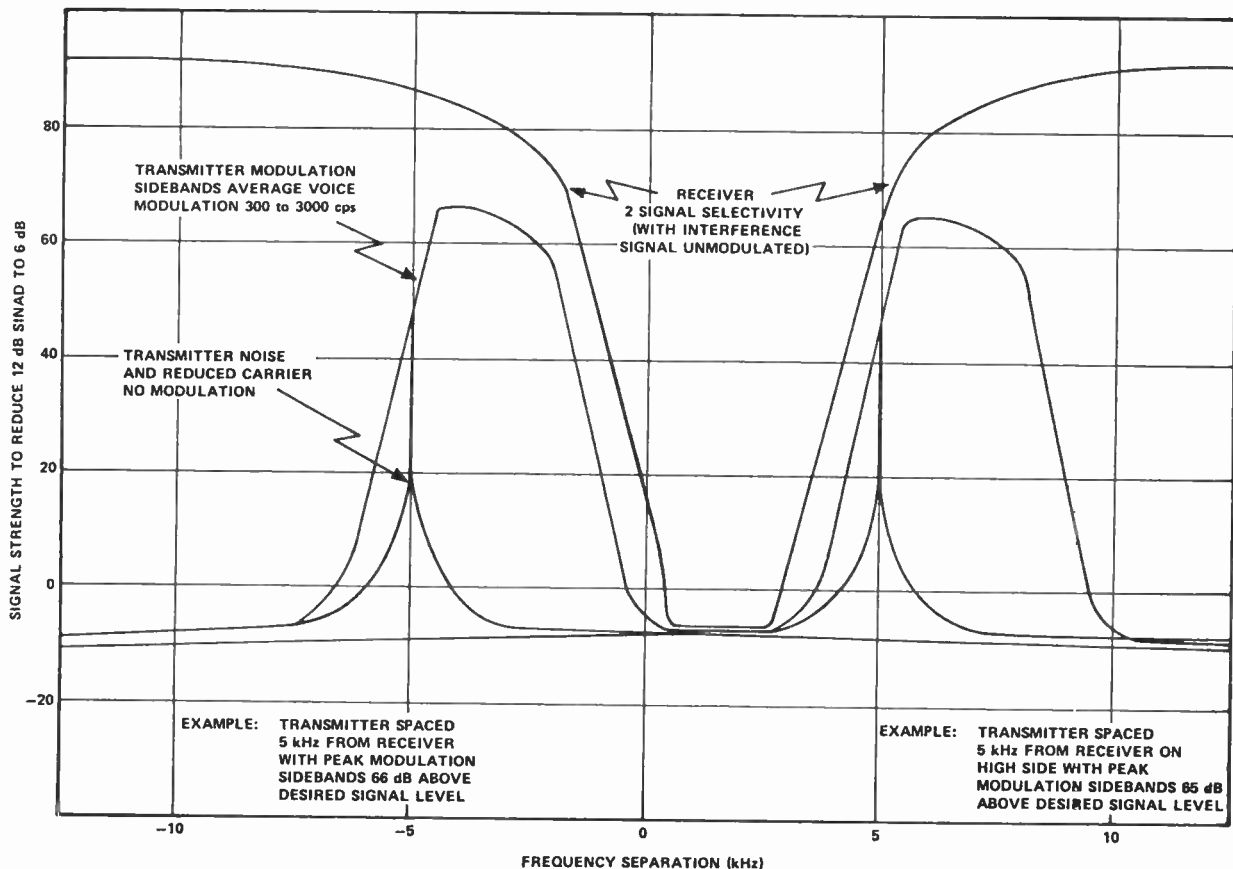


Fig. 9. Interference protection versus frequency separation for SSB.

2) *Two-Signal Performance*: Figs. 7 and 8 are plotted to show the mechanisms of adjacent-channel interference and the average expected interference ranges in systems using SBFM. They can be compared directly with Figs. 1 and 2 for NBFM systems. The conclusions are as follows: 1) the interference problems in SBFM begin to increase most rapidly at about 13-kHz spacing (recall that in NBFM this occurred at about 25-kHz spacing); 2) SBFM systems at 13-kHz spacing would need greater geographic separation than NBFM systems at 25-kHz spacing to minimize adjacent channel interference.

Figs. 9 and 10 show the adjacent-channel interference situations for SSB. In this case, an adjustment was necessary to allow for the difference in communication range produced by FM and SSB systems operating from equal primary power (Fig. 4). The SSB transmitter power was, therefore, boosted 5 dB. It is clear that SSB systems would require much greater geographic separations than either of the FM systems that have been examined. The base station-to-base station interference range situation can be summarized in Table II.

3) *Multiple-Signal Performance*: The intermodulation problem can be analyzed by considering the number and strength of products that are produced when two or more signals of different frequency are combined in a nonlinear device such as the RF section of a receiver or in the power

TABLE II

System	Frequency Spacing (kHz)	Interference Range (mi)
NBFM	25	3.7
SBFM	13	4.6
SSB	5	10.0

output section of a transmitter. From the Appendix, the frequency of the intermodulation products can be found by:

$$F_{IM} = N_1 F_2 \pm N_2 (F_2 - F_1).$$

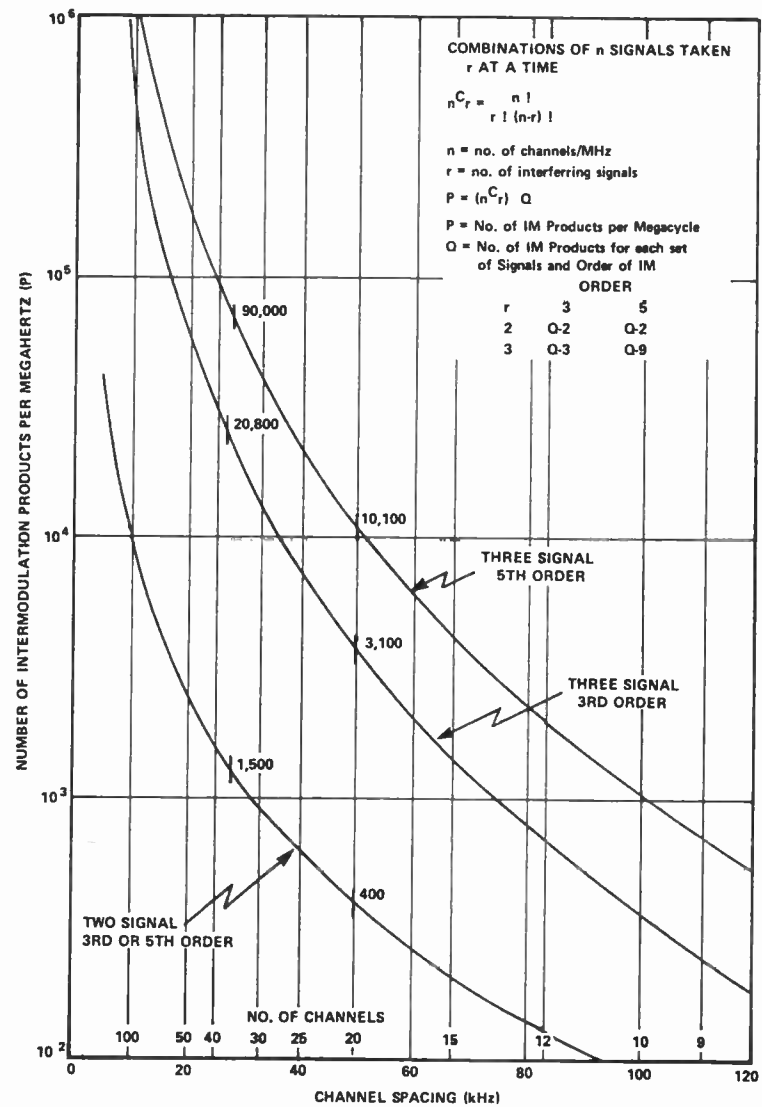
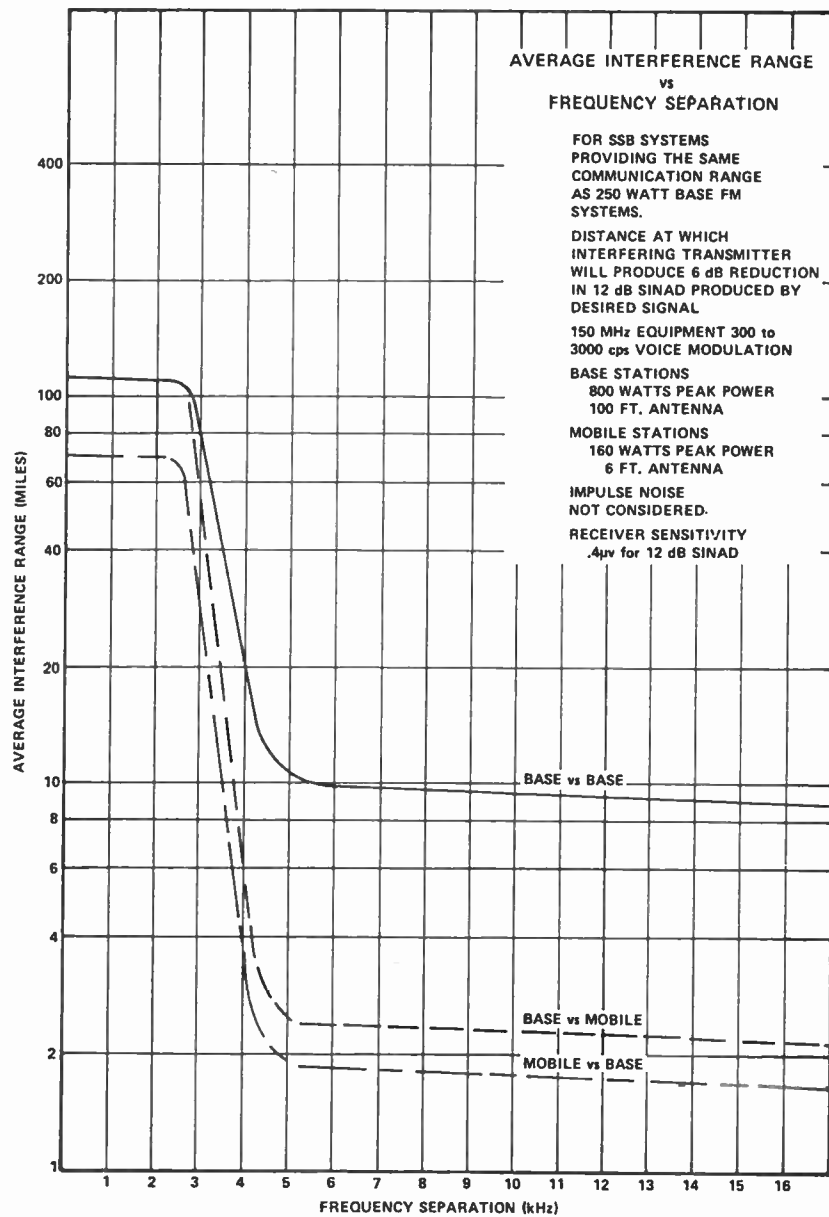
An example follows:

$$\Delta f = F_2 - F_1 = 2.80 \text{ MHz}$$

F_1	F_2			
$N_1 = 1$	$N_1 = 1$	$N_1 = 1$	$N_1 = 1$	$N_1 = 1$
$N_2 = 2$	$N_2 = 1$	$N_2 = 1$	$N_2 = 2$	$N_2 = 2$

F_1	F_2			
39.42	42.22	45.02	47.82	50.62
MHz				

Receivers tuned to any one of the F_{IM} frequencies will experience interference when F_1 and F_2 appear simultaneously. Depending upon the signal strength of F_1 and F_2 ,



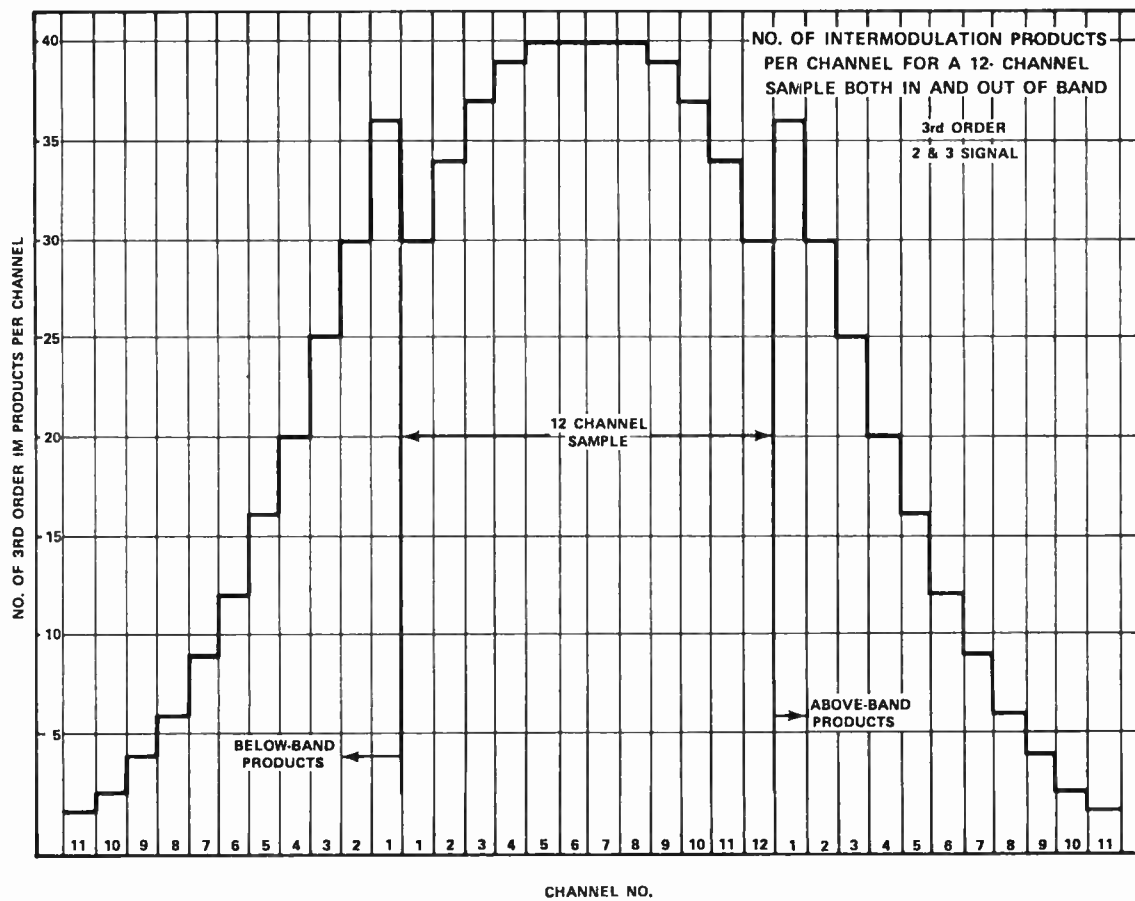


Fig. 12.

the geographic separation between them and the desired receiver, and the receiver RF performance, the interference will be either a nuisance or disruptive.

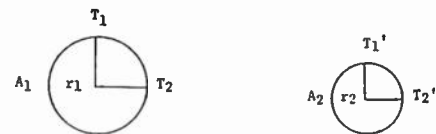
The number of intermodulation products varies as the number of channels within a given spectrum space. Fig. 11 shows the number of intermodulation products that fall within a given megahertz of spectrum space as a function of channel spacing (and number of channels). Splitting channels from present-day spacing (20, 30, 50 kHz) causes the IM products to increase by orders of magnitude.

Another way of examining this problem is to view a discrete number of channels and then assess the effect upon them as more channels are added. In other words, the distribution of IM products for a given number of channels in Fig. 11 should be studied. Fig. 12 shows a group of 12 channels and the number of IM products that these 12 channels produce both within and outside their own band. The middle channels (5, 6, 7, 8), for example, have 40 IM products each. From Fig. 11, 12 channels of third order, 2- and 3-signal IM, produce 792 products. The total shown in Fig. 12 does not include combinations involving the on-channel frequency of the IM product.

Fig. 13 considers other groupings of channels and the number of IM products that fall back upon their middle channels. For example, if the 12 channels of Fig. 12 were split so as to yield 24, the middle channels of the new group

of 24 would have 187 third-order products and many thousands of fifth-order products on each one.

Just as important as the number of intermodulation products, is their strength. Suppose that the present-day channels were to be split, thus potentially doubling the number of interfering transmitters. This can be considered the same as asking the present-day licensees, in a given area, to "squeeze together" into half the present area in order to make room for the new licensees. On the average, therefore, the interfering transmitters will be closer together after channel splitting than before. In the following example, T_1 and T_2 are the location of transmitters before splitting, while T_1' and T_2' are their locations after being "squeezed" into half the area.



If

$$A_2 = \frac{1}{2}A_1,$$

then

$$r_2 = r_1/\sqrt{2}$$

and

$$d_2 = d_1/\sqrt{2} = 0.707d_1$$

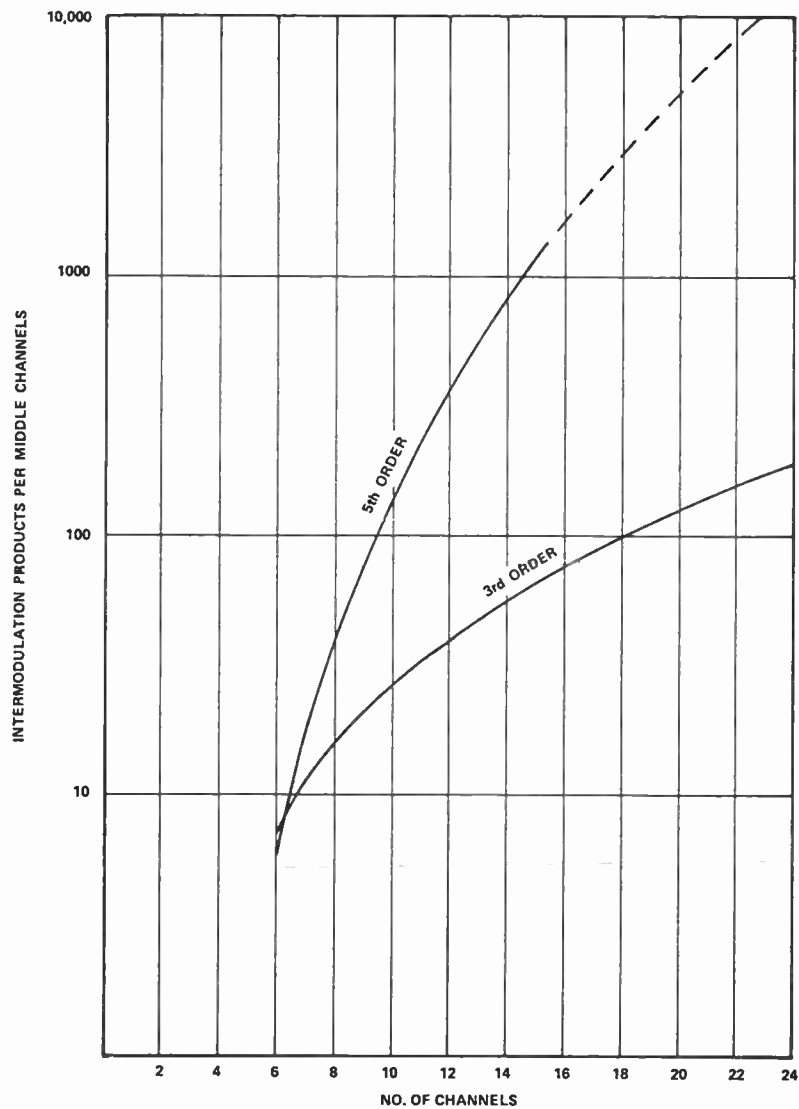


Fig. 13. Number of intermodulation products per middle channel versus number of channels sampled.

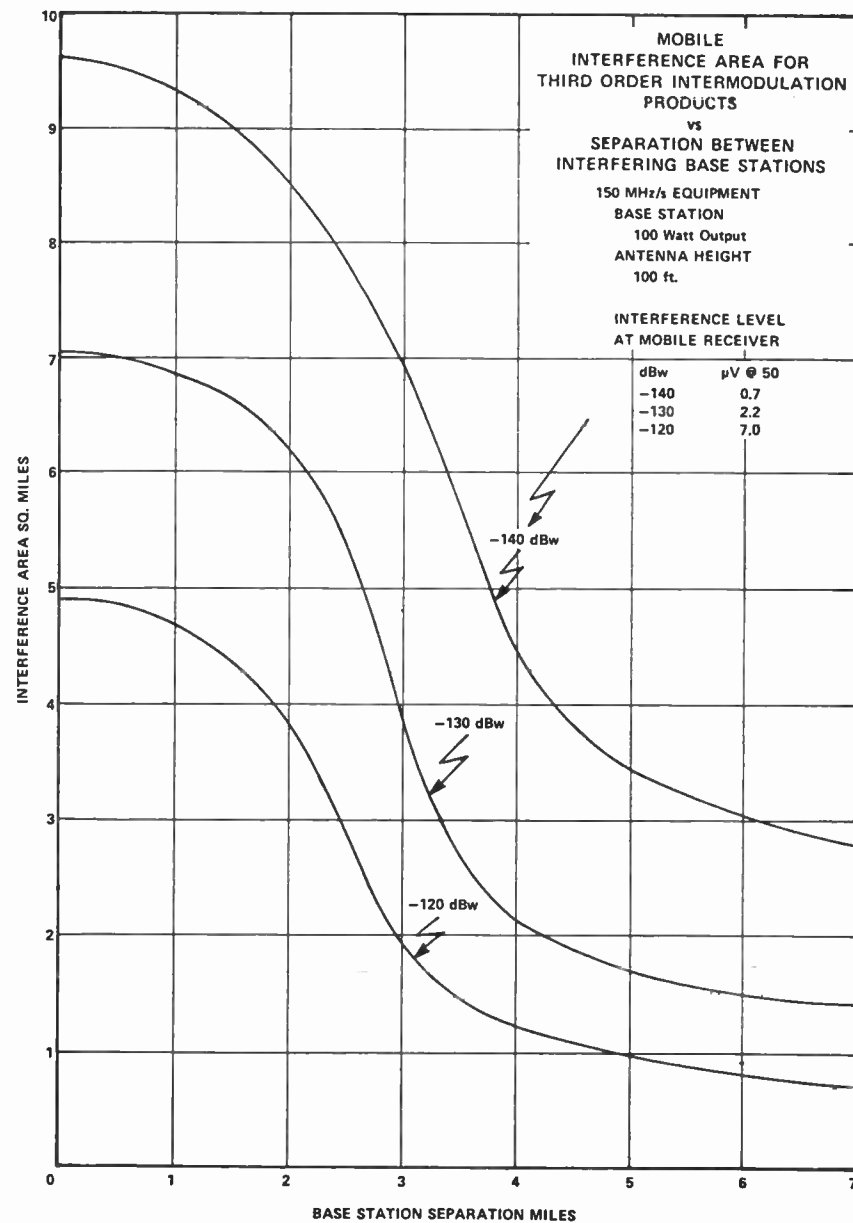


Fig. 14.

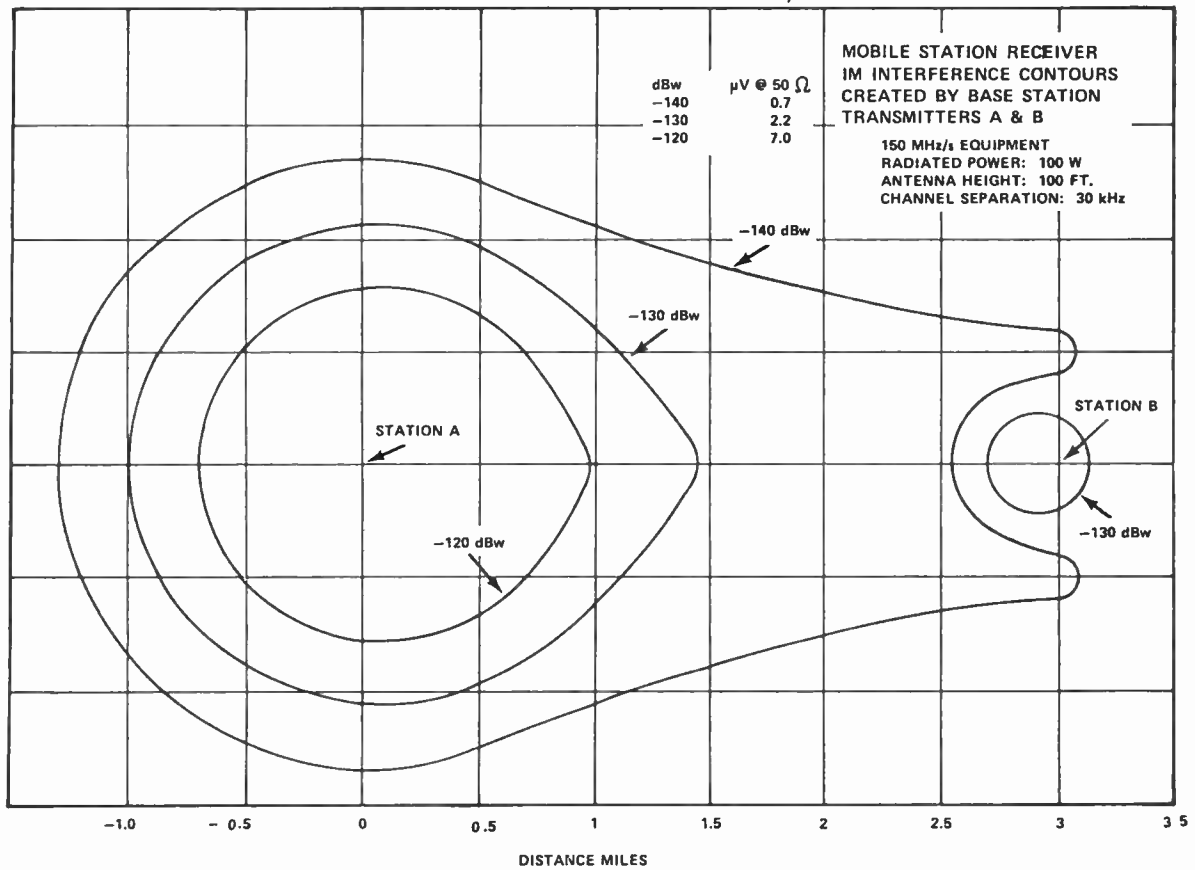


Fig. 15.

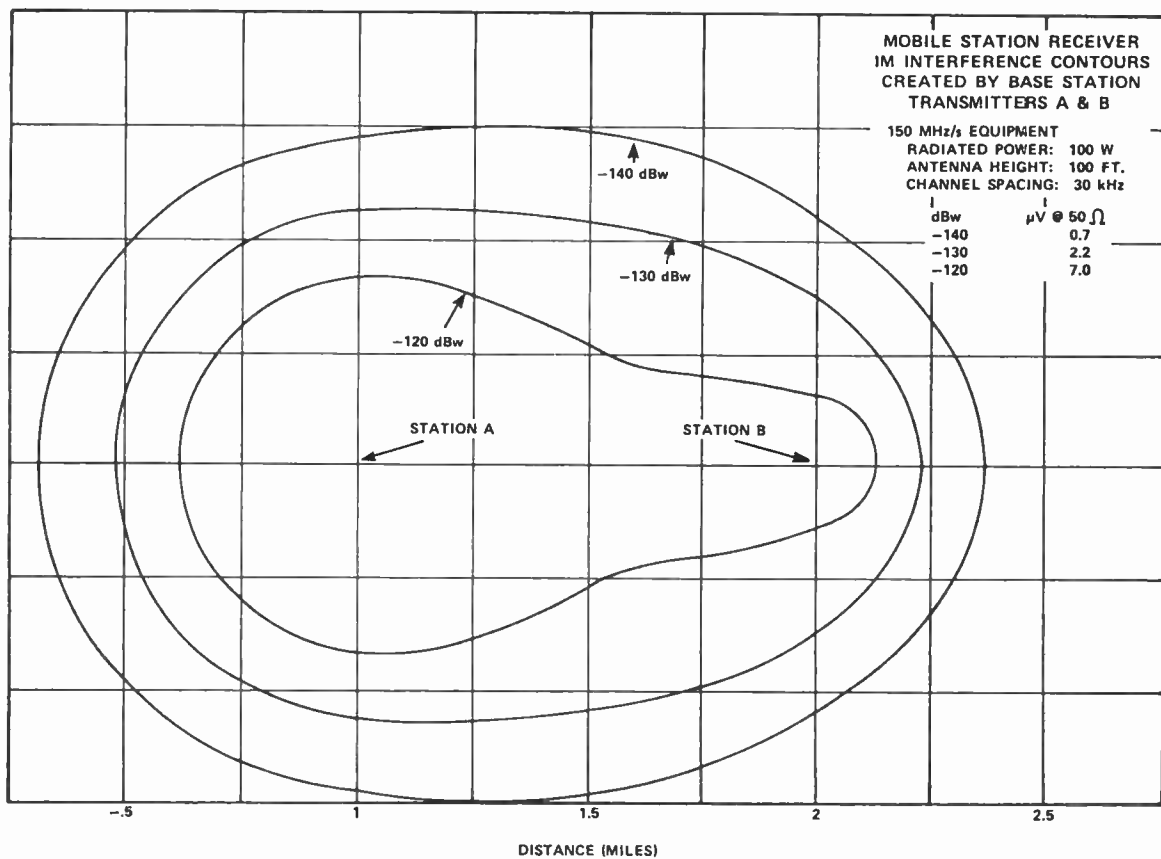


Fig. 16.

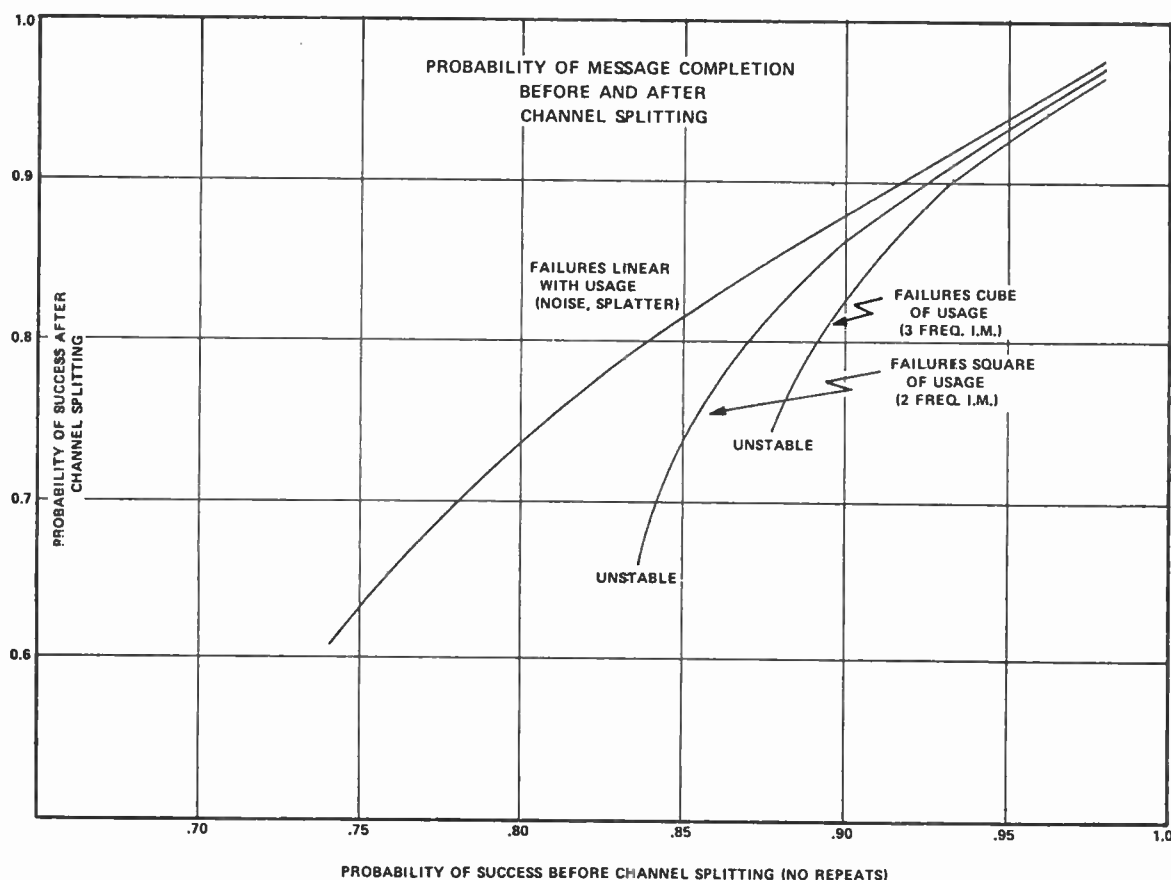


Fig. 17.

or, the two transmitters are 30 percent closer together after splitting. Moving base stations 30 percent closer together is the same as increasing the level of interference at the base station receiver by 3 dB.

It can be shown that the amplitude of third-order interfering signals varies as $2A + B$ or $A + B + C$ where A , B , and C are relative amplitudes expressed in dB. So the potential increase in third-order IM levels to base stations is 9 dB. Fifth-order amplitudes vary as $4A + B$ or $A + 2B + 2C$ giving a potential of 15-dB increase in their levels.

Fig. 14 shows the interference area as a function of base station separation. These curves are computer calculations of the areas bounded by the interference contours created by any two base stations. Figs. 15 and 16 illustrate the method. Since the most rapid changes in Fig. 14 take place between 2- and 4-mile separations, a 30-percent reduction in geographic spacing more than doubles the interference area.

4) System Failure Rate:

a) Basic to the consideration of reliability of a radio communication system is the regenerative or spiralling phenomenon resulting from missed calls due to interference. Interference, cochannel or otherwise, causes missed calls. The amount of this interference is a function of channel usage. When a call is missed, a repeat call will be made which increases system usage, increasing the probability of missed calls and completing the regenerative loop.

Then

$$X = X_0 + P(\text{fail}) X$$

where X is the actual system-use factor, taking into account missed calls and consequent repetitions; X_0 is the system-use factor before calls are missed; and $P(\text{fail})$ is the probability of a message being missed due to interference; or

$$\text{actual usage} = \text{desired usage} + \text{repeats.}$$

The actual usage X varies from zero in an unused system to unity in a system in which all channels are busy all the time. This leads to

$$X_0 = X^{-K} n^n$$

which is derived in the Appendix. The factor K relates system usage to interference (and, therefore, depends upon equipment parameters, geographical factors, etc.). N is a small integer defined in the following section. It should be noted that K , X , and N are variables which are different for each system. These formulas were developed to be used as tools in the analysis of the congestion problem. It is too early to apply them in specific systems.

b) The rate at which increased usage leads to increased interference also depends upon the particular type of interference. Transmitter noise and modulation sidebands cause interference in direct proportion to the usage, for example $N = 1$. Two-frequency intermodulation, however, causes interference in proportion to the square of the usage factor $N = 2$, since two transmitters must be keyed

simultaneously for interference of this type to occur. Likewise, three-signal intermodulation causes interference in proportion to the cube of the usage factor $N = 3$. The probability of failure due to interference is given by

$$P(\text{fail}) = 1 - \exp(-KX^n)$$

as derived in the Appendix.

When the effects of spiralling, due to repeats, are examined simultaneously with the probability of failure, due to the various types of interference discussed previously, Fig. 17 results. Here, for a given initial probability of success, each of the three interference causes discussed before are calculated to include the regenerative effect due to repeated messages.

For example, if the initial success probability is 90.5 percent, nearly 10 percent of all messages must be repeated. This increased usage would decrease the net success probability to 89 percent if the prime interference mode were noise and splatter, to 87.6 percent if the prime mode were two-signal intermodulation, etc. As can be seen the entire system can become unstable if the initial loading were high enough to cause relatively poor probabilities of initial success. This would be typical of many present systems, especially at peak-load hours.

The system failure rate analysis is an attempt to look at the peak-load conditions rather than the "average". Examining the "average" condition is akin to saying "the average potential connected between the ankles and head in an electric chair, considering the short time of application each year, is only a few microvolts—and that will not kill anyone!" It is the peak load for rush hours and emergencies that must be considered when useful service is the objective of Land Mobile Services.

The above approach and derivation for failures in the communication system should be used to indicate the nature of the failure mechanism. The answers indicated are only as good as the assumptions are for K , X , and N , which clearly vary for each system. The above formula must be verified by future repeated applications before it can be utilized as being fully valid. This approach does, however, guide us in our understanding of the problem.

5) Other Modulation Systems:

a) *Amplitude modulation (AM)*: It has been pointed out in the past that when low modulation indexes are used in FM systems, to save bandwidth, the FM signal-to-noise improvement factor reduces as compared to AM. This might lead to a reexamination of AM as a means of modulation. However, for modulation indices of M greater than 1, the FM signal-to-noise ratio is much greater than AM. Even when the FM modulation index is 1, the FM signal-to-noise ratio is 5 dB better than for AM. Furthermore, impulse noise performance for FM is better by the $\sqrt{2}$. Also, it is supposed that an AM system may require less bandwidth than FM, for the same upper limit of audio frequency. The Appendix treats the subject of radiated sideband energy. The point is made that because of transmitter power amplifier nonlinearities, particularly with near-100-percent modulation, the spectrum from an AM transmitter may be broader than that for an FM

transmitter and cause greater adjacent-channel interference. It is important, also, to recognize that FM "capture effect" as an important system design tool, particularly in reducing carrier-beat interference.

No matter what the mechanism for producing narrower bandwidth, however, the result is to produce greater degradation in the presence of impulse noise. The Appendix points out the inherent greater susceptibility of AM systems to this prevalent kind of noise. This one factor, by itself, outweighs all the other arguments against AM, as a land mobile communications tool.

b) *Single-sideband amplitude modulation (SSB)*: The preceding paragraphs of section a) have treated the general subject of AM. Suppressing the carrier and transmitting only one sideband has long been a favored method of reducing bandwidth in point-to-point services and where impulse noise is seldom encountered.

Figs. 6 and 8 emphasize the serious nature of the reduced-bandwidth and impulse-noise problem. Both sliver-band FM and single-sideband AM suffer with respect to narrow-band FM, but SSB covers less than $\frac{1}{4}$ the area that a mobile NBFM system may be expected to serve. Similarly, the point of Section III-B2 must be emphasized; namely, that SSB systems require greater geographic separation than FM systems operating with equivalent primary power.

c) *Double-sideband amplitude modulation, reduced carrier*: This system of modulation reduces the AM carrier by means of a balancing power amplifier. The receiver then synchronously adjusts itself by comparing the double sidebands. A lock condition is established when the receiver center-phase difference is minimum.

Such a system requires twice the bandwidth of a SSB system, hence its degradation due to impulse noise is reduced. If its performance were plotted on Fig. 4, the curve would lie between SSB and SBFM. In no case would there be an improvement over SBFM, and with impulse noise the performance would be poorer.

From Fig. 3 it is apparent that added power is required from DSBAMRC to compete with SSB. This increase is variously estimated to be between 6 and 9 dB. Depending upon the modulating waveforms, these power increases can be even less than 6 dB. Nevertheless, the limiting factor in the adoption of this system is the response to impulse noise. No tests show improvement over FM systems.

d) *Single-sideband frequency modulation*: Much thought has been given to FM systems that radiate only one sideband and thus theoretically require less spectrum space than present systems.

The SSBFM signal is obtained by amplitude modulation of a conventional FM signal with the negative exponential of the Hilbert transform. The Hilbert transform is obtained by rotation of all spectral lines of the modulating signal by 90° . In its pristine form, the SSBFM signal can be considered as an AM which cancels sidebands on one side of the carrier while adding new sidebands to the other. A conventional receiver may be used for reception, assuming excellent limiting to remove the AM.

Actually, the sideband cancellation is dependent upon the linearity of components which produce the 90° phase shift. With the best of today's devices, the higher order sidebands are not completely cancelled, meaning that the bandwidth in the region 50–70 dB below the carrier level may be increased over conventional FM. At 30–50 dB down, the bandwidth may be the same, but at lesser levels the expected improvement will be noticed. Furthermore, the modulation index must be limited to about 2 to realize the reduced bandwidth. From Fig. 3, the overall improvement over SSBM and SSB is nil.

Computation shows that the perfectly produced spectrum of a SSBFM signal is about $\frac{2}{3}$ that of the conventional FM signal. To fully utilize this system it is necessary to alternate the sidebands of the adjacent channel assignments so that two systems can be operated in one conventional channel space. Theoretically, therefore, a 50-percent increase in the number of systems could be expected. However, guard bands must be included to allow for frequency errors in order to prevent the carrier of one channel from being received by a receiver on the nearest adjacent channel. At 150 MHz with a 5-PPM frequency stability, more than 1.5-kHz separation must be allowed. This, coupled with the probability of increased modulation sidebands at levels well below the carrier, leads to the conclusion that the number of systems assignable with SSBFM would be equal to or less than SBFM.

Impulse noise again becomes a formidable obstacle. Because the SSBFM filters are one-sided, the pulse which "rings out" of the filter is not at the receiver center frequency. Measurement of this phenomena shows 10 dB more disturbance at the output of SSBFM receivers than in conventional FM receivers.

IV. CONCLUSIONS

In quest for ways to increase the number of assignable channels in the land mobile radio service, three factors emerge as boundary conditions.

- 1) Narrow bandwidths are not tolerant of impulse noise.
- 2) To overcome the effects of noise, greater transmitter power or more transmitters per area are required, thus producing intermodulation products of greater strength or number.
- 3) Transmitter noise (noise in the final amplifier stage with no modulation and/or noise in the oscillator-multiplier chain) limits the adjacent-channel frequency and geographic spacing.

Narrow-band FM with channel separations of 20–30 kHz represents the optimum modulation method and channel spacing in a "mobile" environment where noise levels and the number of transmitters on the air is increasing.

APPENDIX

A. Theoretical and Measured Sidebands

Frequency-modulation sidebands are a function of modulating frequency and modulation index (ratio of deviation to modulating frequency). The conventional

method of expanding the Bessel function was used to produce the tone-modulation curves of Fig. 18.

Amplitude modulation, in the theoretical distortion-free case, produces only a single pair of sidebands during single-tone modulation; these sidebands are spaced on each side of the carrier by an increment equal to the modulating frequency. In a practical case, however, the modulating process will not be perfectly linear and the result may be expressed by a power series of the form

$$\text{erf} = 1 + b_1 e_m + b_2 e_m^2 + b_3 e_m^3 + \dots + b_n e_m^n.$$

For single-tone modulation, a trigonometric expansion of the above equation with $e_m = a_1 \cos w_m t$ yields the complete sideband energy distribution spectrum. Fig. 19 illustrates the result of this calculation with terms beyond the seventh order ignored.

Fig. 20 shows measured and calculated sidebands for a particular nonlinear amplitude modulation system; the modulation index of 0.547 was chosen as being typical of a communication system using considerable voice processing to maximize average modulation. The particular case shown corresponds to 3.3-percent total distortion which is probably less than could be expected in typical mobile-communications equipment. Increasing either the distortion or the modulation index will result in increased interference to adjacent channels. The spectrum from an AM transmitter, therefore, may not realize the advantage over FM that is normally attributed to AM. Fig. 21 compares modulation spectra for four cases; FM with modulation indices of 5 and 1, and AM with 54.7 percent and approximately 120-percent modulation.

Tone modulation, while lending itself to mathematical analysis, is not typical of actual usage on a voice-communication channel. For this reason the VOSIM was developed as a means of simulating average voice modulation. The VOSIM produces a pulsed output of noise shaped to approximate the energy distribution of a male voice. Its output to the transmitter is adjusted to give an amount of amplitude and frequency processing equivalent to normal usage. Fig. 18 compares modulation sidebands produced by VOSIM modulation with theoretical tone-modulation sidebands.

B. Impulse Noise

In the main body of this paper, the effects of impulse noise upon equipment performance has been displayed. Brief mention of the reasons for the effects is in order in this Appendix.

Since the SSB and DSBAMRC receivers are amplitude-responsive devices, the strength of the disturbance at the output is proportional to the amplitude of the noise impulse at the antenna. In FM receivers, on the other hand, the output disturbance is proportional to the frequency difference between the impulse and the desired signal. Thus in FM receivers, the disturbance has a maximum value which depends upon the maximum phase difference between the desired signal and the impulse. When the two are in phase, very little disturbance is heard. The relative phase is a random condition, thus half the pulses are

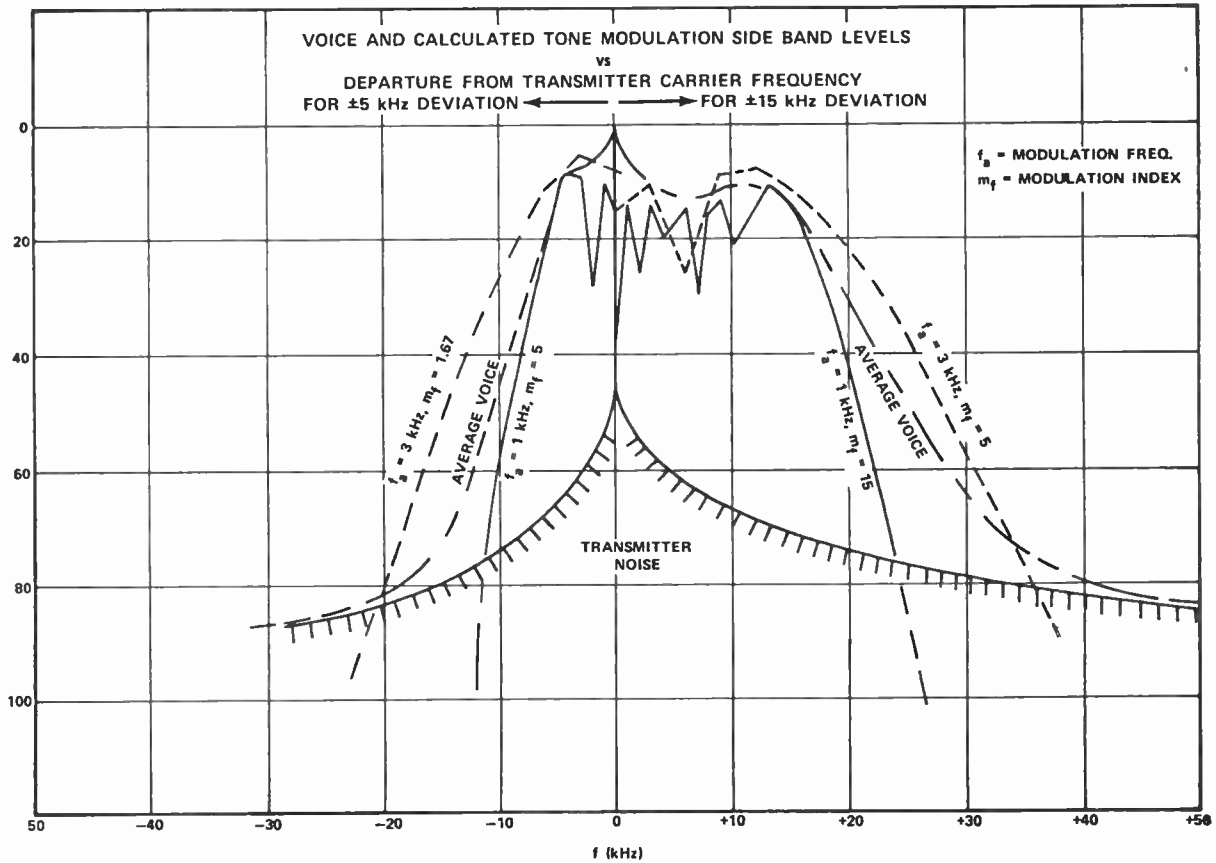


Fig. 18.

within 90° of the carrier and half are greater than 90° out of phase. The length of the disturbance is inversely proportional to the filter bandwidth. FM systems being inherently less sensitive to amplitude variations and greater bandwidths causing less pulse stretching indicate that wide-band FM will be least sensitive to impulse noise. As previously discussed, mention was made of high-repetition-rate noise and its effect upon signal readability.

In modern-day automobiles, the ignition pulse rate can be expressed by the formula

$$P = (N \times r/\text{min})/120$$

where P is pulses per second, N is number of cylinders, and r/min is crank-shaft revolutions per minute.

An 8-cylinder vehicle at 600-r/min idle speed, therefore, produces 40 pulses per second, whereas at near-maximum speeds of 4800 r/min, 320 pulses per second are produced. Many other kinds of noise produce greater repetition rates. Among them are intermodulation beats, adjacent-channel modulation, precipitation noise, generator and alternator noise, and multiple ignition systems. Fig. 22 illustrates the deleterious effects of high repetition rates. Here a reference impulse level was introduced into both NBFM and SBFM receivers. The level of desired signal to maintain 80-percent readability versus pulse repetition rate was recorded for both receivers. Once more the degradation of narrow-bandwidth systems is observed.

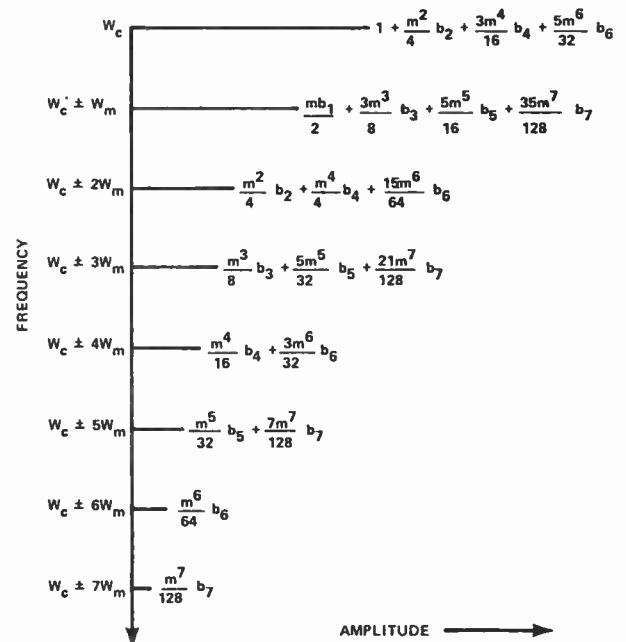


Fig. 19. Modulation products due to distortion through the seventh order. m —degree modulation, b_n —nonlinear modulation constant (n —order of harmonic).

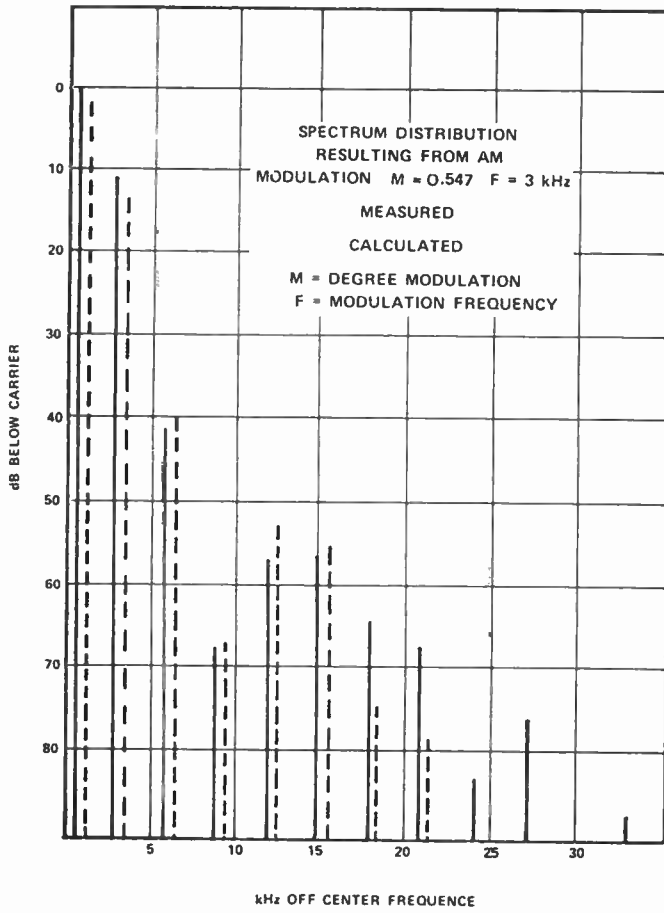


Fig. 20.

C. Intermodulation

Intermodulation is defined as the modulation of the components of a complex wave by each other in a non-linear system. A rigorous mathematical analysis of this phenomenon leads to an infinite power series of the form

$$e_{out} = a_0 + a_1 e_{in} + a_2 e_{in}^2 + a_3 e_{in}^3 + \dots + a_n e_{in}^n.$$

If e_{in} is the sum of two sine waves of different frequencies

$$e_{in} = A \sin w_1 t + B \sin w_2 t.$$

Trigonometric expansion and collection of terms gives the values of the coefficients for each term of the power series. In determining the frequencies at which intermodulation products are found, the third, fifth, and seventh order are of particular concern because they produce frequencies that fall back "in band."

When two frequencies interfere, the products are

$$F_{IM} = N_1 F_2 \pm N_2 (F_2 - F_1)$$

where F_{IM} is intermodulation frequency, F_1, F_2 are interfering frequencies, and N_1, N_2 are integers.

The third-order products are $2F_1 \pm F_2, F_1 \pm 2F_2$.

The fifth-order products are $F_1 \pm 4F_2, 2F_1 \pm 3F_2, 3F_1 \pm 2F_2, 4F_1 \pm F_2$.

The seventh-order products are $F_1 \pm 6F_2, 2F_1 \pm 5F_2, 3F_1 \pm 4F_2, 4F_1 \pm 3F_2, 5F_1 \pm 2F_2, 6F_1 \pm F_2$.

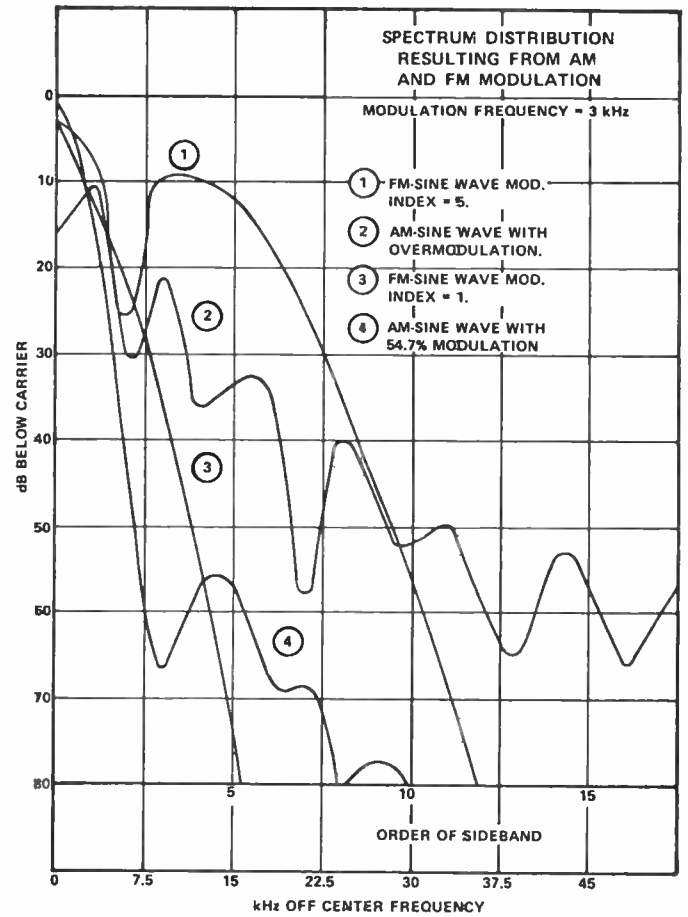


Fig. 21.

The greater the order, the weaker the signal, so it is the third and fifth orders which are of prime concern.

The amplitude of the intermodulation products are just as important as the frequency at which they occur. The resultant amplitude of two intermodulating signals is as follows:

for third-order products,

$$A_{IM} = 2A_1 \pm A_2, A_1 \pm 2A_2$$

for fifth-order products,

$$A_{IM} = A_1 \pm 4A_2, 2A_1 \pm 3A_2, 3A_1 \pm 2A_2, 4A_1 \pm A_2$$

where A_1 and A_2 are in decibels.

D. System Failure Rate

1) *Derivation of Failure-Rate Formula:* This Appendix shows that the probability of a failure is of the exponential form. The probability that no failure has occurred in a time T is denoted as $P(0, T)$. The probability of no failure over a period of time $T + \Delta T$, $[P(0, T + \Delta T)]$ can be expressed as the product of the probability of no failure in $T[P(0, T)]$ times the probability of no failure in $\Delta T[P(0, \Delta T)]$. Thus

$$P(0, T + \Delta T) = P(0, T) \times P(0, \Delta T).$$

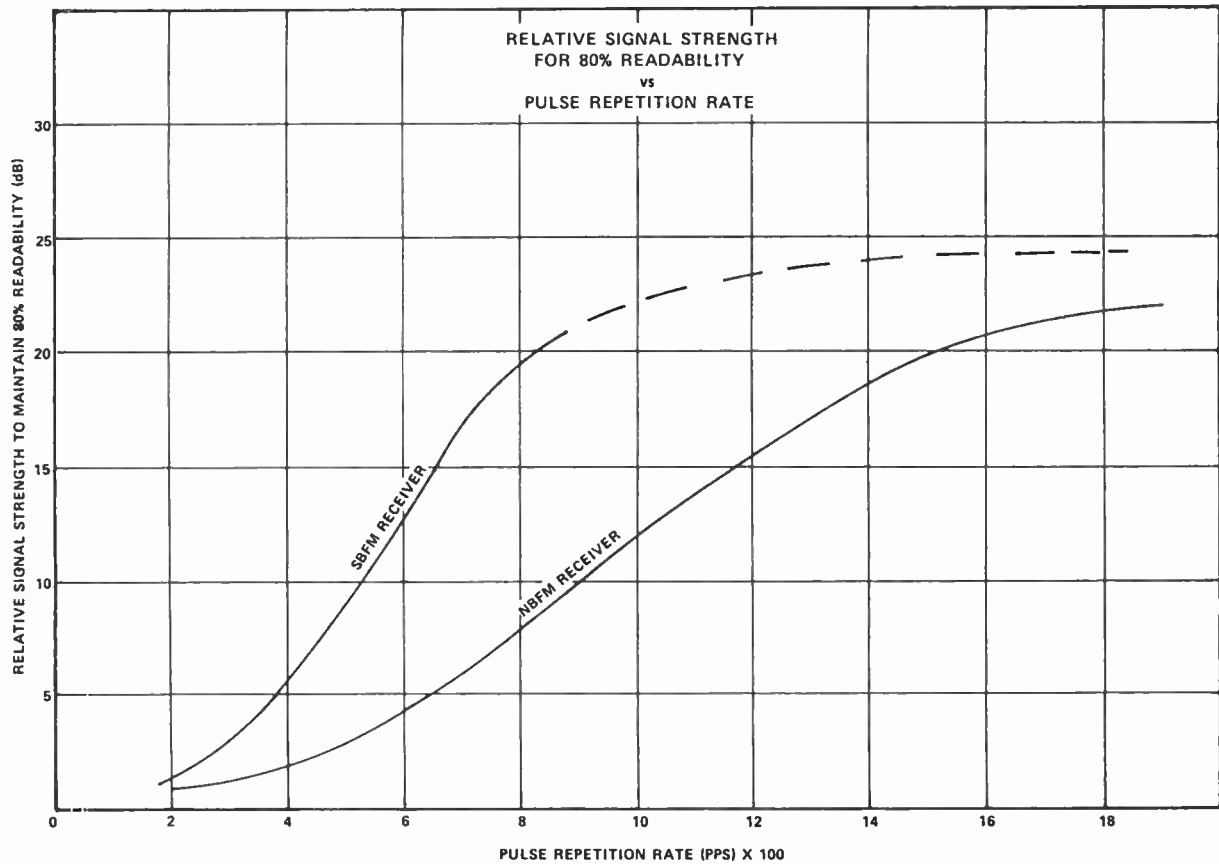


Fig. 22.

However, a separate expression for $P(0, \Delta T)$ can be written. Let U equal instantaneous failure rate during time ΔT .

$$P(0, \Delta T) = 1 - U \Delta T$$

which states that the probability of no failure in ΔT is equal to one minus the average failure rate per unit of time times the period ΔT .

Substituting

$$P(0, T + \Delta T) = 1 - U \Delta T \times P(0, T)$$

$$P(0, T + \Delta T) = P(0, T) - U \Delta T P(0, T)$$

$$[P(0, T + \Delta T) - P(0, T)] / \Delta T = -U P(0, T).$$

As $\Delta T \rightarrow 0$, the following differential equation is obtained,

$$dP(0, T) / dt = -U P(0, T)$$

or by transposing

$$dP(0, T) / P(0, T) = -U dt.$$

This equation has the solution

$$P(0, T) = \exp(-UT).$$

The independent variable was time in the previous derivation and U corresponded to the density of failure. It is now necessary to evaluate U in terms of the system characteristics.

The failure rate U is proportional to some of the channel-usage factor depending on the type of interference involved and hence the particular system in question. Where only one transmitter is sufficient to cause a failure, U is directly proportional to channel usage, as in modulation splatter. Where two transmitters are required as in two-frequency receiver IM; U is proportional to the square of channel usage. Thus

$$U = K_1 X^N$$

where K is a constant depending on the system equipment and geographic factors, N is some integer depending on the type of failure, and X is the channel utilization, i.e., fraction of time the channels as being used.

Since

$$P(0, T) = \exp(-UT) \text{ and } U = K_1 X^N,$$

$$P(0, T) = \exp(-K_1 T X^N).$$

For a large number of observations, each of which is T' seconds long, as for example, 10 seconds long, the probability of no failure is given by $P(0, T)$, where the T can now be considered a constant, and absorbed in K_1 . The only variable is the channel-utilization factor X^N . Therefore

$$P(0, T) = \exp(-K X^N)$$

where $K = K_1 T'$, a new constant.

Note that the probability of failure is $1 - P(0, T)$

$$P(\text{fail}) = 1 - P(0, T) = 1 - \exp(-KX^N).$$

This, then, is the form of the failure-rate probability.

2) *Failure-Rate Equation Including Repeat Messages:* The equations showing the "spiral effect" of repeated messages which increase the failure rate shall be derived in the expression

$$X = X_0 + P(\text{fail})X$$

the new use factor X is equal to the desired use factor X_0 plus the repeats. The repeats required are the new use rate X times the probability of failure $P(\text{fail})$.

But

$$P(\text{fail}) = 1 - \exp(-KX^N)$$

from 1), hence

$$X = X_0 + X - X \exp(-KX^N)$$

$$X = X_0 + X - X \exp(-KX^N)$$

$$X_0 = X \exp(-KX^N).$$

For purposes of illustration consider the case where N is two. (This corresponds to the case of two-frequency receiver IM.) This situation is described as follows:

$$X_0 = X \exp(-KX^2).$$

If no lost calls were repeated, the probability of success would be 90 percent. Therefore

$$\begin{aligned} 0.90 &= \text{probability of success} = 1 - P(\text{fail}) \\ &= \exp(-KX_0^2). \end{aligned}$$

For normalized traffic density X_0 is unity. Substituting unity for X_0 yields $K = 0.105$. When lost calls are repeated X takes on new values.

From the expression

$$X_0 = X \exp(-KX^2)$$

and substituting the known constants, new values for X may be found

$$1 = X \exp(-0.105X^2)$$

from which

$$X = 1.15.$$

This is the condition for stability.

The probability of success is obtained from

$$P(\text{success}) = \exp(-KX^2).$$

For $K = 0.105$ and $X = 1.15$,

$$P(\text{success}) = 0.876$$

which means that in a system whose failure rate is principally a function of two-frequency intermodulation, and whose initial probability of success is 0.90, a new probability of success of 87.6 percent is achieved by increasing the usage factor of the system by 15 percent (from $X_0 = 1.0$ to $X = 1.15$).

The 90 percent is not too meaningful. In a real-life situation the initial 90 probability is academic, since messages must be repeated if they are not received correctly. Then some of these repeat messages will not get through. This is called the "spiral effect" which results in system overload and instability when many repeats are required.

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REFERENCES

- [1] Advisory Committee, *Report of the Advisory Committee for the Land Mobile Radio Services*, Washington, D. C.: U. S. Government Printing Office, Rept. 0-280-469, 1967.
- [2] F. Bauer, "Vehicular radio frequency interference—accomplishment and challenge," *IEEE Trans. Vehicular Technology*, vol. VT-16, pp. 58-68, October 1967.
- [3] H. B. Black, *Modulation Theory*. New York: Van Nostrand, 1953.
- [4] K. Bullington, "Radio propagation at frequencies above 30 megacycles," *Proc. IRE*, vol. 35, pp. 1122-1136, October 1947.
- [5] W. F. Chow, "Impulse noise reduction circuit for communication receivers," *IRE Trans. Vehicular Communications*, vol. VC-9, pp. 1-9, May 1960.
- [6] M. S. Corrington, "Variation of bandwidth with modulation index in frequency modulation," *Proc. IRE*, vol. 35, pp. 1013-1020, October 1947.
- [7] J. P. Costas, "Double sideband vs. single sideband systems," *Proc. IRE*, vol. 45, pp. 534-537, April 1957.
- [8] J. Courtney, "The double standard," presented at the 9th Annual Meeting, Manufacturer's Radio Service, Washington, D. C., May 17, 1966.
- [9] C. L. Cuccia, *Harmonics, Sidebands, and Transients in Communications Engineering*. New York: McGraw-Hill, 1952.
- [10] A. C. Doty, Jr., "Progress toward a uniform standard for vehicular radiation," *1966 IEEE Vehicular Group Conf. Rec.*, pp. 5-12.
- [11] J. L. Egli, "Radio propagation above 40 MC over irregular terrain," *Proc. IRE*, vol. 45, pp. 1383-1391, October 1957.
- [12] "Minimum standards for land mobile communications FM or PM transmitters (25-470 MHz)," EIA Standard RS 152-A, October 1959.
- [13] "Minimum standards for land mobile communication systems using FM or PM in the 25-470 MHz frequency spectrum," EIA Standard RS 237, August 1960.
- [14] W. L. Firestone and H. Magnuski, "Application of single sideband for mobile communication," *IRE Trans. Vehicular Communications*, vol. PGVC-11, pp. 48-54, July 1958.
- [15] W. L. Firestone, "Evaluation of sideband noise and modulation splatter," *1953 IRE Conv. Rec.*, pt. 8, pp. 22-28.
- [16] W. L. Firestone, A. McDonald, and H. Magnuski, "Modulation sideband splatter of VHF and UHF transmitters," *Proc. Natl. Electron. Conf.*, vol. 10, pp. 1-10, February 1955.
- [17] W. L. Firestone, "SSB performance as a function of carrier strength," *Proc. IRE*, vol. 44, pp. 1839-1848, December 1956.
- [18] General Electric Company, "Systems effects of modulation schemes in high density tactical radiocommunications," presented at the 20th Ann. Armed Forces Communications and Electronics Association Conv., Washington, D. C., June 7-9, 1966.
- [19] J. Germain, "Extender operation-ignition noise suppression built right into the radio receiver," *IRE Trans. Vehicular Communications*, vol. VC-11, pp. 40-43, August 1962.
- [20] R. P. Gifford, "What price glory," presented at the APCO Natl. Conv., June 1957.
- [21] —, "The knee of the nose," *IRE Trans. Vehicular Communications*, vol. PGVC-4, pp. 40-51, June 1954.
- [22] K. G. Jansky, "An experimental investigation of the characteristics of certain types of noise," *Proc. IRE*, vol. 27, pp. 763-768, December 1939.

- [23] "Spectrum engineering: The key to progress," Joint Technical Advisory Committee, July 1968.
- [24] H. H. Kallmann and R. E. Spenser, "Transient response of single sideband systems," *Proc. IRE*, vol. 28, pp. 557-561, December 1940.
- [25] I. J. Kaar, "Some notes on adjacent channel interference," *Proc. IRE*, vol. 22, pp. 295-313, March 1934.
- [26] G. J. Kelly, "Choosing the optimum type of modulation—A comparison of several communication systems," *IRE Trans. Communication Systems*, vol. PGCS-6, pp. 14-21, June 1958.
- [27] A. E. Kerwien, "Design of modulation equipment for modern single-sideband transmitters," *Proc. IRE*, vol. 40, pp. 797-803, July 1952.
- [28] A. V. Korolenko and N. H. Shepherd, "Can SSB provide more usable channels in the land mobile service?" *IRE Trans. Vehicular Communications*, vol. VC-9, pp. 47-52, August 1960.
- [29] "Comments on docket no. 15398," The Electronics Industries Associations Land Mobile Section (Industrial Electronics Division), March 31, 1965.
- [30] S. P. Lapin and J. J. Suran, "Impulse noise in narrow-band FM receivers," *AIEE Trans. (Communication and Electronics)*, vol. 74, pp. 450-454, September 1955.
- [31] A. A. MacDonald, "Adjacent-channel design in the Westinghouse type FE heavy duty railroad radio," *IRE Trans. Vehicular Communications*, vol. PGVC-1, pp. 47-64, February 1952.
- [32] H. Magnuski and W. Firestone, "Comparison of SSB and FM for VME service," *Proc. IRE*, vol. 44, pp. 1834-1839, December 1956.
- [33] T. A. McKee, "Practical narrow-band system operation," presented at the 1960 AIEE Summer General Meeting Atlantic City, N. J.
- [34] S. F. Meyer, "Vehicular noise problems in modern land mobile systems," *1958 IRE Natl. Conv. Rec.*, pt. 8, p. 33.
- [35] R. T. Myers, Jr., "Selectivity and the performance of a mobile receiver," presented at the 1961 AIEE Winter General Meeting, New York, N. Y.
- [36] J. R. Neubauer, "Vehicular interference radiation measurement technique," *1965 IEEE Internatl. Conv. Rec.*, vol. 13, pt. 2, pp. 42-50.
- [37] D. E. Noble, "Motorola split channel filing on docket 11253 (Suppl. B)," Motorola, Inc., Chicago, Ill., September 1966.
- [38] H. Nyquist and K. W. Pfleger, "Effect of the quadrature component in single-sideband transmission," *Bell Sys. Tech. J.*, vol. 19, pp. 63-73, January 1940.
- [39] R. A. Richardson, "Radio receiver with impulse noise blanking," U. S. Patent 2 901 601, August 25, 1959.
- [40] W. M. Rust, Jr., "Field test of split channel 50 Mc systems," *IRE Trans. Vehicular Communications*, vol. PGVC-3, pp. 32-35, June 1953.
- [41] W. S. Seeley, "Frequency modulation," *RCA Rev.*, vol. 5, pp. 468-479, April 1941.
- [42] N. H. Shepherd and J. S. Smith, "The Gaussian curse—transmitter noise limits spectrum utilization," *IRE Trans. Vehicular Communications*, vol. PGVC-10, pp. 27-32, April 1958.
- [43] B. M. Short, "Sources of interference inherent in vehicular electrical systems," *General Motors Engrg. J.*, vol. 1, March/April 1954.
- [44] J. S. Smith, "Adjacent channel and the Fourier curse," *IRE Trans. Vehicular Communications*, vol. PGVC-9, pp. 3-11, June 1957.
- [45] —, "Impulse noise reduction in narrow band receivers: A survey of design approaches and compromises," *IRE Trans. Vehicular Communications*, vol. VC-11, pp. 22-26, August 1962.
- [46] J. L. Stewart, "The power spectrum of a carrier frequency modulated by Gaussian noise," *Proc. IRE*, vol. 42, pp. 1539-1542, October 1954.
- [47] J. S. Stover and T. J. McMullin, "Narrow band operation at 40 Mc," *FM-TV Radio Communication*, September 1952.
- [48] H. E. Strauss, "Channel spacing considerations in the 154-174 Mc band," *IRE Trans. Vehicular Communications*, vol. PGVC-3, pp. 44-57, June 1953.
- [49] "An inquiry into the optimum frequency spacing between assignable frequencies in the land mobile service and the feasibility of frequency sharing by television and the land mobile service," Federal Communications Commission, Washington, D. C., FCC Docket 15398.

A METHOD FOR CALCULATING ADJACENT BAND INTERFERENCE

Frequency dependent rejection and frequency distance

1. Introduction

Question 44/1 asks how may currently available models of system parameters of both desired and interfering systems, e.g., emission spectra receiver selectivity, antenna patterns, propagation attenuation, etc., be logically combined in response to specific utilization problems. One way these parameters can be combined is to solve the problem of determining appropriate frequency and/or distance separation criteria for sharing the space-frequency domain. For example, interference problems can be created by the power from an emission in one band overlapping into an adjacent band and interacting with a receiver tuned close to the band edge. In order to eliminate or restrict this adjacent band interference problem, sharing criteria are required which specify power flux density limits and minimum frequency and distance separation limits. Adjacent band problems may occur at any interface of bands allocated to radio astronomy, passive space research, aeronautical and maritime mobile and other bands.

This Report describes basic measures which quantify the interactive effects between interferer and receiver for various frequency distance separations. The measures are:

- frequency dependent rejection (FDR) which is a measure of the rejection produced by a receiver selectivity curve on an unwanted transmitter emission spectra, and
- frequency distance (FD) which is a measure of the minimum distance separation that is required between a victim receiver and an interferer as a function of the difference between their tuned frequencies.

FD and FDR are measures of the interference coupling mechanism between interferer and receiver and are basic solutions required for many interference evaluations. They aid in the solution of co-channel frequency sharing and adjacent band interference problems by providing estimates of the minimum frequency and distance separation criteria between interferer and receiver which are required for acceptable receiver performance.

2. Definitions

The interference level at the receiver is a function of the gains and losses the interference signal will incur between the source and the receiver and is expressed by:

$$I = P_t + G_t + G_r - L_b(d) - FDR(\Delta f) \quad \text{dB} \quad (1)$$

where:

P_i : interferer transmitter power (dB),

G_i : gain of interferer antenna in direction of receiver (dBi),

G_r : gain of receiver antenna in direction of interferer (dBi),

$L_b(d)$: basic transmission loss for a separation distance d between interferer and receiver (dB) (see Recommendation 341).

and

$$FDR(\Delta f) = 10 \log \frac{\int_0^\infty P(f) df}{\int_0^\infty P(f) H(f + \Delta f) df} \quad (2)$$

where:

$P(f)$: emission spectra density generally normalized to unity maximum power spectral density (W/Hz),

$H(f)$: receiver selectivity,

$$\Delta f = f_i - f_r$$

where:

f_i : interferer tuned frequency,

f_r : receiver tuned frequency.

Equation (1) in Report 523 and equation (1) in Report 698 are similar to equation (2) except that equation (2) includes the normalization term $\int_0^\infty P(f) df$. The FDR expression, equation (2), contains only power terms. Modulation characteristics are included only through their effect on the emission spectral density $P(f)$. Interference degradation characteristics are assumed not to change as the receiver is off-tuned. The FDR , because it is considered a loss in equation (1), is defined in the manner of equation (2) to insure that expressed in dB it is ≥ 0 .

In addition to the calculation performed in (1), it is often required to calculate the interference-to-noise (I/N) at the demodulation input or IF output. This measure is also useful in basic electromagnetic compatibility calculations because the I/N number is relatable to degradation, is easy to interpret, and is independent of the gain of the RF and IF amplifier stages. The noise at the receiver input referred to the IF bandwidth is given by:

$$N_0 = 10 \log kT_0 + 10 \log BW_{IF}(\text{Hz}) + \text{noise figure} \quad (3)$$

where:

N_0 : receiver noise power in dBm,

k : Boltzmann's constant,

T_0 : absolute temperature in K.

The I/N ratio is then given by:

$$I/N = I - 10 \log kT_0 - 10 \log BW_{IF}(\text{Hz}) - \text{noise figure} \quad (\text{dB}) \quad (4)$$

The FDR can be divided into two terms, the on-tune rejection (OTR) and the off-frequency rejection (OFR), the additional rejection which results from off-tuning interferer and receiver.

$$FDR(\Delta f) = OTR + OFR(\Delta f) \quad (\text{dB}) \quad (5)$$

where:

$$OTR = 10 \log \frac{\int_0^\infty P(f) df}{\int_0^\infty P(f) H(f) df} \quad (6)$$

$$OFR(\Delta f) = 10 \log \frac{\int_0^\infty P(f) H(f) df}{\int_0^\infty P(f) H(f + \Delta f) df} \quad (7)$$

The OTR , also called the correction factor, under conditions given by [White, 1972], can often be approximated by:

$$OTR \approx K \log \left(\frac{B_T}{B_R} \right), \quad B_R \leq B_T \quad (8)$$

where:

B_R : receiver 3 dB bandwidth (Hz),

B_T : transmitter 3 dB bandwidth (Hz),

$K = 10$ for non-coherent signals,

$= 20$ for pulse signals.

The calculation of OTR can aid in co-channel sharing problems since the OTR is the rejection obtained when the receiver and unwanted transmitter are tuned to the same frequency.

When a maximum value, I_m , of acceptable receiver interference power from an interferer is specified, equation (1) is rearranged to give the required loss

$$L_h(d) + FDR(\Delta f) = P_i + G_i + G_R - I_m \quad (9)$$

Receiver performance is acceptable only if

$$L_h(d) + FDR(\Delta f) \geq P_i + G_i + G_R - I_m \quad (10)$$

The required loss combines a distance dependent term $L_h(d)$ and a frequency dependent term $FDR(\Delta f)$. A curve of the various combinations of the two separations in frequency, Δf , and distance, d , which achieves a specified required loss, ξ , is an FD plot. Figure 1 is an illustrative example. The ordinate in Fig. 1 is the distance separation and the abscissa is the separation in tuned frequency of the interferer and receiver. The FD curve separates the acceptable receiver performance region from the non-acceptable receiver performance region. An FD plot shows the trade-offs in either frequency or distance separation which allow interferer and receiver to coexist in a space frequency environment.

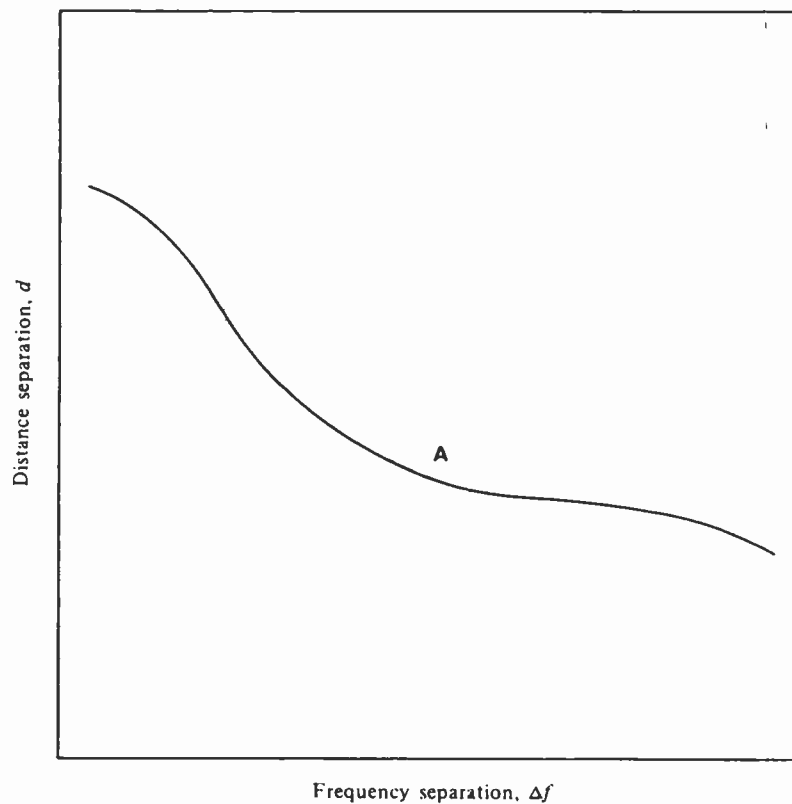


FIGURE 1 — Separations in frequency and distance. The equation describing curve A is $L_h(d) + FDR(\Delta f) = \xi$. Above the curve is the region of acceptable receiver performance. Below the curve is the region of non-acceptable receiver performance.

3. Computation of *FDR* and *FD*

The computation of *FDR* and *FD* is simple and has been implemented on a small computer [Cohen, 1977]. A block diagram of the computation is shown in Fig. 2. The emission spectrum and receiver selectivity are specified at a discrete number of frequencies. Extrapolation slopes define these functions beyond the discrete number of frequencies and interpolation is used to define functional values between discrete data points. The integration is evaluated numerically by the trapezoidal method using a variable integration step size.

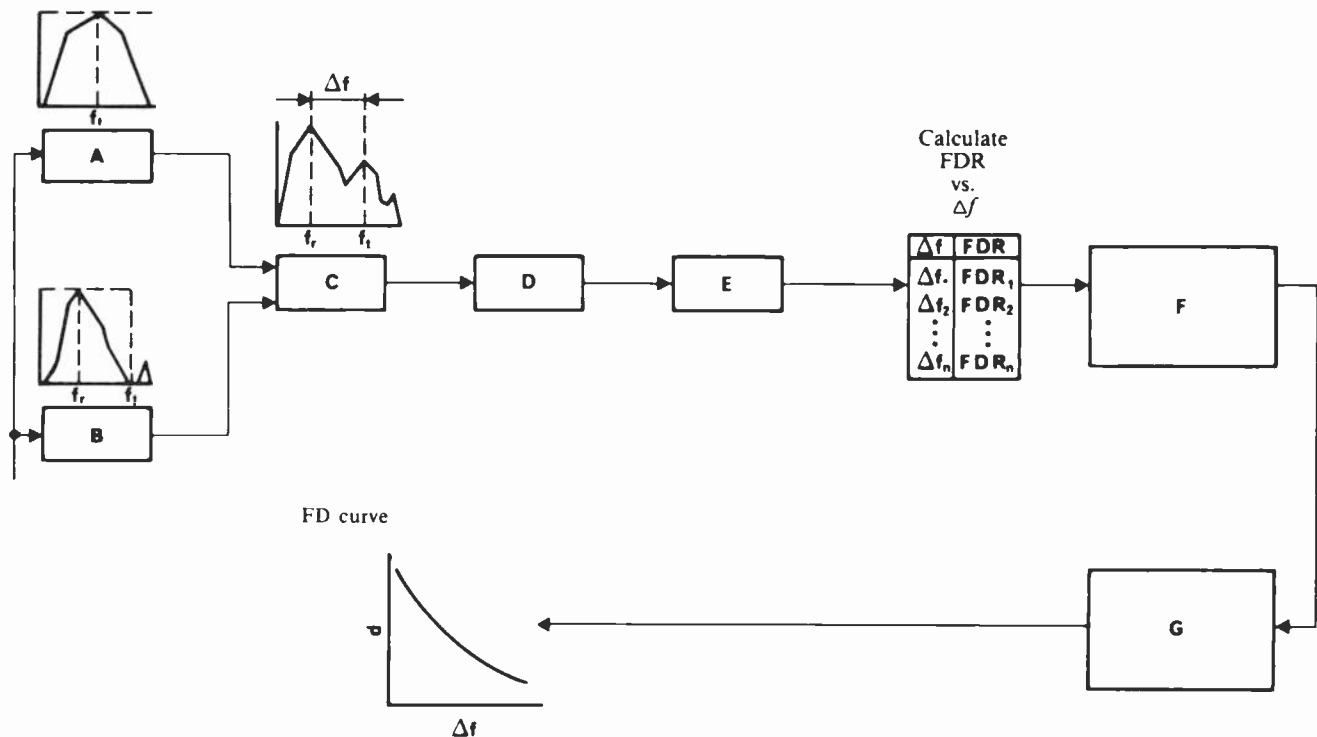


FIGURE 2 — Block Diagram of Calculation process of *FDR* and *FD*

- A: Emission spectrum
- B: Receiver selectivity
- C: Multiply
- D: Integrate
- E: Normalize
- F: Subtract required loss
- G: Inverse propagation

The propagation model might consider tropospheric, ionospheric or space paths. The propagation computation is inverse meaning that the basic transmission loss is input to the propagation model and distance is calculated. The propagation computation must be single-valued in distance for each loss value and thus lobing in the propagation loss cannot be included. The propagation curves included in Recommendation 370 are single-valued and have been included along with a smooth earth [Bremmer, 1949] tropospheric propagation model in the small computer computation [Cohen, 1977].

For computation of *FD* in ground-wave propagation, the curves of Recommendation 368 can be used. In addition a procedure has been proposed [Rásajski and Petrović, 1981] for evaluation of the induced e.m.f. caused by a strong unwanted field, produced by a vertical dipole in a receiving horizontal dipole antenna, enabling a calculation of the *FD* expected for coast station receivers in the HF maritime mobile service with respect to unwanted MF broadcast transmitters.

4. Sample calculation

A sample adjacent band-sharing problem will illustrate the utility of the *FD/FDR* model. Consider a radio relay (Video) link, with transmitter power 30 dBm, located a distance, d , from a radio astronomy site. The tuned frequencies of the radio relay link f_i and radio astronomy receiver f_r are separated in frequency, $f_i - f_r = \Delta f$. The radio astronomy receiver is operating in the band 15.35 to 15.4 GHz. The harmful level of interference to the radio astronomy receiver as calculated from Report 224 is $I_m = -202$ dBW. The *FD/FDR* technique will be used to calculate the trade-offs in frequency, Δf , and distance, d , which will insure the signal level of the radio relay does not exceed the threshold -202 dBW within the radio astronomy receiver.

The emission spectrum of the radio relay and the selectivity curve of the radio astronomy receiver are shown in Figs. 3 and 4 respectively. After offsetting the selectivity curves in frequency Δf , and converting from dB to absolute units, the curves are then multiplied and the product is integrated with respect to frequency to obtain the *FDR* curve versus Δf of Fig. 5.

Assuming for simplicity isotropic gains $G_t = G_r = 0$ dBi, equation (9) is solved to give a required loss = 202 dB. An inverse tropospheric smooth earth (Earth represented as a smooth sphere) propagation model [Bremmer, 1949] which calculates the envelope of the propagation loss (thus insuring a single-valued inverse) was used with the required loss of 202 dB and the *FDR* curve (Fig. 5) to produce the *FD* curve of Fig. 6. The *FD* ordinates of the radio astronomy receiver are the reference (0,0). Simply stated, if the coordinates of the radio relay ($\Delta f, d$) are below the *FD* curve, the harmful interference threshold of the radio astronomy receiver is exceeded. The *FD* plot, Fig. 6, shows the myriad of trade-offs in frequency and distance coordinates which permit acceptable operation of both interferer and receiver.

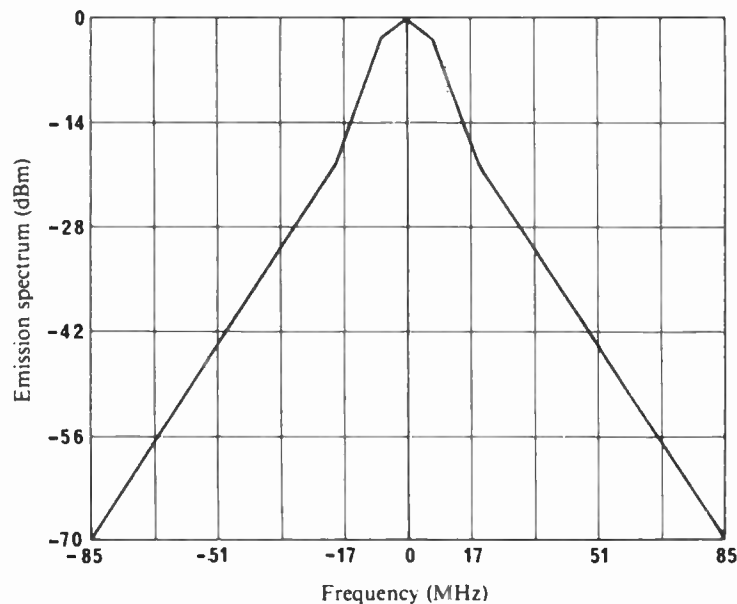


FIGURE 3 — Emission spectrum of radio relay (video)

5. Statistical frequency distance

The *FD* can also be computed in a statistical manner. Jennings *et al.* [1976] have developed a computer technique which produces *FD* curves which are parametric in the percentage of time during which interference is permissible. For example, if the receiver interference criteria permits the interference threshold, I_m , to be exceeded 10% of the time, an *FD* curve can be constructed for this condition. The model convolves cumulative distribution functions of the antenna gains and propagation loss $L_p(d)$ to obtain a statistical distribution function of the combined propagation loss and antenna gain. Then for a specific probability (e.g., 90%, 50%, 10%), the level from this distribution function is combined using equation (1) with a corresponding value of *FDR* to plot a point on the *FD* curve.

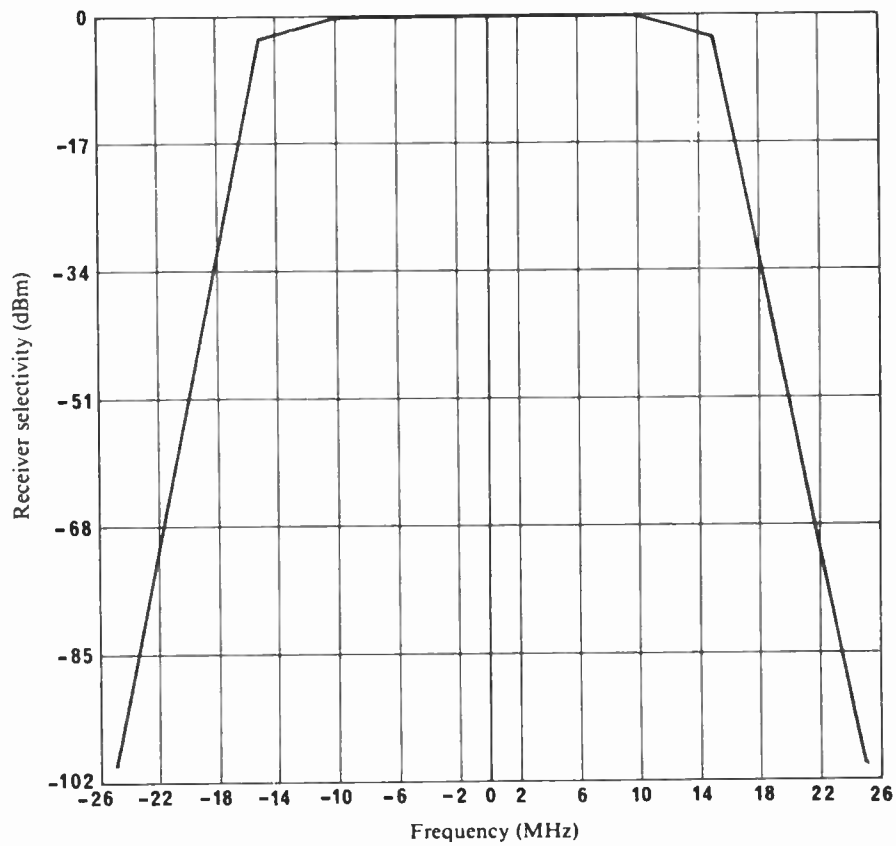


FIGURE 4 — *Frequency selectivity of radio astronomy receiver*

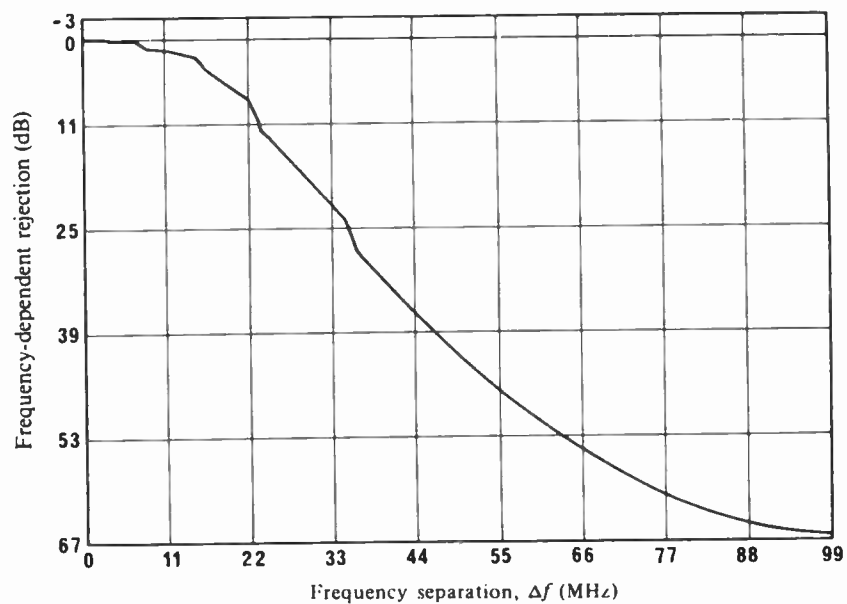


FIGURE 5 — *Frequency dependent rejection, FDR*

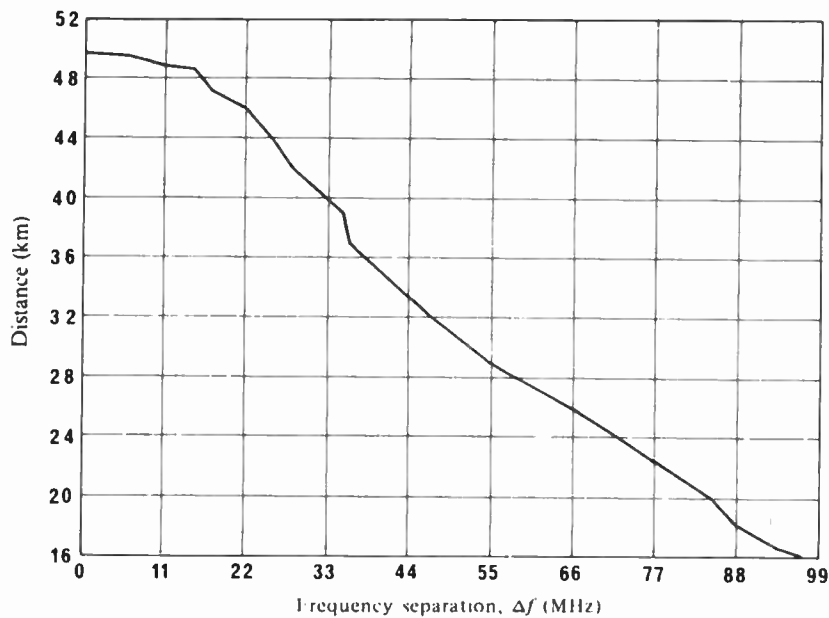


FIGURE 6 — Frequency/distance curve. The frequency $f = 15.35$ GHz was used in the inverse propagation computation. Antenna heights $h_t = h_r = 15.2$ metres. The equation describing the curve is $L_b(d) + FDR(\Delta f) = 202$ dB.

6. Frequency assignment — an application of $FDR(\Delta f)$

The selection of a frequency assignment and geographic location for a new equipment to be placed in a congested telecommunication environment can be aided by using $FDR(\Delta f)$ calculations to prepare denial area plots.

The concept of denial areas was introduced in Annex I of Report 662 which shows that receiver and transmitter usage of the spectrum result in complementary denial: transmitters deny use of a time-frequency-geographic region to receivers wishing to receive another signal and a protected receiver denies a time-frequency-geographic region to transmitters whose operations would interfere with it. Denial areas depend upon geographic data, transmitter powers, antenna pattern and gain, transmitter emission spectrum characteristics, frequency separation (Δf) between transmitter and receiver, and receiver transfer characteristics.

The following example of choosing the operating frequency for a land based radar will illustrate one method by which the frequency distance calculation can be used to determine geographic denial areas. An automated procedure for plotting geographical denial areas for the inclusion of a new radar in an existing radar environment is described in Cohn and Moran [1977]. This automated procedure takes into account the characteristics, geographical location and assigned frequencies of the existing environment. Figure 7 shows denial areas for two different possible assigned frequencies, f_1 (solid line) f_2 (dashed line) for the new radar. If the new radar is assigned frequency f_1 or f_2 and is located geographically within these denial areas, then the I/N threshold is exceeded either for the existing or planned radar, and receiver performance becomes unacceptable.

The denial areas around each existing site are shown as circles because the radar antenna are rotated through 360° and since terrain effects have been neglected. In general, as shown in Annex I of Report 662, when terrain effects are included or when antenna patterns are azimuthally dependent, the denial areas maybe described by any closed contour.

The denial areas are determined by calculating the required basic transmission loss between radars which is given by:

$$L_b(d) = P_t + G_t + G_r - FDR(\Delta f) - (I/N) - N \quad (11)$$

where:

$I/N = 10 \log(i/n)$: is the interference-to-noise threshold for acceptable receiver performance,

N : noise at the receiver input referred to the IF bandwidth.

The computer calculates $FDR(\Delta, f)$ for the $2M$ interactions (there are M existing radars) between all existing radars and the new radar. Equation (11) is then used to obtain the minimum required basic transmission loss between each existing radar and the new radar which will permit acceptable performance for the radar receivers. A propagation model is then used to obtain the separation distance $r = d$.

In a typical assignment problem, a set of denial plots are prepared for a number of frequencies being considered for the proposed new radar. The spectrum manager visually examines these plots to choose the planning parameters (frequency and geographical location) which places the new radar outside a denial area. This results in a compatible operation between the proposed new radar and the existing radar equipment.

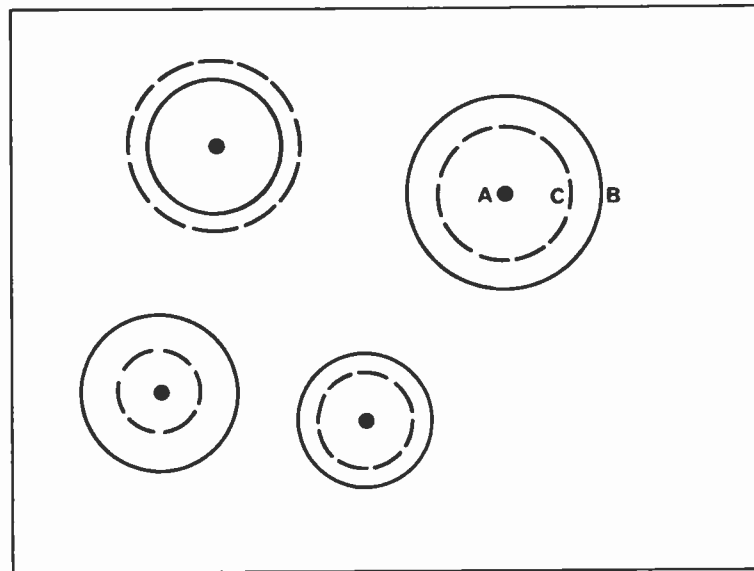


FIGURE 7 - Geographical denial areas for a new radar in a congested frequency environment

- A: existing radar location
- B: denial contour for new radar with assigned frequency, f_1
- C: denial contour for new radar with assigned frequency, f_2

7. Conclusions

The concepts of FDR and FD are defined. The computation of FD and FDR yield the separations in space and frequency required between interferer and receiver which satisfy given threshold values on either I or I/N . These computations are required for sharing problems involving co-channel sharing and adjacent band interference. A simple basic computer technique to compute FD and FDR has been described. The technique is adaptable to a small computer use.

REFERENCES

- BREMMER, H. [1949] *Terrestrial Radiowaves, Theory of Propagation*. Elsevier, Amsterdam, the Netherlands.
- COHEN, D. J. [1977] Frequency Dependent Rejection (FDR) and Frequency Distance (FD) calculation on a small computer. OT Tech. Note, US Dept. of Commerce, Office of Telecommunications, Washington, DC, USA.
- COHN, S. I. and MORAN, W. M. [August, 1977] Radar frequency assignment. *IEEE Trans. Electromag. Compt.*, Vol. EMC-19, 3, 326-330.
- JENNINGS, R. D., VOGLER, L. E. and STEPHENSON, J. J. [1976] Statistical frequency distance curves, initial model. OT Rep. 76-84. US Dept. of Commerce, Office of Telecommunications, Boulder, CO, USA.
- RÁSAJSKI, S. and PETROVIC, Z. [1981] Influence of an unwanted field to the maritime mobile service coast-station receiver operation (in Serbo-Croatian). Proc. 23rd Conference on Electronics, Telecommunications, Automization Processing and Nuclear Techniques, Applications in the Maritime Mobile Service, Zadar, Yugoslavia.
- WHITE, D. R. [1972] *A Handbook Series on Electromagnetic Interference and Compatibility*. Vol. 5. Don White Consultants, Inc., Germantown, MD, USA.

Interference and Propagation Formulas and Tables Used in the Federal Communications Commission Spectrum Management Task Force Land Mobile Frequency Assignment Model

JOHN H. McMAHON

Abstract—The computerized frequency assignment program developed by the FCC Spectrum Management Task Force utilizes monitoring van [1] measured occupancy data and models for propagation, interference, and noise. The propagation model was constructed by the Technical Division of the FCC Office of the Chief Engineer from measured FM and television data [2] and National Bureau of Standards measurements in the UHF/VHF range [3]. The co-channel interference model uses commonly accepted signal ratios between desired and interfering signals. The adjacent channel interference model is based on performance characteristics furnished by the major land mobile (LM) equipment manufacturers. The receiver and transmitter intermodulation interference models and the noise model were taken from the Report of the Advisory Committee for the Land Mobile Services [4]. None of the models is considered immutable. All will be continuously updated.

INTRODUCTION

THE SPECTRUM Management Task Force of the Federal Communications Commission and the first Regional Center in Chicago had their origins in the need for improved methods of spectrum management [1].

Initial efforts have been focussed upon the Land Mobile Service. Particular attention has been given to the Chicago Region (an area of roughly 96 000 mi², with approximate center at Chicago, Ill., which is specifically delineated in the FCC Rules), where LM data are presently being acquired, measured, formulated, assembled, categorized, analyzed, recombined, variously utilized, and stored (subject to continuous updating) in unprecedented quantity, and (due at least in part to the new application and informational filing format (Form 425) which was developed by the Task Force for this purpose) with greatly increased emphasis upon engineering considerations.

The expanding LM data base supports the operations of the automated frequency assignment program ("AFAM") which is based upon the Univac 1106 Computer installed in the Chicago Regional Center (but usable in Washington through a terminal at FCC Headquarters and directly accessible to equipment manufacturers, examiners, and other interested parties). AFAM will be used for all new applications within the designated

area around the regional center to make assignments which will receive minimal interference from all preexisting operations, and which will, in turn, cause minimal interference to the environment.

The computerized frequency assignment program ("AFAM") in part: 1) ensures that the applicant's requested power does not exceed the power required for adequate signal plus noise/noise ($(S + N)/N$) ratios throughout his service area; 2) selects eligible frequencies from the Frequency Availability List and evaluates with regard to

- a) potential adjacent channel interference to the applicant and to the preexisting environment from the applicant;
- b) third- and fifth-order receiver intermodulation interference to or from applicant;
- c) transmitter to transmitter intermodulation interference (where occurring within 2 mi of proposed new station location);
- d) co-channel interference to or from applicant. (In LM, co-channel interference does not necessarily disqualify a frequency, as, in most urban areas, congestion precludes total interference protection, while short duty cycles enable sharing arrangements.)

These procedures depend upon models for propagation, adjacent channel interference, receiver and transmitter intermodulation interference, co-channel interference, as also, a noise model to enable prediction of required received power for base and mobile stations in an urban environment.

PROPAGATION MODEL

The propagation model was constructed for the Spectrum Management Task Force by the Applied Propagation Branch of the FCC Office of Chief Engineer to fit measured data obtained during preparation of FCC Report R-6602, entitled: "Development of VHF and UHF propagation curves for TV and FM broadcasting," [2]. Included in the measured data were 1) field intensities for over 160 fixed paths from FM and TV stations and other test transmitters on VHF and UHF frequencies over various time periods (from months to years) and path lengths (from approximately 38 to more than 600 mi), and 2) mobile measurements starting from within a few miles

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of various VHF and UHF TV transmitters and extending outward as far as 50 mi. The data were measured by a number of parties including the National Bureau of Standards, FCC, RCA, Collins Radio, and various broadcast consultants.

The original FCC television propagation curves in Report R-6602 [2] were based upon an assumed television receiving antenna height of 30 ft, and, accordingly, required adjustment for the usual mobile receiving antenna height of 6 ft used in the LM service. The adjustment from 30 to 6 ft was made by reducing the R-6602 fields by 9 dB, a factor derived from experimental height/gain measurements conducted for the most part in urban areas.

Report R-6602 [2] contains curves of field intensity exceeded at 50 percent of the locations 50 percent of the time ("50, 50 (L, T) curves") for various transmitting antenna heights and for distances of 1 to 200 mi, and, 50, 10 (L, T) curves for distances of 10 to 300 mi. To enhance computer suitability, however, the Task Force model incorporates instead formulas for distances up to 10 mi and tabular values for distances greater than 10 mi. The model includes a correction for terrain roughness as a function of frequency.

For receiving antenna heights other than 6 ft, the model applies a correction comprising 1) a table derived from urban height gain measurements [2] for heights equal to or less than 30 ft and at distances less than 10 mi, and 2) a function of distance, line-of-sight, and antenna height, for heights greater than 30 ft. Within line-of-sight distance, this correction in decibels is approximately proportional to $20 \log (\text{height of receiving antenna})/30$ plus 9 dB. Beyond line-of-sight, the correction gradually decreases to small values.

As previously noted, the propagation model applies tabular data to instances of distances greater than 10 mi. As most cases of other than co-channel interference occur at separations of less than 10 mi between existing and proposed stations, tabular values are used only for co-channel interference (and coverage) predictions.

The majority of interference calculations are then based upon the following formulas:

$$\begin{aligned} &\text{received power (dBW)} \\ &= -32.3 - 20 \log_{10} D + 10 \log_{10} P - 20 \log_{10} F \quad (1) \end{aligned}$$

$$\begin{aligned} &\text{received power (dBW)} \\ &= -107.7 + 20 \log_{10} (HT) + 20 \log_{10} (HR) \\ &\quad - 40 \log_{10} D + 10 \log_{10} P - 20 \log_{10} F \quad (2) \end{aligned}$$

where

D distance (mi),
 P power (W),
 F frequency (MHz),
 HT transmitting antenna height (ft),
 HR receiving antenna height (ft).

Formula (1) will be recognized as the familiar free-space attenuation formula (between dipole antennas). Formula

(2) has been derived as a "best fit" to the aforementioned propagation data [2]; distance and antenna height dependencies are identical with their counterparts in the well-known plane earth propagation formula. Formula (2) predicts median received power values approximately 6 dB greater than comparable predictions by Egli [5]. The procedure utilized in AFAM, however, selects the smaller of the two values for received power given by (1) and (2), respectively.

Interference computations involve comparison of this median received power (that is, the lower value, whether from (1) or (2)) with the interfering power exceeded at 10 percent of the locations within the area under consideration (as determined by applying appropriate location variability factors [5], [6] to the previously selected median predicted power).

Several small corrections (usually less than 2 dB in magnitude) considered applicable to interference calculations by the FCC Applied Propagation Branch have been omitted by the Spectrum Management Task Force, at least for the present, to expedite the thousands of propagation calculations required for each applicant frequency assignment.

ANTENNA HEIGHT AND POWER MODEL

The (proposed or actual) antenna height and power of each applicant are established by a separate (AFAM) subroutine prior to the start of interference calculations in the frequency assignment program.

This subroutine uses a portion of the engineering data (base station location, service rectangle) presently required on FCC Form 425 (entitled: "Application for Radio Station Authorization (Industrial, Public Safety, Land Transportation, Broadcast Remote Pickup, and Citizens Class A)") to determine the distance from the base station to the most distant vertex of the service rectangle. It is then assumed that a (fictitious) mobile station located at that point requires received signal power providing 12-dB Sinad ((Signal + Noise + Distortion)/(Noise + Distortion)) (as computed with values given in the noise model). Median signal power delivered to the mobile is determined by use of the full propagation model. The appropriate location variability factor (LVF) (which effects conversion of the particular value representing 50 percent of locations to the corresponding value for 90 percent of locations) is added to the (previously determined) power required for 12-dB Sinad and the result is compared to the (also previously determined) received power. Location variability factors [6] are as follows:

low band	11 dB
high band	14 dB
UHF band	17 dB.

If the received power exceeds the sum of the LVF and the power required for 12-dB Sinad, transmitter power is reduced by the decibel difference. Conversely, if the received

power is less than the LVF plus the 12-dB Sinad power, the power which can be authorized is increased either by the decibel difference or to the maximum power permitted in the particular service, if less. (In any event, however, decibel differences of 0.5 dB and less are ignored as a practical matter.)

Modifications to this program are available for instances where the applicant fails to provide values for power and antenna height or omits either quantity.

1) When only power is indicated, antenna height of 50 ft is assumed. The decibel difference (between LVF + 12-dB Sinad power and received power) is determined (as previously outlined herein). Antenna height is then increased or decreased (through application of a correction factor of $20 \log_{10} (\text{Adjusted Height}/50)$ to eliminate any decibel difference greater than 0.5 dB, except that antenna heights greater than 100 ft are not used, and, instead, the power to be authorized would be increased for equivalent effect (subject, however, as in the foregoing, to possible limitation by the maximum power permitted in a particular service, if less than that required for equalization).

2) When only antenna height is given, power of 100 W (+20 dBW) is initially assumed, and this value is subsequently increased or decreased (as outlined heretofore) to equalize (that is, reduce any difference to 0.5 dB or less) the LVF plus 12-dB Sinad power and the received power (subject, however, once again, to possible limitation to some lower than required power by any applicable restrictions upon the maximum power permitted in the particular service).

ADJACENT CHANNEL MODEL

Adjacent channel signals most commonly cause interference because of receiver desensitization or transmitter sideband noise. More specialized types of interference (as image, harmonic, spurious response) are neglected in the present adjacent channel model as they require more data than is currently available to the Task Force and usually assume importance only for small spacings between receivers and transmitters, as in antenna farms.

Data on receiver susceptibility to desensitization and transmitter sideband noise were furnished by the major manufacturers of land mobile equipment. All samples of both types of interference were plotted on a common basis of effective interference level below carrier versus frequency offset from carrier. The data showed a considerable range in desensitization susceptibility between the best and poorest receiver represented by the data. Similar variability appeared in the transmitter sideband noise data. Mean curves for each band and standard deviations were determined. It was found that, in essentially all cases, higher interference levels were produced by transmitter sideband noise than by desensitization. Consequently, the adjacent channel model was devised to represent the effects of sideband noise.

Each frequency range required a separate equation to represent the sideband noise accurately. In each case, it

was evident that a good fit of the data could be obtained with two straight lines of different slopes, one line representing sideband noise out to approximately 500 kHz, and the other, from 500 kHz to about 10 MHz. The lines were arbitrarily located one standard deviation above the mean values of noise for each band.

The sideband noise equations follow:

1) 25-76 MHz

- a) $A = 451 + 221 \log_{10} (dF)$, where
 $0.0125 < (dF) \leq 0.020 \text{ MHz}$
- b) $A = 81.1 + 3.9 \log_{10} (dF)$, where
 $0.020 < dF \leq 0.5 \text{ MHz}$
- c) $A = 92.2 + 40.7 \log_{10} (dF)$, where
 $0.5 < dF \leq 10.0 \text{ MHz}$

2) 150-174 MHz

- a) $A = 451 + 221 \log_{10} (dF)$, where
 $0.0125 < (dF) \leq 0.020 \text{ MHz}$
- b) $A = 85.5 + 6.3 \log_{10} (dF)$, where
 $0.020 < dF \leq 0.4 \text{ MHz}$
- c) $A = 96.1 + 32.9 \log_{10} (dF)$, where
 $0.4 < dF \leq 10.0 \text{ MHz}$

3) 450-512 MHz

- a) $A = 446 + 221 \log_{10} (dF)$, where
 $0.0125 < (dF) \leq 0.020 \text{ MHz}$
- b) $A = 73.6 + 1.4 \log_{10} (dF)$, where
 $0.020 < dF \leq 0.4 \text{ MHz}$
- c) $A = 89.2 + 40.8 \log_{10} (dF)$, where
 $0.4 < dF \leq 10.0 \text{ MHz}$

In each equation, A is the amount in decibels that sideband noise is below carrier, and dF is the frequency offset in megahertz.

As a point of interest, it is noted that, as sideband noise interference essentially represents co-channel interference, there are no effective methods of reducing this interference, which can be applied at the victim receiver. Any noise reduction must be achieved through selective filtering at the offending transmitter.

RECEIVER INTERMODULATION (IM) MODEL

Three conditions must occur simultaneously for receiver intermodulation to occur.

- 1) The frequencies of the interfering stations must have a certain numerical relationship to the frequency of the victim receiver.
- 2) The interfering signals must have sufficient ampli-

tude to produce an intermodulation product greater than the receiver threshold.

- 3) The interfering stations must be operating.

The fact that all three conditions must be satisfied simultaneously mitigates the problem of interference due to intermodulation.

Condition 1) alone would be satisfied by a very large number of potential cases of receiver intermodulation, even for a relatively small number of interfering stations, as the number of possible intermodulation frequencies goes up rapidly with the number of frequencies N . Intermodulation combinations for two-signal third-order and for two-signal fifth-order intermodulation, respectively, approximate N^2 . Three-signal third-order combinations are about equal to $N^3/2$; three-signal fifth-order, to N^3 . Thus, for example, in an environment of 100 interfering stations, there are approximately 10 000 two-signal third-order, 10 000 two-signal fifth-order, 500 000 three-signal third-order, and 1 000 000 three-signal fifth-order combinations. And, in metropolitan Chicago, environments exist where as many as 200 potentially interfering signals must be considered. Fortunately, the great majority of frequency combinations coinciding with a particular receiver frequency do not cause intermodulation interference because the signals involved have insufficient amplitude to produce a product which is audible in the receiver. A further reduction in the potential amount of intermodulation interference results from the requirement for simultaneous transmissions. As most LM transmitters operate intermittently and independently, periods of simultaneous transmission are relatively infrequent, particularly for three-signal IM products.

The amount of potential intermodulation interference has been further reduced by recent improvements in receiver intermodulation rejection resulting from increased linearity in the receiver input stages. An even greater reduction can be achieved when necessary by incorporating cavity or crystal filters before the input stages of the receiver.

The enumerated factors indicate that receiver IM interference may not be as serious a source of interference as was originally anticipated by the Task Force. A limited check of LM users by the Chicago Regional Office found few instances of identified receiver intermodulation, and tends to confirm this assessment.

The amount of measured intermodulation data available from the LM equipment manufacturers is exceedingly limited, except for two-signal third-order IM where the interfering signals are one or two channels removed from the receiver frequency. Data from other intermodulation situations are not usually measured by the industry because of the difficulty of such measurements. Three-signal intermodulation measurements require four-signal generators; and, as fifth-order amplitudes are approximately 20 dB lower than third-order levels, fifth-order intermodulation measurements require signal generators of above average spectral purity.

Accordingly, pending further findings as to the receiver IM interference potential, the Task Force will continue to calculate two- and three-signal third- and fifth-order receiver intermodulation products for all computerized frequency assignments. These calculations fill a major portion of the total computer time required for each assignment, as all combinations must be checked in the process.

The present Task Force receiver intermodulation model uses equations developed by the Advisory Committee for the Land Mobile Radio Services [4] which relate powers received at the victim receiver from the several interfering transmitters and their respective offsets to the intermodulation product in each instance:

- 1) *two-signal third-order product*

$$IM = 2A + B + 10 - 60 \log_{10} (dF);$$

- 2) *three-signal third-order product*

$$IM = A + B + C - 81 \log_{10} (dF);$$

- 3) *two-signal fifth-order product*

$$IM = 2A + 3B - 57 - 135 \log_{10} (dF);$$

- 4) *three-signal fifth-order product*

$$IM = A + 2B + 2C - 132 - 195 \log_{10} (dF).$$

A , B , and C are the received power, respectively, from the interfering transmitters. dF is the average of the several offsets from the receiver frequency.

The frequency relationships are:

- 1) *two-signal third-order*

$$F0 = 2F1 - F2;$$

- 2) *three-signal third-order*

$$F0 = F1 - F2 + F3;$$

- 3) *two-signal fifth-order*

$$F0 = 3F1 - 2F2;$$

- 4) *three-signal fifth-order*

$$F0 = 2F1 - 2F2 + F3.$$

$F1$, $F2$, and $F3$ are the respective frequencies of the interfering transmitters. $F0$ is the IM product frequency.

Certain culling procedures which reduce the required number of calculations have been tested and are presently being implemented in the frequency assignment program:

- 1) One cull method recognizes that, unless the sum of the amplitudes of the received powers (as, for example, in the two-signal third-order case, $2A + B$) exceeds a certain value, intermodulation cannot occur, and that, accordingly, the frequency match check can be bypassed.

- 2) A second cull is based upon the fact that, when the environment frequencies are listed in descending order and the algebraic sum of all of these frequencies and the receiver frequency is computed, a change of sign of this sum

indicates that a certain number of the possible combinations can be omitted in the frequency check.

These simple culls reduce the intermodulation model operation time by approximately one-half.

TRANSMITTER INTERMODULATION INTERFERENCE

Transmitter intermodulation is also calculated in the automated frequency assignment program. In this type of interference, a received signal from one transmitter is combined with the output signal of a second transmitter in its output stage to produce intermodulation product frequencies (which are radiated by the second transmitter). This type of interference can only be reduced by the use of selective filters or of isolators at the second transmitter, either of which corrective methods serves to reduce the amplitude of the received signal in the nonlinear circuitry of the transmitter radiating the interference.

Because of the double path loss involved in the generation and reception of this product, the transmitter intermodulation interference range is usually less than 2 mi.

The transmitter intermodulation model uses equations derived from curves given in vol. 2, pt. 2, *Report of the Advisory Committee for the Land Mobile Radio Services* [4]. These equations cover two-signal third- and fifth-order intermodulation only:

1) two-signal third-order transmitter intermodulation

$$a) A = 10.8 + (2.1)|F1 - F2|, \quad \text{where} \\ 0 < |F1 - F2| \leq 0.8 \text{ MHz};$$

$$b) A = 9.3 + (4.0)|F1 - F2|, \quad \text{where} \\ 0.8 \text{ MHz} < |F1 - F2| \leq 5.5 \text{ MHz};$$

$$c) A = 13.4 + (3.2)|F1 - F2|, \quad \text{where} \\ |F1 - F2| > 5.5 \text{ MHz}.$$

2) two-signal fifth-order transmitter intermodulation

$$a) A = 31.0 + (11.4)|F1 - F2|, \quad \text{where} \\ 0 < |F1 - F2| \leq 1.5 \text{ MHz};$$

$$b) A = 36.0 + (7.5)|F1 - F2|, \quad \text{where} \\ |F1 - F2| > 1.5 \text{ MHz}.$$

A is the conversion factor by which the received signal from one transmitter is converted to an IM product at another transmitter.

The only products considered are those in which the frequency of the transmitters radiating the intermodulation is represented by $F1$ in the third- and fifth-order equations ($F0 = 2F1 - F2$, and $F0 = 3F1 - 2F2$, respectively), as the other product with this transmitter frequency at $F2$ is negligible in comparison.

CO-CHANNEL MODEL

The co-channel model used in the frequency assignment model is conventional (and, as both the desired and the undesired signals are on the same channel, receiver con-

version data are not required).

This model assumes that interference exists when the $F(10,50)$ (L,T) interfering signal is 6 dB below the weakest $F(50,50)$ signal required for reception. (In most cases, this signal level equals the receiver noise threshold.) As the interfering signal is considered to be that value exceeded at 10 percent of the locations 50 percent of the time, interference would be worse than predicted for only 10 percent of the cases.

The model calculates two types of co-channel interference:

1) The portion of the base service area in which the base cannot hear the mobile due to interference on the mobile transmit frequency, in which case the interference-free area is approximately a circle centered around the base receiver with radius equal to the distance at which the $F(50,50)$ desired mobile signal is 6 dB stronger than the $F(10,50)$ interfering signal.

2) The portion of the service area in which the mobile cannot hear the base due to interference on the base transmit frequency, in which case the interference-free area is that portion of the service area where the $F(50,50)$ base transmitted signal is 6 dB stronger than the $F(10,50)$ interfering signal. With reasonable accuracy, the interference-free contour can be represented as a circle with center on the line joining the base transmitter and interfering transmitter (but more distant from the interfering transmitter than is the base transmitter).

NOISE MODEL

The frequency assignment program includes a noise model to enable prediction of noise thresholds at base and mobile receivers. This model is based on data given in vol. 2, pt. 2, *Report of the Advisory Committee for the Land Mobile Services* [4] and upon recommendations of Kelly Scientific Corporation which studied the noise model under contract to the Commission [6].

The receiver powers respectively required to produce 12-dB Sinad at the average receiver in the presence of ambient noise are tabulated as follows.

1) Required signal levels at mobile receivers to produce 12-dB Sinad ratio in the presence of noise

- a) low band -127 dBW
- b) high band -137 dBW
- c) UHF band -146 dBW

2) Required signal levels at base receivers to produce 12-dB Sinad ratio in the presence of noise

- a) low band
 - 131 dBW (high noise)
 - 139 dBW (average noise)
 - 143 dBW (low noise)
- b) high band
 - 132 dBW (high noise)
 - 141 dBW (average noise)
 - 148 dBW (low noise)

- c) UHF band
 - 138 dBW (high noise)
 - 145 dBW (average noise)
 - 146 dBW (low noise).

The frequency assignment program presently determines whether a base station location corresponds to high, average, or low noise by calculating the distance from the receiver location to a reference point in downtown Chicago, and arbitrarily categorizing locations within 10 mi of the reference point as high noise, locations between 20 mi as average noise, and locations beyond 20 mi as low noise. This set of simple approximations will be replaced by a map as data become available. One method under consideration is to relate noise grades to peak automotive traffic levels, as it appears that most of the noise at land mobile frequencies may originate in automotive ignition systems [4].

CONCLUSION

The outlined models for propagation, interference, and noise represent the optimum data which the FCC has been able to obtain to date. (Further background in this context may be obtained from such additional sources as the reports of the Joint Technical Advisory Committee [7], the Stanford Research Institute [8], the Electromagnetic Compatibility Analysis Center [9], etc.) It is noted that the entire range of pertinent equipment performance cannot properly be incorporated into any of these models; accordingly, they have been devised to represent the

"middle of the road," possibly slightly biased in the direction of the characteristics of the poorer of the equipments likely to be encountered in the current environment. Absolute accuracy is not claimed in any instance. It is anticipated that the models will be continuously updated and improved to reflect the most recently acquired data and relevant frequency assignment experience.

REFERENCES

- [1] J. H. McMahon, "Capability of the FCC mobile monitoring van," presented at the IEEE 1973 Vehicular Technology Conf., Cleveland, Ohio, Dec. 4-5, 1973; also, this issue, pp. 139-143.
- [2] J. Damelin, W. A. Daniel, H. Fine, and G. V. Waldo, "Development of VHF and UHF propagation curves for TV and FM broadcasting," FCC Rep. R-6602, Sept. 7, 1966.
- [3] P. L. Rice, A. G. Longley, K. A. Norton, and A. P. Barsis, "Transmission loss predictions for tropospheric communication circuits," Nat. Bur. Stand. Tech. Note 101 (Revised), vols. I and II, U. S. Dep. Commerce, May 1, 1966.
- [4] "Report of the Advisory Committee for the land mobile radio services," Federal Communications Commission, Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402.
- [5] J. J. Egli, "Radio propagation above 40 Mc over irregular terrain," *Proc. IRE*, vol. 45, pp. 1383-1391, Oct. 1957.
- [6] R. P. Eckert, P. M. Kelly, E. A. Neham, and P. Walcoff, "Considerations regarding the operation of regional spectrum management centers," Kelly Scientific Corp., Contract RC-10204, Final Rep., Mar. 15, 1973.
- [7] The Joint Technical Advisory Committee of the IEEE and Electronics Industries Association, "Spectrum engineering—The key to progress: A report on technical policies and procedures for increased radio spectrum utilization," Mar. 1968.
- [8] T. I. Dayharsh, T. J. Yung, and W. R. Vincent, "A study of land mobile spectrum utilization," Stanford Res. Inst. Project 7379, FCC Contract RC-10056, July 1969.
- [9] J. A. Zoellner, "Frequency assignment games and strategies," ITT Res. Inst. at the Department of Defense Electromagnetic Compatibility Analysis Center, North Severn, Annapolis, Md. 21402, Nov. 1972.

Aids for the Gross Design of Satellite Communication Systems

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Abstract—Satellite communication systems are being proposed with ever-increasing frequency as integral components of many future commercial, military, and space programs. Thus, many people in all levels of engineering, management, government, and military occupations are being called upon to deliver judgments on this new mode of communications. However, there are sometimes difficulties in developing these judgments, because even gross design of satellite communication systems requires simultaneous manipulation of a half dozen or more parameters.

This paper has been compiled as a computational aid for designers and reviewers of communication systems employing earth satellites as relays. Pertinent design equations are introduced and discussed briefly, with special emphasis placed on the limitations of the equations and the ranges of the parameters. Many of the computational aids, such as charts and nomographs, that are applicable to the gross design of satellite communication systems are presented. The utility of these computational aids is demonstrated in the solutions of some simple satellite communication system design and analysis problems. This paper is intended to be of practical usefulness; there is no suggestion that the theory of communications or satellites is probed in depth or detail.

I. INTRODUCTION

DURING THE NEXT several years, transmission of routine and special communications via active relay

communication satellites will probably become standard practice. During this time period, however, the proposed and operating communications equipment will be far from standard. Satellites in roughly circular orbit probably will be in operation at many different altitudes; satellites in elliptic orbit may have widely differing altitudes at perigee and apogee. Power output of the transponders in different communication satellites may vary by an order of magnitude or more. With the advent of greater booster launch capability, communication satellites may greatly increase in weight, permitting an increased number of transponders per satellite or improved antenna gains or both. The transmitting and receiving frequencies associated with present NASA-sponsored experimental communication satellites are not always identical, and variations may be expected in the future.¹

The ground stations that will transmit to and receive relayed messages from communication satellites in the near future are equally diverse in character. Movable parabolic dish antennas range from a few feet in diameter to a somewhat standard diameter of about 85 feet, and this size could feasibly be increased somewhat if deemed necessary.

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¹ Relay and Telestar I transmit on the same frequency (4170 Mc/s), but do not receive on identical frequencies (1725 and 6390 Mc/s, respectively). None of these frequencies are coincident with the transmit/receive frequencies in Syncom 2 (1900/7400 Mc/s, respectively).

The effective overall receiver noise temperatures available today range from as little as about 30° K to thousands of degrees Kelvin. And required signal-to-noise ratios at the ground receiver may differ considerably, depending on the type of modulation employed.

Even for rather simple problems resulting in gross system design or analysis, the number of variables involved is often a dozen or more, thus precluding the possibility of construction of a few simple "trade-off" curves to indicate the most desirable choice of system parameters. Further complicating the picture is the fact that communication satellite system design involves amplitudes of the parameters (antenna diameters, effective noise temperatures, transmission ranges) which are not covered in design nomographs appearing in standard references published even a few years ago.

For the experienced communications designer, gross system design presents no difficulty; where nomographs end, prior knowledge and paper and pencil are always sufficient. However, the less experienced system analyst may find it a tedious and time-consuming task to assimilate applicable design equations and computational aids to check validity of study conclusions drawn by others on the basis of assumptions of about a dozen parameters.

It is the intent of this paper to bring together a majority of the computational aids, such as charts and nomographs, which are applicable to the gross design of satellite communication systems. Pertinent design equations are introduced and discussed briefly, with special emphasis placed on the limitations of the equations and ranges of the parameters. The utility of these computational aids is demonstrated in the solutions of some simple satellite communication system design and analysis problems. The reader interested in greater theoretical detail should consult the references, especially the text, *Space Communications* [1], and the RAND report, *A Study of Passive Communication Satellites* [2].

II. DESIGN EQUATIONS [3], [4]

Antennas

Antennas are often characterized by their ability to direct radiated power, especially with respect to an idealized isotropic antenna, radiating power equally in all directions. Kraus² points out that an isotropic antenna would have an effective radiating area of

$$A_i = \frac{\lambda^2}{4\pi} \quad (1)$$

where

A_i = maximum effective area of the isotropic antenna

$\lambda = \frac{c}{f}$ = wavelength

c = speed of light

f = radio frequency (c/s).

² Kraus [3], p. 52ff.

TABLE I [3], [5]
POWER GAIN G AND EFFECTIVE AREA A FOR SEVERAL COMMON ANTENNAS*

Antenna	Gain above Isotropic Antenna, G	Maximum Effective Area, A
Isotropic (hypothetical)	1	$\frac{\lambda^2}{4\pi} = 0.079\lambda^2$
Infinitesimal dipole or loop	1.5	$\frac{3}{8\pi}\lambda^2 = 0.119\lambda^2$
Linear half-wavelength dipole	1.64	$\frac{30}{73\pi}\lambda^2 = 0.13\lambda^2$
Optimum horn (mouth area = S)	$10 \frac{S}{\lambda^2}$	$0.81S$
Parabolic reflector (aperture = S , $\eta \approx 0.5$ to 0.6)	$\frac{4\pi\eta S}{\lambda^2}$	ηS
Broadside array (area = S)	$4\pi \frac{S(\max)}{\lambda^2}$	$S(\max)$
Turnstile	1.15	$1.15 \frac{\lambda^2}{2\pi} = 0.0915\lambda^2$

* No heat loss.

The maximum effective area of any antenna is given by³

$$A = G \frac{\lambda^2}{4\pi} \quad (2)$$

where

G = maximum gain of the subject antenna relative to an ideal isotropic antenna.

The maximum power gain and effective area of several common antennas are given in Table I.

Parabolic Antenna Gain

The parabolic reflector antenna is of particular interest in communication satellite systems. Let the physical aperture of the parabolic reflector be given by

$$S = \pi \frac{D^2}{4}$$

D = diameter (feet).

From (2), it is apparent that the gain⁴ of an antenna can be expressed as

$$G = \frac{4\pi A}{\lambda^2} \quad (3)$$

It is common practice to express the gain of certain antennas (parabolic reflector, broadside array, etc.) in terms of a constant multiplied by the physical antenna

³ From the viewpoint of communication satellite system design, the examples given in Section III show the quantity of interest to be the ratio of antenna area to effective noise temperature of the antenna-receiver combination. This implies that an antenna of small cross-sectional area and low effective noise temperature might be as good or better than an antenna of large cross-sectional area and also large effective noise temperature. Noise temperature is discussed in Section II.

⁴ Here, and in all subsequent statements, "antenna gain" implies the maximum power gain of the antenna relative to the (arbitrarily assumed) unit power gain of an isotropic antenna.

aperture. Thus, the gain of the parabolic reflector is generally written (see Table I):

$$G = \frac{4\pi\eta S}{\lambda^2} \quad (4)$$

Theoretically, for a circular aperture, $A \leq S$; hence $0 \leq \eta \leq 1.0$, and η is taken to be equivalent to antenna "efficiency." Usually, η is found to lie in the range 0.5 to 0.6, although exceptions to this statement exist, e.g., the high efficiency of the BTL "horns" constructed as segments of parabolic reflectors.

In this paper an efficiency of 54 percent will be assumed,⁵ thus giving an apparent power gain for a parabolic antenna of

$$G = 0.54 \left(\frac{\pi D}{\lambda} \right)^2 \quad (5)$$

which can be expressed as

$$G = 5.5 \times 10^{-6} f^2 D^2 \quad (6)$$

or, in decibels,

$$G_{dB} = 20 \log f + 20 \log D - 52.6 \quad (7)$$

where in (6) and (7)

f = megacycles/second

D = aperture diameter (feet).

The solution for G_{dB} is found in the nomogram, Fig. 1.

Parabolic Antenna Beamwidth

If the circular aperture of a large parabolic reflector is uniformly illuminated, the beam angle (in degrees) between the half-power points is given by

$$\theta = 58 \frac{\lambda}{D} \quad (8)$$

where

λ = wavelength

D = diameter of circular aperture, and

θ = beam angle between half-power points (degree).

In actual antenna installations, illumination intensity across the aperture often is not uniform, but decreases from the center out to the edges with a corresponding reduction in gain, increase in beamwidth, and reduction in side lobes. Thus, a more realistic expression for beam angle between half-power points is

$$\theta \approx 70 \frac{\lambda}{D} \quad (9)$$

This is approximately equivalent to

$$\theta \approx \frac{70\,000}{fD} \quad (10)$$

⁵ An efficiency of 54 percent is "conventional" ([5]); efficiencies of 60 percent or higher have been attained with some of the most recent large parabolic antennas.

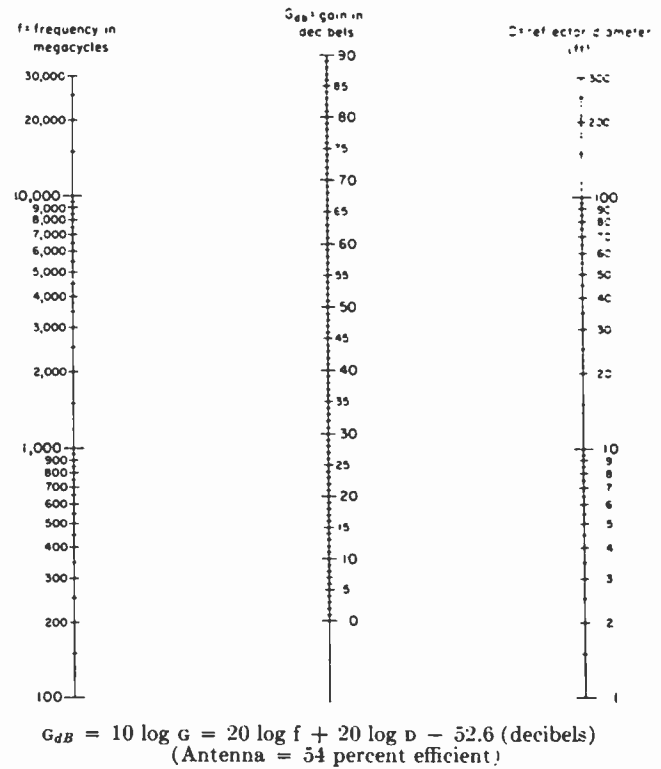


Fig. 1. Nomogram for determination of apparent power gain G_{dB} of a parabolic reflector.

where

f = frequency in megacycles/second

D = diameter of circular aperture in feet.

A nomogram of θ as a function of frequency and diameter is given in Fig. 2.

Free Space Path Loss

For a receiver and transmitter axially aligned and displaced in space by a distance much greater than the transmitted wavelength, the received power is given by

$$P_R = \frac{P_T G_T}{4\pi d^2} \cdot A_R \quad (11)$$

where

P_R = power available at output terminals of receiving antenna

P_T = power radiated from transmitting antenna

d = distance between antennas

G_T = gain of transmitting antenna, and

A_R = effective area of receiving antenna.

But, from (3)

$$G_T = \frac{4\pi A_T}{\lambda^2} \quad (12)$$

where

A_T = effective area of transmitting antenna, and

λ = wavelength.

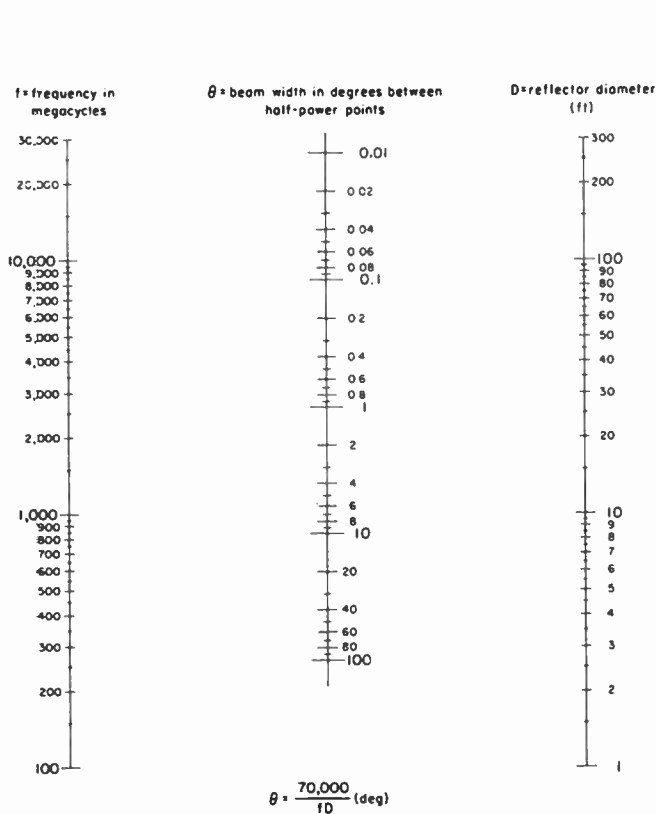


Fig. 2. Nomogram for determination of beamwidth (degree) between half-power points for a parabolic reflector.

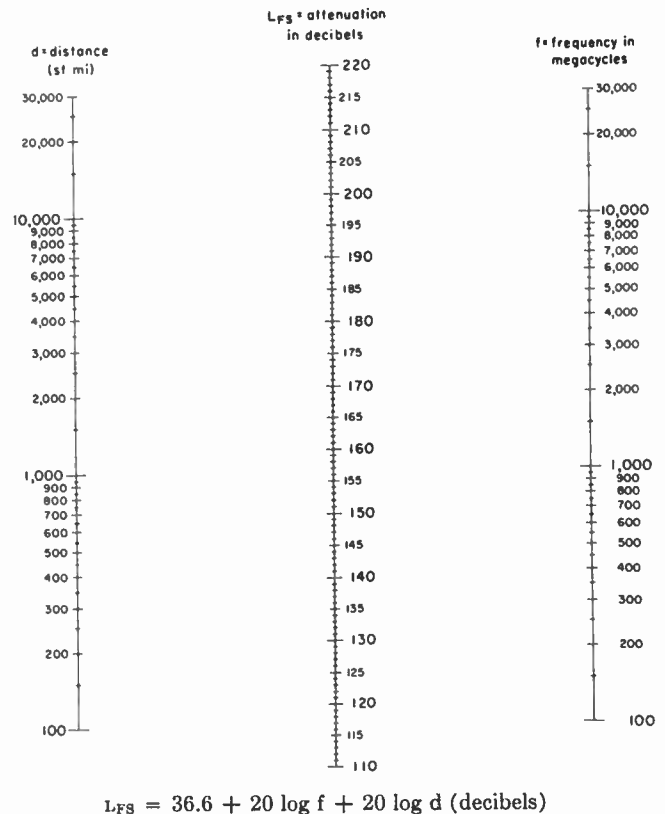


Fig. 3. Nomogram for solution of free space path loss L_{FS} between isotropic antennas.

Thus, combining (11) and (12)

$$P_R = P_T \cdot \frac{A_R A_T}{d^2 \lambda^2}. \quad (13)$$

When both receiving and transmitting antennas are isotropic, the ratio of transmitted to received power is

$$\left(\frac{P_T}{P_R} \right)_{iso} = \frac{(4\pi)^2 d^2}{\lambda^2}. \quad (14)$$

Free space path loss between isotropic antennas is defined to be

$$L_{FS} = 10 \log \left(\frac{P_T}{P_R} \right)_{iso} = 10 \log \frac{(4\pi)^2 d^2}{\lambda^2}. \quad (15)$$

For a nomograph, it is convenient to use

$$\left(\frac{P_T}{P_R} \right)_{iso} = 4.56 \times 10^3 f^2 d^2 \quad (16)$$

where

f = megacycles/second, and

d = statute miles

thus giving

$$L_{FS} = 36.6 + 20 \log f + 20 \log d \text{ (decibels)}. \quad (17)$$

The solution of L_{FS} for distances and frequencies pertinent to communication satellites is given by the nomogram, Fig. 3.

Effective Noise Temperature

It is becoming increasingly common to characterize the noise at the input of a receiver in terms of the effective noise temperature

$$T = \frac{N}{k \, df} \quad (18)$$

where

T = effective receiver input noise temperature (degrees Kelvin),

N = noise power in the frequency increment df (watts),

k = Boltzmann's constant, $1.38 \times 10^{-23} \frac{\text{joules}}{^\circ\text{Kelvin}}$, and

df = increment in frequency (c/s).

Conversely, if the effective noise temperature and receiver bandwidth are known, the total noise power at the input of the receiver is taken to be

$$N_t = k T B \quad (19)$$

where

N_t = total effective receiver input noise power (watts)

T = effective noise temperature ($^\circ\text{Kelvin}$)

k = Boltzmann's constant (joules/ $^\circ\text{Kelvin}$), and

B = receiver bandwidth (c/s).

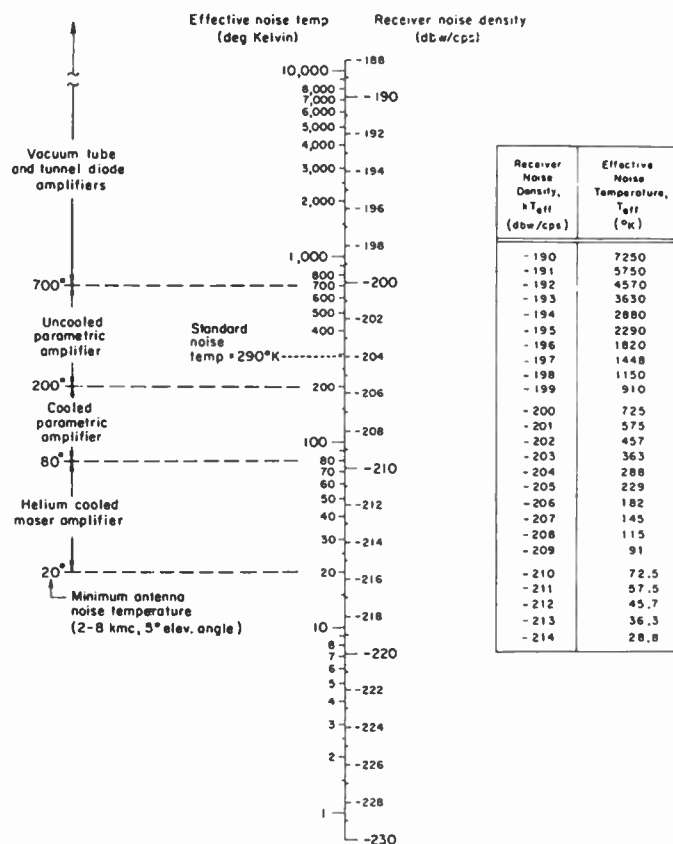


Fig. 4. Conversion of effective receiver noise temperature to receiver noise density.

Since k is constant, the receiver noise density N [watts/(c/s)] can be directly related to the effective noise temperature T . A conversion chart is given in Fig. 4. Use of Fig. 4 is illustrated by the following example. Let the effective noise temperature of a ground receiver be 180° K and let the bandwidth of the incoming signal be 10 megacycles. Figure 4 indicates the receiver noise density to be -206 dBW/(c/s). Then the total effective receiver input noise power in the 10-Mc/s bandwidth is

$$N_t(\text{dBW}) = -206 + 70 = -136 \text{ dBW}.$$

It is noted that effective noise temperature, as discussed here, tends to be the result of a myriad of noise effects, not all of which are directly attributable to the internally generated noise in the receiver itself.

Other causes of noise are ([6], [7], and [1]):

- cosmic noise (not significant in 1-10 Gc/s band)
- earth's atmosphere (not significant in 1-10 Gc/s band for antenna elevations 7° or more above the horizon)
- rain (noise temperature may exceed 100°K in 1-10 Gc/s band)
- local interference
- ground in vicinity of antenna
- earth, satellite, and sun in alignment (will cause temporary communication blackout)
- earth, satellite, and moon in alignment (not significant in 1-10 Gc/s band), and
- losses between antenna and receiver.

Carrier-to-Noise Ratio

The equations presented in the preceding paragraphs are now combined to give a power ratio of transmitted signal strength at the receiver input relative to the effective noise power at the receiver input.

Carrier power is loosely defined here to mean the total radiated power over the RF bandwidth of the transmitter. The radiated carrier power, transmitter, and receiver gains, system losses, and bandwidth are related by the following equations for one-way and two-way (passive reflector) communication.

1) One-way Transmission:

$$\frac{C}{N_t} = \frac{P_T G_T G_R}{k T_{eff} B_{IF} L_{FS}} \quad (20)$$

where

C/N_t = carrier-to-noise power ratio,

P_T = transmitter power,

G_T = transmitter antenna power gain,

G_R = receiver antenna power gain,

k = Boltzmann's constant,

T_{eff} = receiver effective noise temperature (includes coupling losses, etc.),

B_{IF} = receiver IF bandwidth,⁶ and

L_{FS} = free space path loss.

The use of the following nomograms greatly facilitates the solution of the previous expression. However, direct use of the nomograms requires that (20) be in decibel (10 log₁₀) form:

$$\frac{C}{N_t}(\text{dB}) = P_T(\text{dBW}) + G_T(\text{dB}) + G_R(\text{dB}) - L_{FS}(\text{dB}) - k T_{eff} B_{IF}(\text{dBW}) \quad (21)$$

Figure 5 is useful for converting transmitted power in the IF band into a form commensurate with values obtained from nomograms for the other terms in (21).

2) Two-way Transmission (Passive Reflector):

$$\frac{C}{N_t} = \frac{P_T G_T G_R G_{PR}}{k T_{eff} B_{IF} L_{FSu} L_{FSd}} \quad (22)$$

where

C/N_t = carrier-to-power noise ratio,

P_T = transmitter power,

⁶ In the examples to follow, the receiver intermediate frequency (IF) bandwidth will usually be assumed to be twice the information bandwidth (baseband). This step is taken in view of the high probability that some form of frequency modulation (FM) or pulse code modulation (PCM) will be employed in future communication satellite systems. In the event that suppressed carrier single sideband modulation is under consideration, the IF bandwidth will be the same as the information bandwidth.

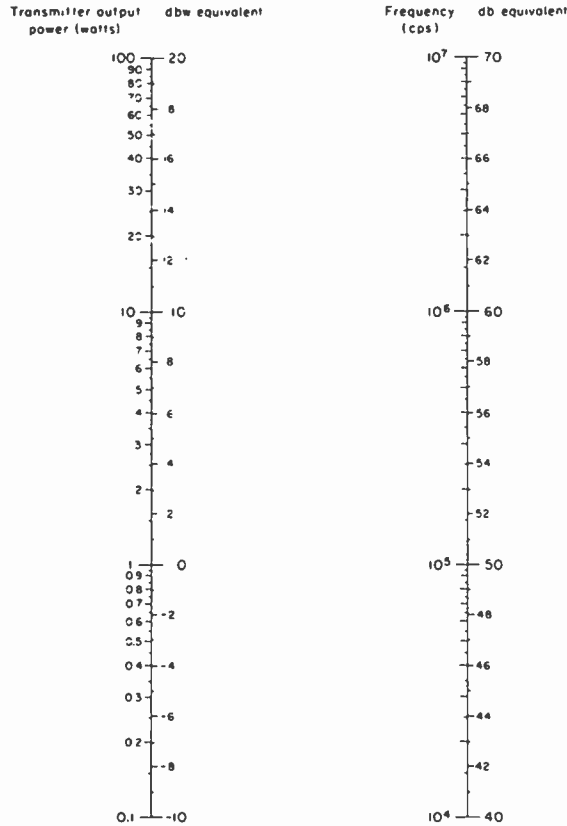


Fig. 5. Conversion of power and frequency values to decibels.

G_T = transmitter gain.

G_R = receiver gain,

G_{PR} = passive reflector gain = $\frac{4\pi}{\lambda^2} A_{PR}$,

k = Boltzmann's constant,

T_{eff} = receiver effective noise temperature (includes coupling losses, etc.).

B_{IF} = receiver IF bandwidth,⁶

L_{FSu} = free space path loss for up-link, and

L_{FSd} = free space path loss on down-link.

In decibel form suitable for use with the nomograms, (22) becomes

$$\frac{C}{N_t} (\text{dB}) = P_T (\text{dBW}) + G_T (\text{dB}) + G_R (\text{dB}) + G_{PR} (\text{dB}) - L_{FSu} (\text{dB}) - L_{FSd} (\text{dB}) - kT_{eff} B_{IF} (\text{dBW}). \quad (23)$$

As mentioned previously, Fig. 5 can be used to convert transmitted power and IF bandwidth into convenient forms.

Slant Range

The communication path length from a satellite to a point on earth varies from the altitude h to the maximum slant range S_M , where S_M is defined as the distance from

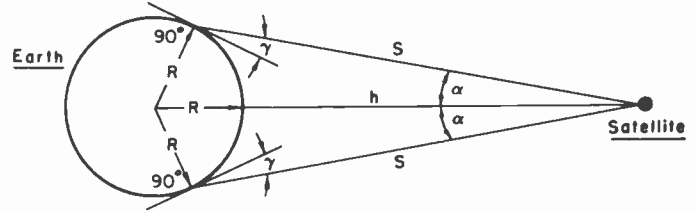


Fig. 6. Geometry of the slant range problem. R = radius of earth (assumed spherical), h = altitude of satellite above earth's surface, S = slant range ($S \leq S_M$), γ = receiver antenna elevation angle above local horizontal, α = half-angle of earth coverage.

the satellite to a point of tangency on the earth's surface and is a function of h . Due to noise from the ground in the vicinity of the antenna, it is generally necessary to maintain the receiving antenna elevation angle at least 5 to 10 degrees above the local horizontal. Hence, for a given satellite altitude, the maximum communication path distance will also be a function of elevation angle γ .

The geometry of the problem is illustrated in Fig. 6, where it is seen that for a given elevation angle γ and satellite altitude h , the largest slant range S over which communication would take place is given by

$$S = (R + h) \frac{\sin \left[\frac{\pi}{2} - \gamma - \sin^{-1} \left(\frac{R}{R + h} \cos \gamma \right) \right]}{\cos \gamma} \quad (24)$$

Graphs of S as a function of h and various values of γ are given in Figs. 7 and 8.

Since communication satellites are usually considered to be in random orbits in the range 3000- to 12 000-mile altitude, or are assumed to be in stationary orbit at 22 300-mile altitude, some simplified expressions can be obtained:

for $h = 3000$ to $12\,000$; $\gamma = 0^\circ$ to 20°

$$S \doteq h + 2500 - 66\gamma \quad (\text{error less than 2 percent}) \quad (25)$$

for $h = 22\,300$; $\gamma = 0^\circ$ to 20°

$$S \doteq 26\,000 - 70\gamma \quad (\text{error less than 0.2 percent}) \quad (26)$$

where

S = slant range (statute mi),

γ = elevation angle (degrees), and

h = satellite altitude (statute mi).

Ranges of Salient Parameters

In satellite communication systems, as in similar communication systems, the variation in allowable transmission frequencies, parabolic antenna sizes, noise temperature, etc., are essentially bounded. The nature of these bounds is outlined in Table II. Note that these bounds are not "absolute," but are those most likely to be encountered in practice now and in the near future.

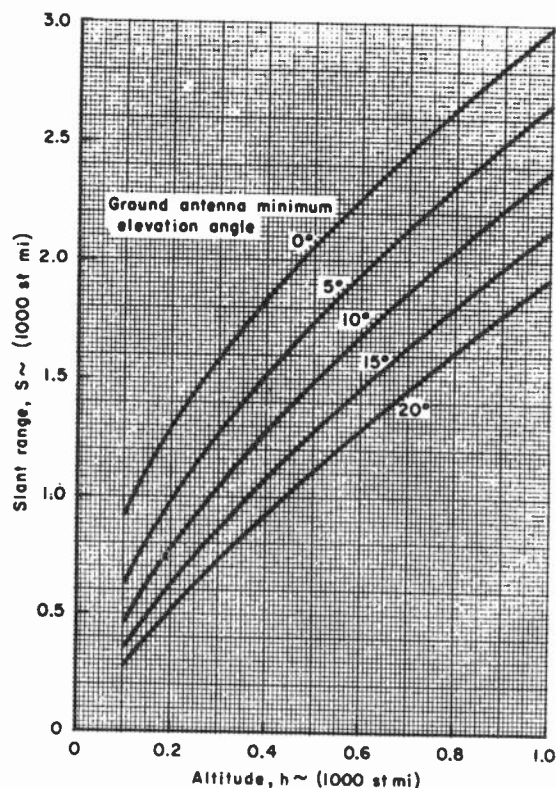


Fig. 7. Slant range as a function of satellite altitude and ground antenna minimum elevation angle (low-orbital altitudes).

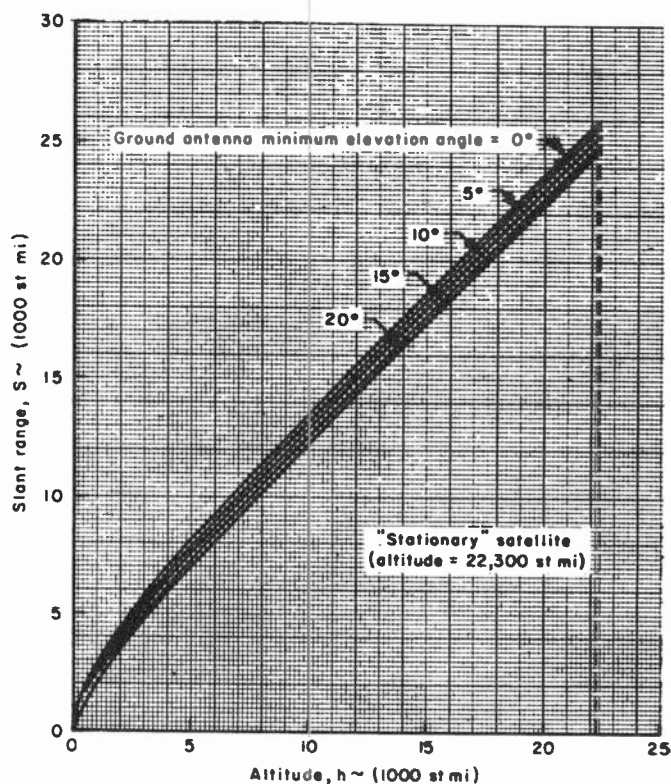


Fig. 8. Slant range as a function of satellite altitude and ground antenna minimum elevation angle (medium-to-stationary orbital altitudes).

TABLE II
RANGES OF SALIENT PARAMETERS IN COMMUNICATION SATELLITE SYSTEMS

Parameters	Bounds		Most Likely Range	
	Lower	Upper	Lower	Upper
Frequency	100 Mc/s	20 000 Mc/s	800 Mc/s	10 000 Mc/s
Vertical altitude	100 miles	22 300 miles		
Maximum slant range	900 miles	26 000 miles		
Free space path loss	120 dB	205 dB		
Parabolic antenna diameter	2 feet	120 feet		
Parabolic antenna gain	10 dB	70 dB		
Parabolic antenna beamwidth between half-power points	0.04 degree	40 degrees		
Transmitter power:				
1) ground	10 watts	100 kW		
2) satellite transponder	1 watt	1000 watts	1 watt	10 watts
Receiver effective noise temperature	30° Kelvin	3000° Kelvin		
Receiver noise density	-214 dBW/(c/s)	-194 dBW/(c/s)		

Constants, Units, and Definitions

Velocity of light,

$$\begin{aligned}
 c &= 299\,793.0 \text{ km/s} \\
 &= 186\,280.0 \text{ mi/s} \\
 &= 161\,875.6 \text{ nmi/s} \\
 &= 983\,573 \times 10^6 \text{ feet/s}
 \end{aligned}$$

$$1 \text{ mile} = 5280 \text{ feet} = 1.609 \text{ km} = 0.86899 \text{ nmi}$$

$$1 \text{ nmi} = 6076.10333 \text{ feet} = 1.852 \text{ km} = 1.1508 \text{ mile}$$

$$1 \text{ km} = 3281^+ \text{ feet} = 0.5399 \text{ nmi} = 0.624 \text{ mile}$$

$$\text{Degrees Kelvin} = ^\circ\text{C} + 273.18 = \frac{5}{9} [^\circ\text{F} + 459.72]$$

$$\text{Boltzmann's constant} = 1.38 \times 10^{-23} \frac{\text{joules}}{^\circ\text{Kelvin}}$$

$$\text{dBW} = \text{dB relative to 1 watt}$$

$$\text{dBm} = \text{dB relative to 1 milliwatt}$$

$$\text{dB for power is } 10 \log_{10} \frac{P_2}{P_1}$$

$$\text{dB for voltage is } 20 \log_{10} \frac{V_2}{V_1}$$

Earth diameter:

Mean	
4.18055×10^7	feet
7917.780	miles
6880.419	nmi
12 742.46	km

Equatorial	
4.185286×10^7	feet
7926.678	miles
6888.151	nmi
12 756.78	km

III. EXAMPLES OF GROSS SYSTEM DESIGN AND ANALYSIS

The use of the nomograms discussed previously is demonstrated in Section III in the context of some gross system design and analysis problems considered typical of future communication satellite systems.

Generally, the intricacies of system design involving losses or gains due to particular methods of signal processing will not be explicitly considered here. However, in view of the likelihood that future communication satellite systems will employ frequency modulation (FM) or pulse code modulation (PCM), a carrier-to-noise ratio of 20 dB taken over twice the base bandwidth will be considered as adequate for a voice-quality link [8].

The present status of communication satellite systems is one of great flux and change. There is a wide spectrum of missions to which communication satellites can be applied; and a seemingly limitless variation in technical parameters is technically feasible. Therefore, it is emphasized that the examples presented here are for illustrative purposes only, and are not intended to be indicative of systems presently under consideration or specifically intended for implementation in the future.

Example One: Channel Capacity

An active repeater, medium altitude, circular orbit communication satellite system is proposed in which, for more reliable operation, each satellite contains more than one transponder. For a set of transponder and ground-station characteristics, it is desired to know how many duplex telephone voice channels can be accommodated by a single satellite. The required input data information is given below.

An orderly approach to the problem is outlined in the solution section, following the input data. The solution has been rounded down to the nearest number divisible by 60, since 60 channels is the basic "super group" used in telephone communications.

(Note that the ground-to-satellite "up-link" is not considered in this example. The reason for this is simple: specification of satellite and ground receiver characteristics establishes "down-link" channel capacity. The small output power radiated by the satellite, and the maximum effective area of the ground receiving antenna are the principal limiting factors. A matching "up-link" channel

capacity can be assured by requiring adequate ground transmitter antenna gain and power output. Present equipment capabilities permit comparatively greater flexibility in setting the ground transmitter requirements.)

Input Data:

- | | |
|--|---------------------|
| 1) Satellite-to-ground transmitting frequency | 4×10^9 c/s |
| 2) Parabolic antenna diameter (ground receiver) | 60 feet |
| 3) Satellite transponder power output | 2 watts |
| 4) Satellite transmitter effective antenna gain | 3 dB |
| 5) Satellite orbital altitude | 6000 mi |
| 6) Ground antenna minimum elevation angle | 5 degrees |
| 7) Required carrier-to-noise ratio over twice the baseband | 20 dB ⁷ |
| 8) Ground receiver effective noise temperature | 150° Kelvin |
| 9) Required bandwidth/channel | 4000 c/s |
| 10) Number of transponders/satellite | 4 |

Solution:

- | | |
|---|-----------|
| 1) A given ground receiver parabolic antenna diameter of 60 feet and, an operating frequency of 4000 Mc/s results in a ground antenna gain of | 55 dB |
| A satellite transponder power output of 2 watts is equivalent to | 3 dBW |
| The given satellite transmitter antenna gain is | 3 dB |
| The sum gives equipment gain of | 61 dB |
| 2) A given satellite altitude of 6000 miles and a minimum ground receiver elevation angle of 5 degrees results in a maximum slant range of 8800 miles, with a corresponding free space path loss of | 188 dB |
| The difference between equipment gain and path loss gives the received signal at ground station as | -127 dBW |
| 3) If the required carrier-to-noise ratio over twice the baseband is | 20 dB |
| then the allowable effective receiver noise power is | -147 dBW |
| 4) A given receiver effective noise temperature of 150°K results in an effective noise density of | -207 dBW/ |
| The difference between allowable | (c/s) |

⁷ It is shown in Fig. 3 of Heitzman's paper, that a 20-dB carrier-to-baseband noise ratio can be equivalent to an audio output signal-to-noise ratio of 30 to 50 dB, depending on the type of demodulation employed in the (ground) receiver. Thus, requiring a 20-dB carrier-to-twice baseband noise ratio provides for a conservative design.

noise power and effective noise density is

60 dB,
 10^6 c/s

- 5) Since noise power is determined over twice the baseband, then the useful information bandwidth is 0.5×10^6 c/s
 An allocation of 4000 (c/s)/channel results in

$$\frac{5 \times 10^5}{4 \times 10^3} = 125 \text{ channels/transponder}$$

(Round down to 120)

- 6) If there are N transponders in the satellite, then the number of duplex channels which can be provided by each satellite is (approximately)
 $N \times (\text{no. channels/transponder}) = \frac{4 \times 120}{2} =$

$$\frac{4 \times 120}{2} = 240 \text{ Duplex channels/satellite}$$

Example Two: Variation in Channel Capacity

A narrow-band, active repeater, elliptic orbit satellite system is proposed for emergency use. One-way communication is considered adequate. For a set of satellite, orbital, and ground-station characteristics, it is desired to determine the variation in carrier-to-noise ratio as a function of satellite altitude at perigee and apogee.

Input Data:

Ground-to-Satellite

- 1) Transmitted frequency 6×10^9 c/s
- 2) Transmitted power 10 watts
- 3) Ground parabolic antenna diameter 4 feet
- 4) Satellite orbital altitude 200 to 2000 miles
- 5) Ground antenna minimum elevation angle 10 degrees
- 6) Satellite receiver antenna effective gain 1 dB
- 7) Satellite receiver antenna effective noise temperature 1200° K
- 8) Satellite receiver RF bandwidth 30 000 c/s
- 9) Satellite information bandwidth 3000 c/s

Satellite-to-Ground

- 10) Transmitted frequency 4×10^9 c/s
- 11) Satellite transponder power output 2 watts
- 12) Satellite transmitter antenna effective gain -6 dB
- 13) Ground parabolic antenna diameter 4 feet
- 14) Ground antenna minimum elevation angle 10 degrees
- 15) Ground receiver effective noise temperature 290° K
- 16) Ground receiver RF bandwidth 30 000 c/s
- 17) Ground receiver information bandwidth 3000 c/s

Solution:

Ground-to-Satellite

- 1) A given ground transmitter parabolic antenna diameter of 4 feet and an operating frequency of 6000 Mc/s results in a ground transmitter antenna gain of 35 dB
- 2) A ground transmitter power output of 10 watts is equivalent to 10 dBW
- 3) The given satellite receiver antenna gain is 1 dB
- 4) The sum gives an equipment gain of 46 dB
- 5) A given satellite altitude of 200 to 2000 miles and a minimum ground transmitter elevation angle of 10 degrees results in a maximum usable slant range of 760 to 3800 miles with a corresponding free space path loss of 170 to 183 dB
- 6) The difference between equipment gain and path loss gives the received signal level at the satellite: -124 to -137 dBW
- 7) A given satellite receiver effective noise temperature of 1200° K results in an effective noise density of -198 dBW/c/s
- 8) Twice the information bandwidth of 3000 c/s is equivalent to 38 dB
- 9) The sum gives a resultant noise power of -160 dBW
- 10) Hence, the input carrier-to-noise ratio (over twice the baseband) at the satellite is 36 to 23 dB

Satellite-to-Ground

- 1) A given ground receiver parabolic antenna diameter of 4 feet and an operating frequency of 4000 Mc/s results in a ground receiver antenna gain of 32 dB
- 2) A satellite transponder power output of 2 watts is equivalent to 3 dBW

- 3) The given satellite transmitter antenna gain is -6 dB
- 4) The sum gives an equipment gain of 26 dB
- 5) A given satellite altitude of 200 to 2000 miles and a minimum ground transmitter elevation angle of 10 degrees results in a maximum usable slant range of 760 to 3800 miles with a corresponding free space path loss of 167 to 180 dB
- 6) The difference between equipment gain and path loss gives the received signal level at the ground receiver -138 to -151 dBW
- 7) A given ground receiver effective noise temperature of 290 °K results in an effective noise density of -204 dBW/(c/s)
- 8) Twice the information bandwidth of 3000 c/s is equivalent to 38 dB
- 9) The sum gives a resultant noise power of -166 dBW
- 10) Hence, the input carrier-to-noise ratio over twice the baseband at the ground receiver is 28 to 15 dB

Example Three: Analysis of a Given System

This example is illustrative of the type of analysis often performed in evaluating existing data. The problem is outlined in the following quotation from a discussion of a stationary orbit communication satellite system [9].

... The ground receiving antenna needed is a quasi-fixed 60-foot diameter dish, receiver temperature not higher than 80° K. Wideband frequency modulation is assumed.

The one-watt repeater could relay 600 one-way channels and each pair of repeaters could relay 600 duplex channels. Assuming that 16 repeaters could be carried in an early 24-hour satellite, its total circuit capacity would be 4800 duplex channels—a very large capacity.

A serious problem is the availability of frequency spectrum. Each repeater would require an RF bandwidth of about 100 Mc/s for receiving and a similar bandwidth for sending.

Elsewhere in the article it is noted that "directivity affords a significant saving in satellite power (an antenna gain of about 18 dB for a beamwidth which covers the visible part of the earth)..."

Note that no operating frequency is specified in this proposed system. Such specification is unnecessary, since parabolic antenna gain and free space path loss are both directly dependent on frequency squared; hence, their

ratio is independent of operating frequency. However, in order to utilize the nomograms, a frequency must be chosen: in following with the other examples, a frequency of 4000 Mc/s is assumed, since a value in this range would probably be employed due to other considerations.

Wide-band (100 Mc/s) frequency modulation has been given, so in the following analysis a carrier-to-noise power ratio in twice the baseband will be determined. Extending the analysis on the succeeding pages would show that if conventional frequency modulation (FM) were used, the system specified previously would have a modulation index M of approximately 19. Therefore, a rough comparison of the FM system with a system employing suppressed carrier single-sideband (SSB) modulation shows a carrier power ratio of $3/(2M^2) \cong 0.002$; i.e., the FM system will require about one five-hundredth the power needed to transmit the same 600 voice channels using SSB modulation. This improvement is obtained, of course, at the expense of increased bandwidth. In this case, the given 100-Mc/s bandwidth occupied by the FM system is $2(1 + M) = 40$ times the bandwidth required for an equivalent SSB system. If FM with feedback (in the ground receiver) or pulse code modulation (PCM) had been employed, even greater improvements could be shown [10].

Input Data:

- 1) Satellite-to-ground transmitting frequency (assumed) 4×10^9 c/s
- 2) Ground parabolic antenna diameter 60 feet
- 3) Satellite transponder power output 1.0 watts
- 4) Satellite effective antenna gain 18 dB
- 5) Satellite orbital altitude 22 300 miles
- 6) Ground antenna minimum elevation angle (assumed) 5 degrees
- 7) Ground receiver effective noise temperature 80 °Kelvin
- 8) RF-bandwidth 10^8 c/s
- 9) Required bandwidth/channel (assumed) 4000 c/s
- 10) Total number of channels/repeater 600

Solution:

- 1) A given ground receiver parabolic antenna diameter of 60 feet and an assumed operating frequency of 4000 Mc/s results in a ground receiver antenna gain of 55 dB
A satellite transponder power output of 1.0 watts is equivalent to 0 dBW
The given satellite transmitter gain is 18 dB
The sum gives an equipment gain of 73 dB
- 2) A given satellite altitude of 22 300 miles and a minimum ground receiver elevation angle of 5 degrees results in a maximum slant range of 25 650

- miles, with a corresponding free space path loss of 197 dB
- The difference between equipment gain and path loss gives the received signal at the ground station -124 dBW
- 3) A given ground receiver effective noise temperature of 80 °K results in an effective noise density of -210 dBW/(c/s)
- The total information bandwidth (baseband) is 600 channels $\times$ 4000 (c/s)/channel = 2.4 Mc/s.
- Twice the baseband is proportional to 67 dB
- Hence, the noise power in twice the baseband is -143 dBW
- 4) Thus, the carrier-to-noise ratio over twice the baseband is 19 dB*

* As noted previously, Heitzman shows that a carrier-to-noise ratio of 20 dB is quite adequate for good quality voice circuits, when a modulation-demodulation scheme such as conventional FM or FM with feedback is used.

REFERENCES

- [1] A. V. Balakrishnan, *Space Communications*. New York: McGraw-Hill, 1963.
- [2] S. H. Reiger, *A Study of Passive Communication Satellites*. The RAND Corporation, Santa Monica, Calif., R-415-NASA, February 1963.
- [3] J. D. Kraus, *Antennas*. New York: McGraw-Hill, 1950.
- [4] S. Silver, *Microwave Antenna Theory and Design*, Radiation Laboratory Series, vol. 12. New York: McGraw-Hill, 1949.
- [5] International Telephone and Telegraph Corp., *Reference Data for Radio Engineers*, 4th ed. New York: American Book-Stratford, 1956.
- [6] J. R. Pierce, "Communication satellites," *Scientific Am.*, vol. 205, no. 4, October 1961.
- [7] H. J. Pratt, "Propagation, noise, and general systems considerations in earth-space communications," *IRE Trans. on Communication Systems*, vol. CS-8, pp. 214-221, December 1960.
- [8] R. E. Heitzman, "A study of the threshold power requirements of FMFB receivers," *IRE Trans. on Space Electronics and Telemetry*, vol. 8, pp. 249-256, December 1962.
- [9] B. H. Klein et al., *Communication Satellites and Public Policy: An Introductory Report*, The RAND Corporation, Santa Monica, Calif., RM-2925-NASA, December 1961.
- [10] E. Bedrosian, "Power-bandwidth trade-offs for feedback FM systems: A comparison with pulse-code-modulation," The RAND Corporation, Santa Monica, Calif., RM-2787-NASA, October 1961.

Radio Propagation at Frequencies Above 30 Megacycles*

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Summary—Radio propagation is affected by many factors, including the frequency, distance, antenna heights, curvature of the earth, atmospheric conditions, and the presence of hills and buildings. The influence of each of these factors at frequencies above about 30 megacycles is discussed, with most of the quantitative data being presented in a series of nomograms. By means of three or four of these charts, an estimate of the received power and the received field intensity for a given point-to-point radio transmission path ordinarily can be obtained in a minute or less.

The theory of propagation over a smooth spherical earth is presented in a simplified form that is made possible by restricting the frequency range to above about 30 megacycles, where variations in the electrical constants of the earth have only a secondary effect. The empirical methods used in estimating the effects of hills and buildings and of atmospheric refraction are compared with experimental data on shadow losses and on fading ranges.

I. INTRODUCTION

METHODS of calculating ground-wave propagation over a smooth spherical earth have been given by Burrows and Gray and by Norton for all values of distance, frequency, antenna height, and ground constants.^{1,2} These two methods are different in form but they give essentially the same results. Both methods are relatively simple to use at the lower frequencies where grounded antennas are in common use, but their complexity increases as the frequency increases. At frequencies above 30 or 40 megacycles, elevated antennas are in common use, and the radio path loss between two horizontal antennas tends to be equal to the loss between two vertical antennas. In addition, both types of transmission tend to be independent of the electrical constants of the ground, so that considerable simplification is possible. This paper presents a series of nomograms which have been found useful in solving radio propagation problems in the very-high-frequency range and above. These charts are arranged so that radio transmission can be expressed in terms of either the received field intensity or the received power delivered to a matched receiver. The field-intensity concept may be more familiar, but the power-transfer concept becomes more convenient as the frequency is increased.

In addition to the smooth-earth theory, an approximate method is included for estimating the effects of hills and other obstructions in the radio path. The phenomena of atmospheric refraction (bending away from straight-line propagation), atmospheric ducts

(tropospheric propagation), and atmospheric absorption are discussed briefly, but the principal purpose is to provide simplified charts for predicting radio propagation under average weather conditions. It is expected that, normally, the nomograms will provide the desired answer directly without any additional computation, except the addition of the decibel values obtained from three or four individual charts. The basic formulas are presented as an aid to understanding the principles involved and as a more accurate method, should one be required. This paper does not consider sky-wave propagation, although ionospheric reflections may occur at frequencies above 30 megacycles and may cause occasional long-distance interference between systems operating on the same frequency.³

A convenient starting point for the theory of radio propagation is the condition of two antennas in free space, which is discussed in terms of both received field intensity and received power. Since most radio paths cannot be considered to be free-space paths, the next step is to determine the effect of a perfectly flat earth, and this is followed by the effect of the curvature of the earth. After the basic smooth-earth theory is completed, there is a discussion of the variations in received power caused by atmospheric conditions and by irregularities on the earth surface, but the methods used in predicting these factors are necessarily less exact than the data for a smooth spherical earth in a uniform atmosphere.

II. FREE-SPACE FIELD

A free-space transmission path is a straight-line path in a vacuum or in an ideal atmosphere, and sufficiently removed from all objects that might absorb or reflect radio energy. The free-space field intensity E_0 at a distance d meters from the transmitting antenna is given by

$$E_0 = \frac{\sqrt{30g_1P_1}}{d} \text{ volts per meter} \quad (1)$$

where P_1 is the radiated power in watts and g_1 is the power-gain ratio of the transmitting antenna. The subscript 1 refers to the transmitter and the subscript 2 will refer to the receiver. For an ideal (isotropic) antenna that radiates power uniformly in all directions, $g=1$. For any balanced antenna in free space (or located more than a quarter-wavelength above the ground), g is the power-gain ratio of the antenna relative to the isotropic antenna. A small doublet or dipole whose over-all physical length is short compared with a half-wavelength has a directivity gain of $g=1.5$ (1.76 decibels) and a half-

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¹ C. R. Burrows and M. C. Gray, "The effect of earth's curvature on ground-wave propagation," *Proc. I.R.E.*, vol. 29, pp. 16-24; January, 1941.

² K. A. Norton, "The calculation of ground-wave field intensities over a finitely conducting spherical earth," *Proc. I.R.E.*, vol. 29, pp. 623-639; December, 1941.

³ E. W. Allen, "Very-high-frequency and ultra-high-frequency signal ranges as limited by noise and co-channel interference," *Proc. I.R.E.*, vol. 35, pp. 128-136; February, 1947.

wave dipole has a gain of $g=1.64$ (2.15 decibels) in the direction of maximum radiation. In other directions of transmission the field is reduced in accordance with the free-space antenna pattern obtained from theory or measurement. Consequently, the free-space field intensity in a direction perpendicular to a half-wave dipole is

$$E_0 = \sqrt{\frac{30 \times 1.64 P_1}{d}} \sim 7 \sqrt{\frac{P_1}{d}} \quad (2)$$

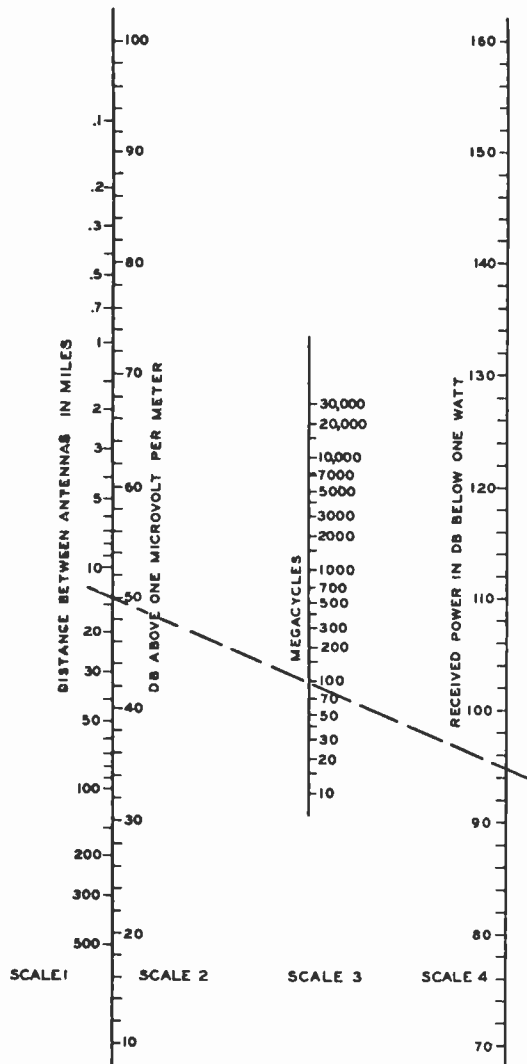


Fig. 1—Free-space field intensity and received power between half-wave dipoles, 1 watt radiated.

This field intensity in microvolts per meter for 1 watt of radiated power is shown on scale 2 of Fig. 1 as a function of the distance in miles shown on scale 1. For radiated power of P watts, the correction factor to apply to the field intensity or power is $10 \log P$ decibels. For example, the free-space field intensity at 100 miles from a half-wave dipole radiating 1 watt is 33 decibels above 1 microvolt per meter (about 45 microvolts per meter). When the radiated power is 50 watts (17 decibels above 1 watt), the received field intensity is $33+17$

$=50$ decibels above 1 microvolt per meter (about 315 microvolts per meter). It will be noted that the field intensity is related to the energy density of the radio wave at the receiving antenna, but is independent of the type of the receiving antenna.

The directivity gain of an array of n dipoles (sum of driven and parasitic elements) of optimum design is approximately equal to n times the gain of one dipole, although some allowance should be made for antenna power losses. The theoretical power-gain ratio of a horn, paraboloid, or lens antenna whose aperture has an area of B square meters is $g=4\pi B/\lambda^2$; however, the effective area is frequently taken as one-half to two-thirds of the actual area of the aperture to account for antenna inefficiencies.

III. RELATION BETWEEN THE RECEIVED POWER AND THE RADIATED POWER

Before discussing the modifications in the free-space field that result from the presence of the earth, it is convenient to show the relation between the received field intensity (which is not necessarily equal to the free-space field intensity) and the power that is available to the receiver. The maximum useful power P_2 that can be delivered to a matched receiver is given by

$$P_2 = \left(\frac{E\lambda}{2\pi} \right)^2 \frac{g_2}{120} \text{ watts} \quad (3)$$

where

E =received field intensity in volts per meter

λ =wavelength in meters $=300/F$

F =frequency in megacycles

g_2 =power-gain ratio of the receiving antenna.

This relation between received power and the received field intensity is shown by scales 2, 3, and 4 in Fig. 1 for a half-wave dipole. For example, the maximum useful power at 100 megacycles that can be picked up by a half-wave dipole in a field of 50 decibels above 1 microvolt per meter is 95 decibels below 1 watt.

A general relation for the ratio of the received power to the radiated power obtained from (1) and (3) is

$$\frac{P_2}{P_1} = \left(\frac{\lambda}{4\pi d} \right)^2 g_1 g_2 \left(\frac{E}{E_0} \right)^2 \quad (4)$$

When both antennas are half-wave dipoles, the power-transfer ratio is

$$\frac{P_2}{P_1} = \left(\frac{1.64\lambda}{4\pi d} \right)^2 \left(\frac{E}{E_0} \right)^2 = \left(\frac{0.13\lambda}{d} \right)^2 \left(\frac{E}{E_0} \right)^2 \quad (4a)$$

and is shown on Fig. 1 for free-space transmission ($E/E_0=1$).

When the antennas are horns, paraboloids, or multi-element arrays, a more convenient expression for the ratio of the received power to the radiated power is given by

$$\frac{P_2}{P_1} = \frac{B_1 P_2}{(\lambda d)^2} \left(\frac{E}{E_0} \right)^2 \quad (4b)$$

where B_1 and B_2 are the effective areas of the transmitting and receiving antennas, respectively. This relation is obtained from (4) by substituting $g = 4\pi B/\lambda^2$, and is shown on Fig. 2 for free-space transmission when $B_1 = B_2$. For example, the free-space loss at 4000 megacycles between two antennas of 10 square feet effective area is about 72 decibels for a distance of 30 miles.

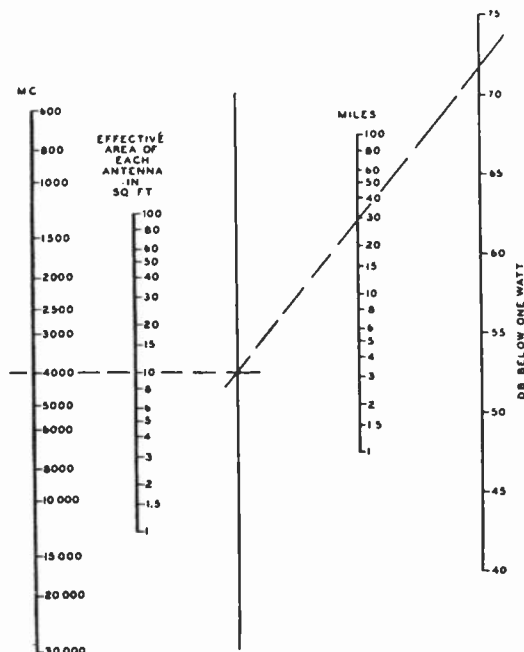


Fig. 2—Received power in free space between two antennas of equal effective areas, 1 watt radiated.

IV. TRANSMISSION OVER PLANE EARTH

The presence of the ground modifies the generation and the propagation of the radio waves so that the received field intensity is ordinarily less than would be expected in free space. The ground acts as a partial reflector and as a partial absorber, and both of these properties affect the distribution of energy in the region above the earth. The principal effect of plane earth on the propagation of radio waves is indicated by the following equation:^{4,5}

$$E = E_0 \left[\underbrace{1}_{\text{Direct Wave}} + \underbrace{R e^{j\Delta}}_{\text{Reflected Wave}} + \underbrace{(1-R) A e^{j\Delta}}_{\text{Surface Wave}} + \underbrace{\dots}_{\text{Induction Field and Secondary Effects of the Ground}} \right]. \quad (5)$$

R is the reflection coefficient of the ground and is ap-

proximately equal to -1 when the angle θ between the reflected ray and the ground is small. The commonly used concept of a *perfectly conducting* earth, for which the reflection coefficient for vertical polarization is $+1$ for any angle of incidence, may cause some misunderstanding at this point. In practice, the principal interest is in low angles, and as the angle θ approaches zero the reflection coefficient approaches -1 for any finite value for the conductivity of the earth, even if it were made of solid copper. The magnitude and phase of the reflection coefficient can be computed from the following equation:⁶

$$R = \frac{\sin \theta - z}{\sin \theta + z} \quad (6)$$

where

$$z = \sqrt{\epsilon_0 - \cos^2 \theta} / \epsilon_0 \text{ for vertical polarization}$$

$$z = \sqrt{\epsilon_0 - \cos^2 \theta} \text{ for horizontal polarization}$$

$$\epsilon_0 = \epsilon - j60\sigma\lambda$$

ϵ = dielectric constant of the ground relative to unity in free space

σ = conductivity of the ground in mhos per meter

λ = wavelength in meters

$$j = \sqrt{-1}$$

$$e^{j\Delta} = \cos \Delta + j \sin \Delta.$$

The quantity A is the surface-wave attenuation factor which depends upon the frequency, ground constants, and type of polarization. It is never greater than unity and decreases with increasing distance and frequency, as indicated by the following approximate equation:⁷

$$A \approx \frac{-1}{1 + j \frac{2\pi d}{\lambda} (\sin \theta + z)^2}. \quad (7)$$

⁴ It will be noted that for vertical polarization this expression agrees with the data given by Burrows and subsequently included in Terman's "Radio Engineer's Handbook," p. 699, first edition, but for horizontal polarization it is the negative of that given in these references. This change was necessary in order to make equations (5) and (6) independent of polarization. The pseudo-Brewster angle frequently mentioned in the literature occurs when the reflection coefficient is a minimum and is approximately equal to the value of θ for which $\sin \theta = |z|$; this occurs with vertical polarization only, since $z > 1$ for horizontal polarization. The reflection coefficient is sometimes modified by a divergence factor to give a first approximation of the effect of the curvature of the earth, but this additional complication does not seem essential here. The effect of the curvature of the earth is discussed in the next section, and for conditions of frequency and antenna height where some interpolation is required, the possible variations due to atmospheric conditions are usually greater than the error introduced by the omission of the divergence factor. The measured data on the plane-earth reflection coefficient agrees reasonably well with the theoretical values at frequencies below about 1000 megacycles. At higher frequencies the magnitude of the reflection coefficient is sometimes less than 1, presumably due to multiple reflections from the irregularities on the earth's surface. Measured values as low as -0.2 at 10,000 megacycles over rolling country have been reported by W. M. Sharpless. The low value of reflection coefficient is not expected to be important for ground-to-ground transmission, but it tends to smooth the lobes that occur in high-angle radiation and, hence, may be important in air-to-ground transmission.

⁷ This approximate expression is sufficiently accurate as long as $A < 0.1$, and it gives the magnitude of A within about 2 decibels for all values of A . However, as A approaches unity, the error in phase approaches 180 degrees. More accurate values are given by Norton, where in his nomenclature $A = f(P, B)e^{j\phi}$.

⁴ Charles R. Burrows, "Radio propagation over plane earth-field strength curves," *Bell Sys. Tech. Jour.*, vol. 16, pp. 45-75; January, 1947.

⁵ Kenneth A. Norton, "The propagation of radio waves over the surface of the earth and in the upper atmosphere, part II," *PROC. I.R.E.*, vol. 25, pp. 1203-1236; September, 1937.

The angle Δ used in (5) is the phase difference in radians resulting from the difference in the length of the direct and reflected rays. It is equal to $4\pi h_1 h_2 / \lambda d$ radians, when the distance d between antennas is greater than about five times the sum of the two antenna heights h_1 and h_2 .

The effect of the ground shown in (5) indicates that ground-wave propagation may be considered to be the sum of three principal terms; namely, the direct wave, reflected wave, and surface wave. The first two types correspond to our common experience with visible light, but the surface wave is less familiar. Since the earth is not a perfect reflector, some energy is transmitted into the ground and is absorbed. As this energy enters the ground, it sets up ground currents, which is another way of saying that the distribution of the electromagnetic field in the region near the surface of the earth is distorted relative to what it would have been over an ideal perfectly reflecting surface. The surface wave is defined as the vertical electric field for vertical polarization, or the horizontal electric field for horizontal polarization, that is associated with these ground currents.⁸ The practical importance of the surface wave is limited to a region above the ground of about 1 wavelength over land or 5 to 10 wavelengths over sea water, since for greater heights the sum of the direct and reflected waves is larger in magnitude. Thus the surface wave is the principal component of the total ground wave at frequencies less than a few megacycles, but it is of secondary importance in the very-high-frequency range (30 to 300 megacycles) and it usually can be neglected at frequencies above 300 megacycles.

A physical picture of the various components of the ground wave can be obtained from (5), but an equivalent expression which is more convenient for this discussion is

$$\frac{E}{E_0} = 2 \sin \frac{\Delta}{2} + j[(1 + R) + (1 - R)A]e^{j(\Delta/2)}. \quad (8)$$

When the angle $\Delta = 4\pi h_1 h_2 / \lambda d$ is greater than about 0.5 radian, the terms inside the brackets (which include the surface wave) are usually negligible, and a sufficiently accurate approximation is given by

$$\frac{E}{E_0} = 2 \sin \frac{2\pi h_1 h_2}{\lambda d}. \quad (8a)$$

In this case the principal effect of the ground is to produce interference fringes or lobes so that the field intensity, at a given distance and for a given frequency, oscillates around the free-space field as either antenna height is increased.

When the angle Δ is less than about 0.5 radian, the

⁸ Another component of the electric field associated with the ground currents is in the direction of propagation. It accounts for the success of the wave antenna at lower frequencies, but it is always smaller in magnitude than the surface wave as defined above. The components of the electric vector in three mutually perpendicular co-ordinates are given by Norton.

receiving antenna is below the maximum of the first lobe and the surface wave may be important. A sufficiently accurate approximation for this condition is⁹

$$\left| \frac{E}{E_0} \right| = \left| \frac{4\pi h_1' h_2'}{\lambda d} \right|. \quad (8b)$$

In this equation $h' = h + jh_0$ where h is the actual antenna height and $h_0 = \lambda / 2\pi z$ has been designated as the minimum effective antenna height. The magnitude of the minimum effective height $|h_0|$ is shown in Fig. 3 for sea water and for "good" and "poor" soil. "Good" soil corresponds roughly to clay, loam, marsh, or swamp, while "poor" soil means rocky or sandy ground.

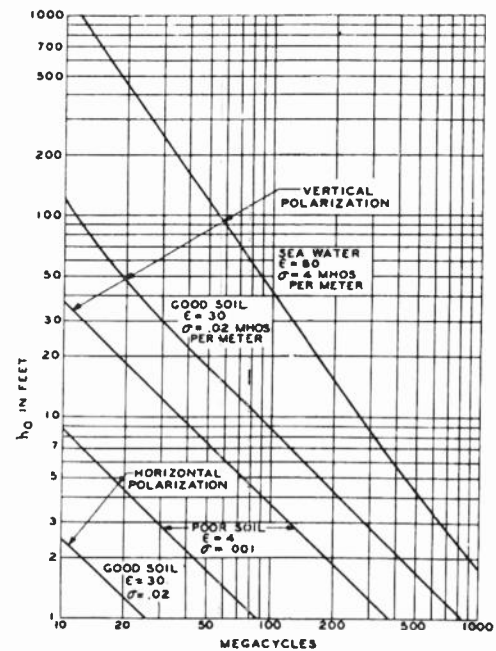


Fig. 3—Minimum effective height.

The surface wave is controlling for antenna heights less than the minimum effective height, and in this region the received field or power is not affected appreciably by changes in the antenna height. For antenna heights that are greater than the minimum effective height, the received field or power is increased approximately 6 decibels every time the antenna height is doubled until free-space transmission is reached. It is ordinarily sufficiently accurate to assume that h' is equal to the actual antenna height or the minimum effective antenna height, whichever is the larger.

The ratio of the received power to the radiated power

⁹ This approximate expression is obtained from (8) by assuming:

$$\sin \theta = \frac{h_1 + h_2}{d} \ll 1 \quad (1)$$

$$\sin \frac{2\pi h_1 h_2}{\lambda d} = \frac{2\pi h_1 h_2}{\lambda d} \quad (2)$$

$$A = -\frac{\lambda}{j2\pi d z^2} \quad (3)$$

for transmission over plane earth is obtained by substituting (8b) into (4), resulting in

$$\frac{P_2}{P_1} = \left(\frac{\lambda}{4\pi d}\right)^2 g_1 g_2 \left(\frac{4\pi h_1' h_2'}{\lambda d}\right)^2 = \left(\frac{h_1' h_2'}{d^2}\right)^2 g_1 g_2. \quad (9)$$

This relation is independent of frequency, and is shown on Fig. 4 for half-wave dipoles ($g = 1.64$). A line through the two scales of antenna height determines a point on the unlabeled scale between them, and a second line through this point and the distance scale determines the

watts is 24 decibels above 1 watt, the received power is $135.5 - 24 = 111.5$ decibels below 1 watt. (The free-space power transfer shown on Fig. 1 indicates a received power of $91 - 24 = 67$ decibels below 1 watt, so Fig. 4 is controlling.) The received field intensity can be obtained from Fig. 1, which shows that a received power of 111.5 decibels below 1 watt corresponds to a received field intensity of about 23 decibels above 1 microvolt per meter at a frequency of 30 megacycles. Should one antenna be only 10 feet above "good" soil, rather than 50 feet, the minimum effective height of 30 feet shown on Fig. 3 should be used on one of the height scales on Fig. 4 in determining the transmission loss. It will be noted that this example assumes a perfectly flat earth. The curvature of the earth introduces an additional loss of about 4 decibels, as discussed in the next section.

In addition to the effect of plane earth on the propagation of radio waves, the presence of the ground may affect the impedance of an antenna and thereby may have an effect on the generation and reception of radio waves. This effect usually can be neglected at frequencies above 30 megacycles, except where whip antennas are used. The impedance in the presence of the ground oscillates around the free-space value, but the variations are unimportant as long as the center of the antenna is more than a quarter-wavelength above the ground. A convenient method of showing the effect of the change in impedance of a balanced antenna near the ground is to replace the directivity gain g in the preceding formulas by the arbitrary factor of $g' = g/r$ where r is the ratio of the input resistance in the presence of the ground to the input resistance of the *same* antenna in free space. This assumes an impedance match between the antenna and the transmitting equipment with proper tuning to balance out any reactance.

For horizontal dipoles less than a quarter-wavelength above the ground, the ratio r is less than unity. It approaches zero as the antenna approaches a perfectly conducting earth, but in practice it does not reach zero at zero height because of the finite conductivity of the earth. The wave antenna and the top-loaded antenna frequently used at lower frequencies are sometimes called horizontal antennas, but since they are used to radiate or receive vertically polarized waves they are not horizontal antennas in the sense used here.

For vertical half-wave dipoles the factor r is approximately equal to unity, since the height of the center of the antenna can never be less than a quarter-wavelength above the ground. For very short vertical dipoles, however, the ratio r is greater than unity and it approaches a value of $r = 2$ for antennas very near to the ground. This means that, whereas a short vertical dipole whose total length $2l$ is small compared with the wavelength has an input radiation resistance of $80(\pi l/\lambda)^2$ ohms in free space, it has a resistance of $160(\pi l/\lambda)^2$ ohms near the ground.

Correct results for a vertical whip antenna working against a perfect counterpoise are obtained by using

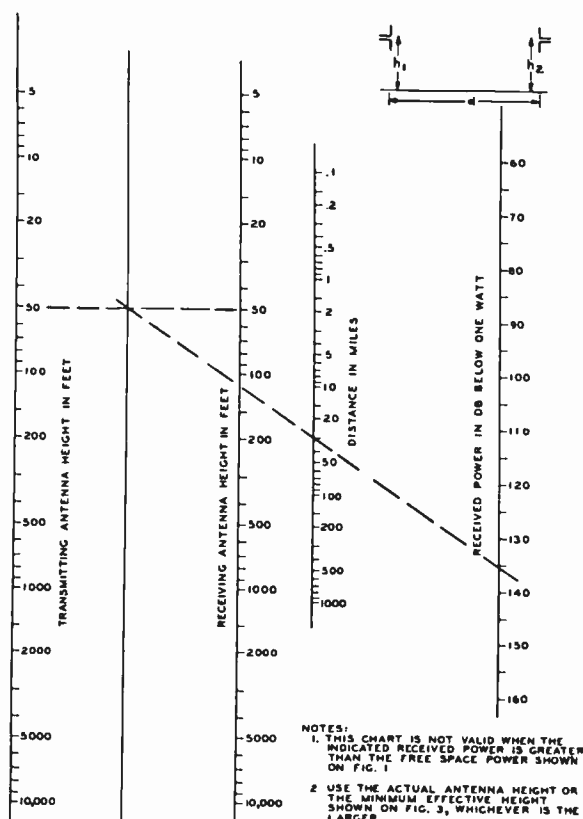


Fig. 4—Received power over plane earth between half-wave dipoles, 1 watt radiated.

received power for 1 watt radiated. When the received field intensity is desired, the power indicated on Fig. 4 can be transferred to scale 4 of Fig. 1, and a line through the frequency on scale 3 indicates the received field intensity on scale 2. The results shown on Fig. 4 are valid as long as the value of received power indicated is lower than shown on Fig. 1 for free-space transmission. When this condition is not met, it means that the angle Δ is too large for (8b) to be accurate and that the received field intensity or power oscillates around the free-space value as indicated by (8a).

As an example, consider a 250-watt, 30-megacycle transmitter with both transmitting and receiving dipoles mounted 50 feet above the ground and separated by a distance of 30 miles over *plane* earth. The transmission loss is shown on Fig. 4 to be 135.5 decibels. Since 250

$r=2$. This means that a vertical whip antenna of length l is 3 decibels less efficient than a dipole of length $2l$ (located more than a quarter-wavelength above the ground) for either transmitting or receiving. The power efficiency at the receiver is not important when external noise is controlling.

V. DIFFRACTION AROUND THE CURVATURE OF THE EARTH

Radio waves are bent around the earth by the phenomenon of diffraction, with the ease of bending decreasing as the frequency increases. Diffraction is a fundamental property of wave motion, and in optics it is the correction to apply to geometrical optics (ray theory) to obtain the more accurate wave optics. In other words, all shadows are somewhat "fuzzy" on the edges and the transition from "light" to "dark" areas is gradual, rather than infinitely sharp. Our common experience is that light travels in straight lines and that shadows are sharp, but this is only because the diffraction effects for these very short wavelengths are too small to be noticed without the aid of special laboratory equipment. The

sight, but it introduces an additional loss. The magnitude of this loss increases as either the distance or the frequency is increased and it depends to some extent on the antenna height. The loss resulting from the curvature of the earth is indicated by Fig. 5 as long as neither antenna is higher than the limiting value shown at the top of the chart. This loss is in addition to the transmission loss over plane earth obtained from Fig. 4.

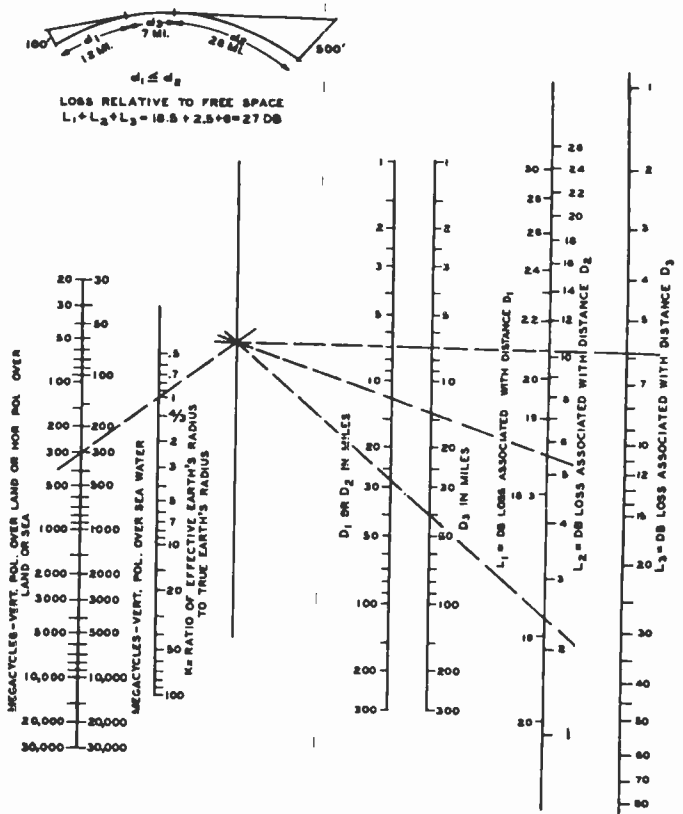


Fig. 5—Diffraction loss caused by curvature of the earth, assuming neither antenna height is higher than shown on scale A.

order of magnitude of the diffraction at radio frequencies may be obtained by recalling that a 1000-megacycle radio wave has about the same wavelength as a 1000-cycle sound wave in air, so that these two types of waves may be expected to bend around obstacles with approximately equal facility.

The effect of diffraction around the earth's curvature is to make possible transmission beyond the line-of-

Fig. 6—Decibel loss relative to free-space transmission at points beyond line-of-sight over a smooth earth.

For example, at 150 megacycles, with antenna heights of less than 175 feet, the curvature of the earth in a 50-mile land path introduces a loss of 22 decibels (for $k=1$) in addition to the loss over plane earth. (The losses for $k=1$ are pure diffraction phenomena which would occur even in a vacuum. In the next section it will be shown that atmospheric refraction may cause a similar effect, although the cause is different. The parameter k is introduced to account for refraction in the earth's atmosphere, so that Fig. 5 shows the combined effects of diffraction and refraction.)

When either antenna is as much as twice as high as the limiting value shown on Fig. 5, this method of correcting for the curvature of the earth indicates a loss that is too great by about 2 decibels, with the error increasing as the antenna height increases. An alternate method of determining the effect of the earth's curvature is given by Fig. 6. This method is derived in the Appendix and is approximately correct for any antenna

height, but it is theoretically limited in distance to points at or beyond the line-of-sight, assuming that the curved earth is the only obstruction. Fig. 6 gives the loss relative to free-space transmission (and hence is used with Figs. 1 or 2) as a function of three distances: d_1 is the distance to the horizon from the lower antenna, d_2 is the distance to the horizon from the higher antenna, and d_3 is the distance beyond the line-of-sight. In other words, the total distance between antennas $d = d_1 + d_2 + d_3$. The distance to the horizon is shown in Fig. 7 for various values of k and antenna height. As an example,

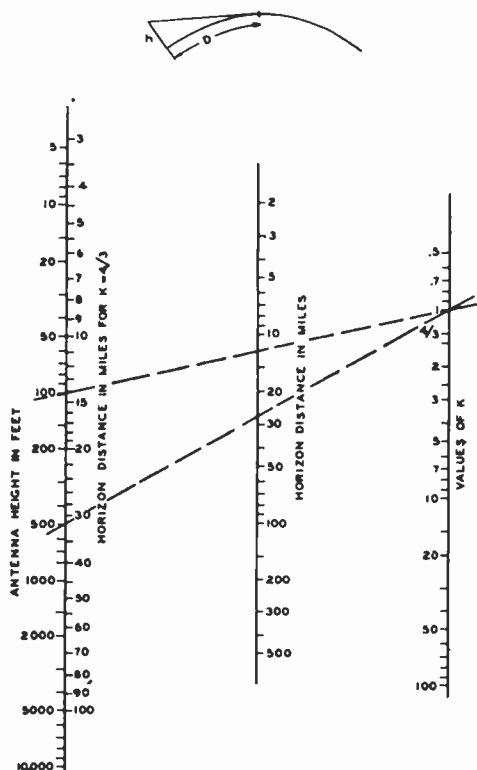


Fig. 7—Distance to the horizon.

consider a radio system operating at 300 megacycles over smooth earth with antenna heights of 500 and 100 feet. Fig. 7 indicates that $d_1 = 12$ miles and $d_2 = 28$ miles for a value of $k = 1$. Table I shows the loss relative to free-space transmission, as obtained from Fig. 6, for various distances at and beyond the line-of-sight.

In Table I, the estimated received power at line-of-sight is 21 decibels less than would be expected in free space, and it decreases about 0.8 decibels for each mile beyond line-of-sight. At distances well within line-of-sight, the earth can be considered flat. There is no accurate method of joining the curve for points well within line-of-sight to the curve for points beyond line-of-sight, but one or both of the following empirical methods may be helpful. The data for flat earth, given in Fig. 4, can be used at distances near grazing, provided that each antenna height is interpreted as the height above an im-

aginary plane drawn tangent to the earth at the point of reflection. An alternate method is to use Fig. 6 at points near grazing by considering the loss L_3 to be negative whenever d_3 is negative. In either case, the estimated received power should not be greater than would be obtained over flat earth.

For more accurate results at and beyond the line-of-sight, the field intensity or received power computed by means of Fig. 6 should be increased by

$$10 \log \left[\frac{1}{\sqrt{2}} \left(1 + \frac{d_1}{d_2} + \frac{d_3}{d_2} \right) \right]$$

decibels as long as one antenna height is higher than the value shown on the top of Fig. 5. In the region of antenna heights where Fig. 5 is applicable, it is easier to use and more accurate than the data on Fig. 6.

TABLE I
SAMPLE COMPUTATIONS BEYOND LINE-OF-SIGHT
300 Megacycles—Antenna Heights, 500 and 100 Feet

Miles				Decibel Losses			Decibel Loss in Addition to the Free-Space Loss
d	d_1	d_2	d_3	L_1	L_2	L_3	
40	12	28	0	18.5	2.5	0	21
45	12	28	5	18.5	2.5	4	25
50	12	28	10	18.5	2.5	8.5	29.5
55	12	28	15	18.5	2.5	13.5	34.5
60	12	28	20	18.5	2.5	19	40
65	12	28	25	18.5	2.5	24	45

VI. ATMOSPHERIC REFRACTION AND ABSORPTION

Thus far it has been assumed that the radio waves are traveling through a vacuum, or through an ideal atmosphere which has a dielectric constant of unity at all points and has zero absorption. Actually, the dielectric constant of the air is slightly greater than 1 and is variable. It depends on the pressure and temperature of the air and on the amount of water vapor present, so that it varies with weather conditions and with the height above the ground. The change in dielectric constant in several thousand feet is never more than a few parts in ten thousand, but this variation is sufficient to have an appreciable effect on radio propagation.

Whenever the dielectric constant varies with the height above the ground, the path of a radio wave deviates from a straight line. This change in direction is called refraction. A general solution of the problem which would allow any possible distribution of dielectric constant with the height above the ground at any point along the radio path is virtually impossible because of a large number of variables involved, so some simplifying assumptions are needed in order to obtain an engineering solution. The first assumption usually made is that of horizontal stratification, which means that for any given height the dielectric constant has the

same value at all distances along the radio path. Typical solutions based on this assumption have been worked out, but the problem is still too complex for most applications. A simple engineering solution can be obtained by making the additional assumption that the dielectric constant is a linear function of the height. On this basis, the effect of atmospheric refraction can be included in the expression of diffraction around the smooth earth (without discarding the useful concept of straight-line propagation) by multiplying the actual earth's radius by

$$k = \frac{1}{1 + \frac{a}{2} \frac{\Delta\epsilon}{\Delta h}}$$

where a is the radius of the earth and $\Delta\epsilon$ is the change in dielectric constant in going from height h to $h+\Delta h$. Physically, the phenomenon of refraction is entirely separate from the concept of diffraction discussed in the preceding section, although for computational purposes the two effects are combined by introducing the parameter k in Figs. 5 and 6.

The dielectric constant normally decreases with increasing height ($k > 1$) and the radio waves are bent toward the earth. However, under certain atmospheric conditions the dielectric constant may increase ($0 < k < 1$) over a reasonable height, thereby causing the radio waves in this region to bend away from the earth. Since the earth's radius is about 2.1×10^7 feet, a decrease in dielectric constant of only 2.4×10^{-8} per foot of height results in a value of $k = 4/3$, which is commonly assumed to be a good average value. When the dielectric constant decreases about four times as rapidly (or by about 10^{-7} per foot of height), the value of $k = \infty$. This means that, as far as radio propagation is concerned, the earth can be considered flat, since any ray that starts parallel to the earth will remain parallel.

When the dielectric constant decreases more rapidly than 10^{-7} per foot of height, radio waves that are radiated parallel to or at an angle above the earth's surface may be bent downward sufficiently to be reflected from the earth. After reflection the ray is again bent toward the earth, and the path of a typical ray is similar to the path of a bouncing tennis ball. The radio energy appears to be trapped in a duct or wave guide between the earth and the maximum height of the radio path. This phenomenon is variously known as trapping, duct transmission, anomalous propagation, or guided propagation. It will be noted that in this case the path of a typical guided wave is similar in form to the path of sky waves, which are lower-frequency waves trapped between the earth and the ionosphere. However, there is little or no similarity between the virtual heights, the frequencies, or the causes of refraction in the two cases.

In addition to the simple form of a duct where the earth is the lower boundary, trapping may also occur in an elevated duct. For example, assume an ideal case

where the curve of the dielectric constant versus the height above the ground can be represented by three straight lines. The lower segment corresponds to the height interval of 0 to 100 feet above the ground and in this region the dielectric constant decreases very slowly, or it may even increase. The middle segment corresponds to a height interval of 100 to 150 feet and in this region the dielectric constant decreases more rapidly than 10^{-7} per foot. The third section corresponds to heights greater than 150 feet and the dielectric constant decreases at a rate less than 10^{-7} per foot. In this ideal case it can be shown that most of the radio energy (at frequencies above about 300 megacycles) is trapped within a height interval of about 50 to 150 feet above the ground, and that the actual path for any given ray is approximately a sine wave whose axis is 100 feet above the ground.

The phenomenon of trapping is of considerable interest, but quantitative data on radio propagation in a duct are beyond the scope of this paper. The concept of an effective earth's radius used in Figs. 5 and 6 fails in this case because the parameter k is negative, and negative values are contrary to the original assumptions in diffraction theory. However, experience indicates that the received field intensity or received power is seldom greater than would be expected for plane earth ($k = \infty$), so this limitation is not expected to be serious.

Meteorological measurements indicate that the actual curve of dielectric constant versus the height above the ground is frequently a curved line which may have one or more sharp bends, rather than a straight line as required in using the concept of an effective earth's radius.¹⁰ Theoretical considerations indicate that this curve can be approximated with reasonable accuracy by a series of straight lines as long as each individual line corresponds to a change in height of not more than 20 to 50 wavelengths. At 30 megacycles, for example, the actual curve of dielectric constant versus height can be approximated by a number of straight lines, each of which has a slope corresponding to the average change in dielectric constant over a height interval of 600 to 1500 feet. Since most of the radio energy transmitted between two ground stations travels in the first of these height intervals, the concept of effective earth radius is a useful one and is sufficiently accurate at 30 megacycles. As the frequency increases, however, more than

¹⁰ The investigators in this field usually use M units rather than the dielectric constant. The M unit is defined as

$$M = \left(\sqrt{\epsilon} - 1 + \frac{h}{a} \right) 10^6$$

where ϵ is the dielectric constant at height h , and a is the radius of the earth. The M unit provides a number of convenient size (usually 200 to 500) and is modified by the term h/a for use on a flat earth diagram. The relation between the parameter k and M units is given by

$$k = \frac{10^6}{M'a} = \frac{.048}{M'}$$

where M' is the change in M units per foot of height.

one segment must be considered, since the straight-line approximation is valid over smaller and smaller height intervals. At 3000 megacycles, for example, this interval is only 6 to 15 feet, and the concept of effective earth radius becomes inadequate for analytical use. Considerable progress has been made toward formulating a method of correcting for atmospheric refraction that avoids these limitations, but the complexity of the problem and the amount of basic data required indicate that ordinarily a statistical study of fading ranges may be preferred to an analytical solution.

The experimental data on fading in the 30- to 150-megacycle range can be correlated reasonably well with the concept of effective earth's radius, if it be assumed that the value of k is rarely less than 0.8 and is seldom greater than 2 or 3. At higher frequencies the received signal at distances beyond the line-of-sight is seldom less than would be expected for $k=0.8$ and may be equal to or above the free-space value.¹¹ This means that the fading range at 3000 megacycles over a path 10 miles beyond the optical line-of-sight may be as much as 60 or 70 decibels. The per cent of time that the signal is either extremely high or extremely low depends on meteorological conditions, which, in turn, are functions of the geography and season of the year as well as the daily weather variations. Within the line-of-sight, the received power at frequencies above 2000 or 3000 megacycles may vary from several decibels above to 15 decibels or more below the free-space value, even over a good optical path. A good optical path is defined as one with full first-Fresnel-zone clearance, as discussed in the next section. The fading appears to be more severe over sea water than over land, but whether this difference results primarily from a difference in atmospheric conditions or from a difference in the reflecting properties of sea water and land has not been clearly established.

The atmosphere not only affects the direction of a radio wave but also it may introduce some absorption in the transmission path. The presence of rain, snow, or fog introduces an additional attenuation which depends on the amount of moisture and on the frequency. During a rain of cloudburst proportions the attenuation at 10,000 megacycles (3 centimeters) may reach 5 decibels per mile, and at 30,000 megacycles (1 centimeter) it may be in excess of 25 decibels per mile.^{12,13} In addition to the effect of moisture, some selective absorption may result from the oxygen, nitrogen, and other components of the atmosphere. The first absorption peak due to water vapor occurs at a wavelength of about 1.25

centimeters and the first peak for oxygen occurs at about 0.5 centimeters. These absorption bands are well known at frequencies of infrared and visible light, and are to be expected as the radio spectrum is extended to higher frequencies.

VII. TRANSMISSION OVER SHARP RIDGES

The preceding discussion assumes that the earth is a perfectly smooth sphere. The modification in these results caused by the presence of hills, trees, and buildings is difficult or impossible to compute, but the order of magnitude of these effects may be obtained from a consideration of the other extreme case, which is propagation over a perfectly absorbing knife edge.

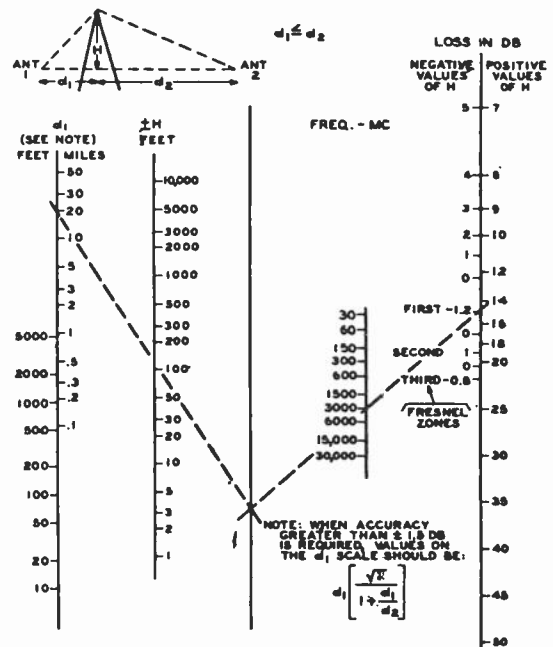


Fig. 8—Shadow loss relative to free space.

The diffraction of plane waves over a knife edge or screen causes a shadow loss whose magnitude is shown on Fig. 8.¹⁴ The height of the obstruction H is measured from the line joining the two antennas to the top of the ridge. It will be noted that the shadow loss approaches 6 decibels as H approaches 0 (grazing incidence), and that it increases with increasing positive values of H . When the direct ray clears the obstruction, H is negative, and the shadow loss approaches 0 decibels in an oscillatory manner as the clearance is increased. In other words, a substantial clearance is required over line-of-sight paths in order to obtain "free-space" transmission.

There is an optimum clearance, called the first-Fresnel-zone clearance, for which the transmission is theoretically 1.2 decibels better than in free space. Phys-

¹¹ The theory of trapping would indicate that the received signal may be considerably higher than indicated by free-space transmission. Instantaneous peaks of 18 to 20 decibels above free space have been reported, but the average signal is greater than 3 or 4 decibels above the free-space value for only a small percentage of the total time.

¹² S. D. Robertson and A. P. King, "The effect of rain upon the propagation of waves in the 1- and 3-centimeter regions," *Proc. I.R.E.*, vol. 34, pp. 178-180; April, 1946.

¹³ G. E. Mueller, "Propagation of 6-millimeter waves," *Proc. I.R.E.*, vol. 34, pp. 181-183; April, 1946.

¹⁴ The theory of diffraction over a knife edge is discussed in several textbooks including J. C. Slater and N. H. Frank, "Introduction to Theoretical Physics," McGraw-Hill Book Co., New York, N. Y. 1933, pp. 315-323.

ically, this clearance is of such magnitude that the phase shift along a line from the antenna to the top of the obstruction and from there to the second antenna is about $\frac{1}{2}$ wavelength greater than the phase shift of the direct path between antennas. When this phase difference is 1 wavelength, the path clears the first two Fresnel zones, and there is theoretically a loss of about 1 decibel relative to free space. Similarly, when the phase difference is $3/2$ wavelengths the path clears the first three Fresnel zones, and this is a gain of about 0.8 decibel relative to free space. The locations of the first three Fresnel zones are indicated on the right-hand scale on Fig. 8, and by means of this chart the required clearances can be obtained. At 3000 megacycles, for example, the direct ray should clear all obstructions in the center of a 40-mile path by about 120 feet to obtain full first-zone clearance. The corresponding clearance for a ridge 100 feet in front of either antenna is 4 feet. Should the ridge project above the direct path by 4 feet, the shadow loss is about 15 decibels. It will be noted that the effective clearance obtained on a particular path will vary with the weather conditions, since the effect of atmospheric refraction is neglected in Fig. 8.

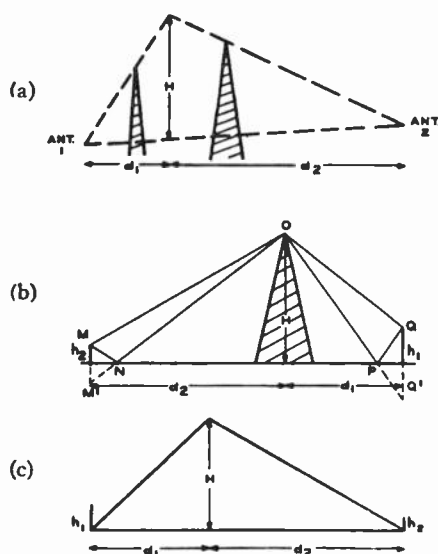


Fig. 9—Ideal profiles used in developing theory of diffraction over hills.

The problem of two or more knife-edge obstructions between the transmitting and receiving antennas, such as is shown in Fig. 9(a), has not been solved rigorously. However, graphical integration indicates that the shadow loss for this case is equivalent within 2 or 3 decibels to the shadow loss for the knife edge represented by the height of the triangle composed of a line joining the two antennas and a line from each antenna through the top of the peak that blocks the line-of-sight from that antenna.

Thus far it has been assumed that the transmission between the two antennas would be approximately the

same as in free space, if the obstacles could be removed. This assumption is usually valid only at centimeter wavelengths, and at lower frequencies it is necessary to include the effects of waves reflected from the ground. This results in four paths, namely, MOQ , MOQ' , $M'OQ$, and $M'OQ'$, shown on Fig. 9(b) for a single obstruction. Each of these paths is similar in form to the single path illustrated by Fig. 9(a). The sum of the field intensities over these four paths, considering both magnitude and phase, is given by the following equation:

$$\left| \frac{E}{E_0} \right| = S_1 \left[1 - \frac{S_2}{S_1} e^{-j(\Delta+b)} - \frac{S_3}{S_2} e^{-j(\Delta+c)} + \frac{S_4}{S_1} e^{-j(b+c)} \right] \quad (12)$$

where

E = received field intensity

E_0 = free-space field intensity

S_1 = magnitude of the shadow loss over path MOQ

S_2 = magnitude of the shadow loss over path MOQ'

S_3 = magnitude of the shadow loss over path $M'OQ$

S_4 = magnitude of the shadow loss over path $M'OQ'$

$\Delta = 4\pi h_1 h_2 / \lambda (d_1 + d_2)$ radians

b is approximately equal to $4\pi h_2 H / \lambda d_2$ radians

c is approximately equal to $4\pi h_1 H / \lambda d_1$ radians.

This equation assumes that the reflection coefficient is -1 and that the actual antenna heights are greater than the minimum effective antenna height h_0 . This means that the surface wave is neglected, and the equation fails when either antenna height approaches zero. The angles b and c are phase angles associated with the diffraction phenomena, and the approximate values given above assume that H is greater than h_1 or h_2 . This assumption permits the shadow losses to be averaged so that $S_1 = S_2 = S_3 = S_4 = S$. After several algebraic manipulations, (12) can be reduced to

$$\left| \frac{E}{E_0} \right| = 2(2S) \left| \sin \frac{\Delta}{2} \cos \frac{b-c}{2} + j \left(\sin^2 \frac{b+c}{4} - \sin^2 \frac{b-c}{4} \right) e^{j(\Delta/2)} \right| \quad (13)$$

where S is the average shadow loss for the four paths. This means that the shadow triangle should be drawn from a point midway between the location of the actual antenna and the image antenna, as shown in Fig. 9(c). For small values of H this equation is approximately equal to

$$\left| \frac{E}{E_0} \right| = 2(2S) \sin \frac{\Delta}{2} \quad (14)$$

Since the field intensity over plane earth (assuming that the antenna heights are greater than the minimum effective height h_0) is $2E_0 \sin \Delta/2$, the first-order effect of

the hill is to add a loss of $20 \log 2S$ decibels, which is shown by the nomogram on Fig. 10.

The complete expression given in (12) indicates that, under favorable conditions, the field intensity behind sharp ridges may be greater than over plane earth. This result has been found experimentally in a few cases, but the correlation between theory and experiment is not

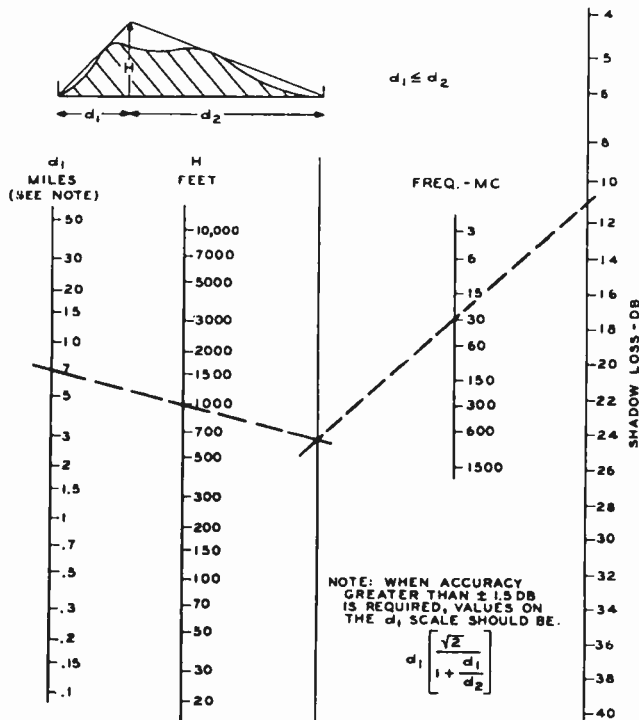


Fig. 10—Shadow loss relative to smooth earth.

complete. In general, the field intensity predicted by either (12) or (13) tends to be too high; that is, shadow losses rather than gains occur on most of the paths on which measured data are available. The less-approximate expression given in (14) agrees more closely with experimental data, is more conservative, and is easier to use. Consequently, it is usually assumed that the effect of obstructions to line-of-sight transmission (at least in the 30- to 150-megacycle range), is to introduce the loss shown on Fig. 10 in addition to the normal loss over smooth earth for the antenna heights and distances involved. Measured results on a large number of paths in the 30- to 150-megacycle range indicate that about 50 per cent of the paths are within 5 or 6 decibels of the values predicted on this basis. The correlation on 10 per cent of the paths is no better than 10 to 12 decibels, and an occasional path may differ by 20 decibels.

VIII. MISCELLANEOUS FACTORS AFFECTING PROPAGATION

The height of an antenna located over plane earth is the height of the center of the antenna above ground level. Locating an antenna on a hill which slopes down-

ward toward the distant terminal usually increases the received power. The magnitude of this improvement can be estimated by assuming that the effective antenna height (for use on Fig. 4) is the difference in elevation between the antenna and the bottom of the hill, *providing* that first-Fresnel-zone clearance is obtained over the immediate foreground. At 30 megacycles this means a clearance of about 20 feet at a distance of 20 feet, 40 feet at a distance of 100 feet, 90 feet at a distance of 500 feet, etc. The required clearance decreases as the square root of the wavelength, and may be obtained from Fig. 8. When these clearances are not met, it is convenient to assume that the effective antenna height is the difference in elevation between the antenna and the point where the actual profile intercepts the curve of required clearance (first Fresnel zone).

Built-up areas have little effect on radio transmission at frequencies below a few megacycles, since the size of any obstruction is usually small compared with the wavelength, and the shadows caused by steel buildings and bridges are not noticeable except immediately behind these obstructions. However, at 30 megacycles and above, the absorption of a radio wave in going through an obstruction and the shadow loss in going over it are not negligible, and both types of losses tend to increase as the frequency increases. The attenuation through a brick wall, for example, may vary from 2 to 5 decibels at 30 megacycles and from 10 to 40 decibels at 3000 megacycles, depending on whether the wall is dry or wet. Consequently most buildings are rather opaque at frequencies of the order of thousands of megacycles. Shadow losses at street level in the downtown area of large cities may be of the order of 30 decibels or more at frequencies in the 30- to 150-megacycle range, and the received power may vary 15 to 20 decibels within a few feet because of wave interference caused by multiple-path transmission. As the frequency increases the number of possible multiple paths also increase, so that there is some tendency to fill in the deep shadow regions. This means that the average shadow loss at street level may not increase as rapidly with frequency as the shadow loss behind an isolated ridge, and this is one reason for limiting the distance scale on Fig. 10 to values greater than 0.1 mile.

When an antenna is surrounded by moderately thick trees and below tree-top level, the average loss at 30 megacycles resulting from the trees is usually 2 or 3 decibels for vertical polarization and is negligible with horizontal polarization.¹⁵ However, large and rapid variations in the received field intensity may exist within a small area, resulting from the standing-wave pattern set up by reflections from trees located at a distance of as much as 100 feet or more from the antenna. Consequently, several near-by locations should be inves-

¹⁵ National Defense Research Council Report, Division 13, "Effect of hills and trees as obstructions to radio propagation," C. M. Jansky and S. L. Bailey; November, 1943.

tigated for best results. At 100 megacycles the average loss from surrounding trees may be 5 to 10 decibels for vertical polarization and 2 or 3 decibels for horizontal polarization. The tree losses continue to increase as the frequency increases, and above 300 to 500 megacycles they tend to be independent of the type of polarization. Above 1000 megacycles trees that are thick enough to block vision present an almost solid obstruction, and the diffraction loss over or around these obstructions can be obtained from Fig. 8.

IX. MINIMUM ALLOWABLE INPUT POWER

The effective use of the preceding data for estimating the received power requires a knowledge of the power levels needed for satisfactory operation, since the principal interest is in the signal-to-noise ratio. The signal

been adjusted so that most of peaks of speech power can be transmitted without causing overmodulation in the transmitter. It follows that the required input power for a single-channel voice circuit is of the order of 140 decibels below 1 watt, which is roughly equivalent to 1 microvolt across a 70-ohm input resistance. This limiting input power is approximately correct (within 3 or 4 decibels) for both amplitude and frequency modulation, since the radio-frequency signal-to-noise ratio must be above that required for marginal operation before the use of frequency modulation can provide appreciable improvement in the audio signal-to-noise ratio.

The input power must be greater than 140 decibels below 1 watt when circuits of above marginal quality or greater bandwidth are desired, and when external noise rather than set noise is controlling. Man-made noise is

TABLE II
FIGURES TO USE

Type of Terrain	Both Antennas Lower in Height than Shown on Fig. 5	One or Both Antenna Heights Higher than Shown on Fig. 5	
		Within Line- of-Sight	Beyond Line- of-Sight
Plane earth Smooth earth Irregular terrain	Fig. 4 or 1 Figs. 4 and 5 Figs. 4, 5, and 10	Figs. 4 or 1 or 2 Figs. 4 or 1 or 2 Figs. 4 and 10 or 1 or 2 and 8	Figs. 1 or 2 and 6 Figs. 1 or 2 6 and 10

level required at the input to the receiver depends on several factors, including the noise introduced by the receiver (called first-circuit or set noise), the type and magnitude of any external noise, the type of modulation, and the desired signal-to-noise ratio. A complete discussion of these factors is beyond the scope of this paper, but the fundamental limitations are listed below in order to show the order of magnitude. The theoretical minimum noise level is that set by the thermal agitation of the electrons, and its root-mean-square power in decibels below 1 watt is 204 decibels minus $10 \log$ (bandwidth) where (bandwidth) is approximately equal to twice the audio (or video) bandwidth.¹⁶ The set noise of a typical receiver may be 5 to 15 decibels higher than the theoretical minimum noise. The lower values in this range of "excess" noise are more likely to be met in the very-high-frequency range, while the higher values are more probable in the super-high-frequency range. This means that the set noise in a 3000-cycle audio band may be 151 to 161 decibels below 1 watt. Measured data indicate that the carrier power needs to be 12 to 20 decibels higher than the noise power to provide an average signal-to-noise ratio that is sufficient for moderate intelligibility. This assumes that the modulation level has

frequently controlling at 30 megacycles, but is less serious at 150 megacycles. Above 500 megacycles, set noise is almost always controlling. For circuits requiring a high degree of reliability, a margin should also be included for the fading range to be expected during adverse weather conditions.

X. SUMMARY AND EXAMPLES

In any given radio propagation problem some of the factors described above are important, while others can be neglected. Table II indicates the figures that apply to any given situation.

Whenever Fig. 4 is used, reference should be made to Figs. 1 and 3 as a check on its proper use. When Fig. 10 is used in determining the effects of hills, the profile is usually drawn on rectangular co-ordinates (neglecting the earth's curvature), and the shadow triangle is drawn to the base of the antenna (half way between the antenna and its image). Curved co-ordinates are sometimes used, but they are not necessary since the loss caused by the curvature of the earth is either negligible or has already been considered in Figs. 5 or 6. Fig. 8 is used for determining the first-zone clearance and for estimating the shadow losses, when the transmission without the obstruction is expected to be the same as in free space. In the latter case, the shadow triangle is

¹⁶ Harald T. Friis, "Noise figures of radio receivers," *Proc. I.R.E.*, vol. 32, pp. 419-422; July, 1944.

drawn from the actual antennas, and curved co-ordinates are useful since the curvature of the earth should be included in the profile.

Various examples of the use of these figures have been given during the discussion of each individual chart, but further examples may help to illustrate the relations between the various figures. Assume a transmitting dipole located 250 feet above the ground and a receiving dipole on a 30-foot mast. The estimated transmission losses at 30, 300, and 3000 megacycles over smooth earth are shown on Fig. 11 for $k=4/3$ for various distances between these two dipoles. The solid lines indicate values obtained from the figures and the dashed lines show the region where some interpolation is required.

The received power depends on the radiated power and the antenna-gain characteristics, as well as on the transmission loss between dipoles. A typical 30-megacycle transmitter may radiate 250 watts, so that at a

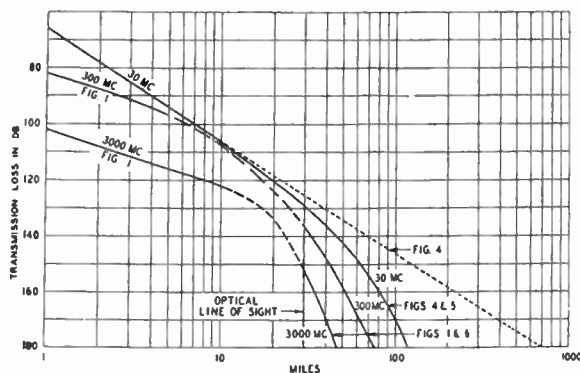


Fig. 11—Transmission over smooth earth at 30, 300, and 300 megacycles; half-wave dipoles at 250 and 30 feet.

distance of 30 miles the received power is $10 \log 250 - 129 = 105$ decibels below 1 watt. (The value of 129 decibels is obtained from Fig. 11.) Similarly, a 300-megacycle transmitter may radiate 50 watts from a 5-decibel antenna, and when a 5-decibel receiving antenna is used the estimated received power at 30 miles is $10 \log 50 + 5 + 5 - 137 = 110$ decibels below 1 watt. At 3000 megacycles the radiated power may be 0.1 watt and antenna gains of 28 decibels each are not uncommon, so the received power at 30 miles is $10 \log 0.1 + 28 + 28 - 152 = 106$ decibels below 1 watt. (The values of radiated power used in this example are not the maximum continuous-wave powers that can be obtained, but the downward trend with increasing frequency is a characteristic of the available tubes.)

Over irregular terrain it is assumed that the shadow loss based on knife-edge diffraction theory is to be added to the transmission loss obtained from smooth-earth theory. The computation of shadow losses for the profile shown on Fig. 12(a) is given in Table III.

The estimated transmission loss for 30 and 300 megacycles, including the shadow loss from Table III, is

shown by the solid lines on Fig. 12(b), while the dashed lines are the corresponding values over smooth earth taken from Fig. 11. Superimposed on these average val-

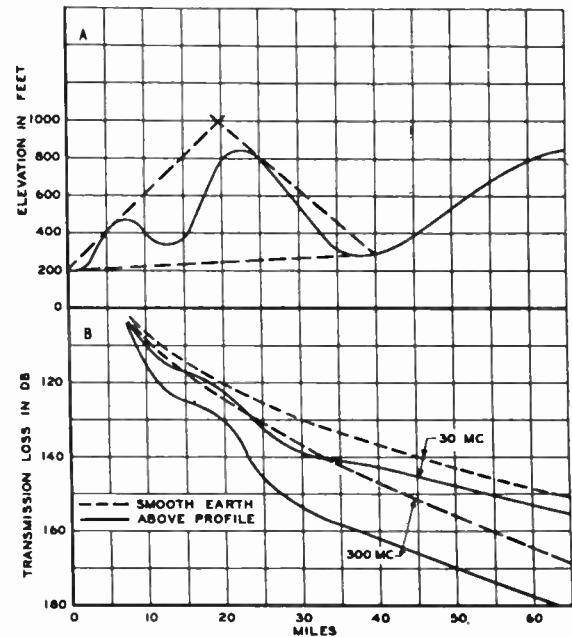


Fig. 12—Transmission loss over irregular terrain at 30 and 300 megacycles; half-wave dipoles at 250 and 30 feet.

ues will be unpredictable variations of ± 6 to 10 decibels resulting from the effects of trees and buildings and from profile irregularities that were smoothed out in drawing the profile shown in Fig. 12(a).

TABLE III
SHADOW-LOSS COMPUTATIONS

Miles from Transmitter	H (feet)	d_1 (miles)	Shadow Loss in Decibels Obtained from Fig. 10	
			30 megacycles	300 megacycles
12.5	200	4.5	3.5	9
20	70	6.5	2	4
25	310	4.5	5.5	13
35	750	14.5	7	16
40	760	20	6	14
50	610	18	5	12
60	490	16.5	4.5	11

APPENDIX

DERIVATION OF DIFFRACTION LOSS BETWEEN ELEVATED ANTENNAS

The derivation of the method shown in Fig. 6 for determining the effect of the curvature of the earth is based on the data in the appendix to the paper by Burrows and Gray,¹ and their nomenclature is used in the following discussion.

The best available equation for radio propagation over spherical earth below the line of sight is

$$\frac{E}{E_0} = (8\pi\zeta_a)^{1/2} \left| \sum_{s=0}^{\infty} f_s(h_1)f_s(h_2) \frac{\exp(-i\tau_s\zeta_a)}{\delta + 2\tau_s} \right| \quad (15)$$

where the parameters τ_s are functions of the ground constants and the height functions $f_s(h)$ are independent of the distance between antennas. The other symbols are defined below:

$$\zeta_a = \frac{2\pi d}{\lambda} = \zeta_1 + \zeta_2 + \zeta_3$$

$$\left(\frac{2\pi k a}{\lambda} \right)^{2/3}$$

$$\delta = z^2 \left(\frac{2\pi k a}{\lambda} \right)^{2/3}$$

d = distance between antennas

a = radius of the earth

λ = wavelength

k = ratio of $\frac{\text{effective earth's radius}}{\text{true earth's radius}}$

$$z = \frac{\sqrt{\epsilon_0 - 1}}{\epsilon_0} \text{ for vertical polarization}$$

$$= \sqrt{\epsilon_0 - 1} \text{ for horizontal polarization.}$$

The height function $f_s(h_1)$ can be represented by

$$f_s(h_1) = \frac{3}{\sqrt{2\pi\zeta_1}} \frac{\exp(i\tau_s\zeta_1)N_1}{\sqrt{-2\tau_s}[J_{1/3}(z_s) + J_{-1/3}(z_s)]} \quad (16)$$

where

$$\zeta_1 = \frac{2\pi d_1}{\lambda} = \left(\frac{2\pi k a}{\lambda} \right)^{2/3}$$

$d_1 = \sqrt{2ka}h_1$ = distance to horizon from antenna height h_1

z_s is a function of τ_s .

The factor N_1 is approximately equal to 1 for values of $\zeta_1 > 6$, but its value for $\zeta_1 < 6$ is still to be determined.

Substituting the value of $f_s(h_1)$ given in (16) and a similar one for $f_s(h_2)$ into (15) results in

$$\left| \frac{E}{E_0} \right| = \sqrt{\frac{\zeta_a}{8\pi\zeta_1\zeta_2}} N_1 N_2 \sum_{s=0}^{\infty} 4[\delta + 2\tau_s] \left[\frac{\exp\left(-\frac{i\tau_s}{2}(\zeta_a - \zeta_1 - \zeta_2)\right)}{1/3\sqrt{-2\tau_s}[J_{1/3}(z_s) + J_{-1/3}(z_s)][\delta + 2\tau_s]} \right]^2 \quad (17)$$

The quantity inside the second pair of brackets after the summation sign is in the same form as in (4a) in the paper by Burrows and Gray,¹ so that their solution

$[L(\delta)F_L]$ can be substituted in the above equation, resulting in

$$\frac{E}{E_0} = \sqrt{\frac{\zeta_1 + \zeta_2 + \zeta_3}{8\pi\zeta_1\zeta_2}} N_1 N_2 [2F_{L/2}]^2 [L(\delta)]^2 \delta \quad (18)$$

when $\delta \gg \tau_s$.

This step involves the assumption that

$$\sum_{s=0}^{\infty} A_s^2 = \left[\sum_{s=0}^{\infty} A_s \right]^2$$

where A_s is any function of s . This assumption is not justifiable in the general case, but in this instance it affects the loss L_s (shown on Fig. 6) only in the region near

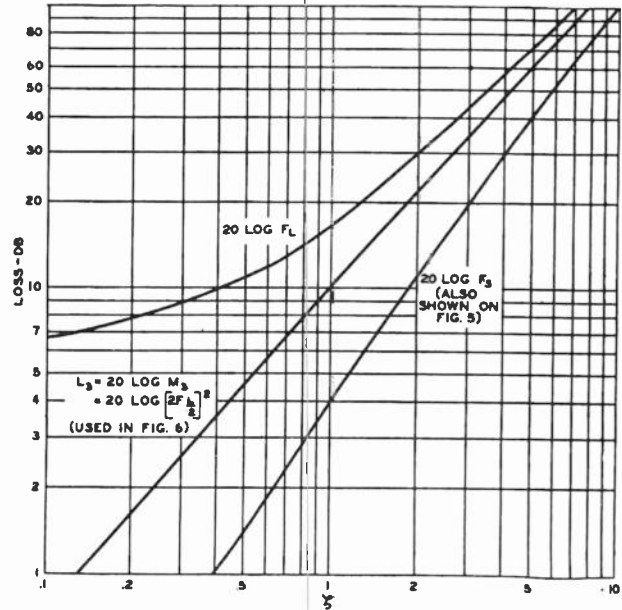


Fig. 13—Attenuation factors used in theory of diffraction over smooth earth.

the line-of-sight. When the loss L_s is greater than about 30 decibels, the first term ($s=0$) is accurate within one or two decibels; when the loss L_s is less than 30 decibels (which occurs near the line-of-sight), the above assumption may introduce an error of about ± 3 decibels. Since these possible errors are no greater than the effect of a small change in the assumed value of the parameter k , the over-all accuracy is not greatly impaired, and this procedure simplifies the problem considerably.

The parameter $20 \log F_L$ (taken from Fig. 10 of the Burrows and Gray paper) is shown on Fig. 13 as a function of ζ_3 , since $L = \zeta_3$ for large values of δ . Also, for large values of δ , $L(\delta) = 1/\sqrt{\delta}$. Consequently, (18) reduces to

$$\frac{E}{E_0} = \sqrt{\frac{1 + \frac{d_1}{d_2} + \frac{d_3}{d_2}}{8\pi\zeta_1}} N_1 N_2 M_s$$

$$= \left[\frac{N_1}{\sqrt{5.656\pi\zeta_1}} \right] [N_2] [M_s] \left[\frac{1}{\sqrt{2}} \left(1 + \frac{d_1}{d_2} + \frac{d_3}{d_2} \right) \right]^{1/2} \quad (19)$$

where $M_3 = [2F_{L/2}]^2$ and $20 \log M_3$ is plotted in Fig. 13. The term in the first set of brackets is a function of d_1 (since N_1 depends on d_1 but is independent of d_2 and d_3); the factor in the second set of brackets is a function of d_2 ; and the factor in the third set of brackets is a function of d_3 . The fourth term is small, *providing* that d_1 is defined as the distance to the horizon from the *lower* antenna, and it ordinarily can be neglected.

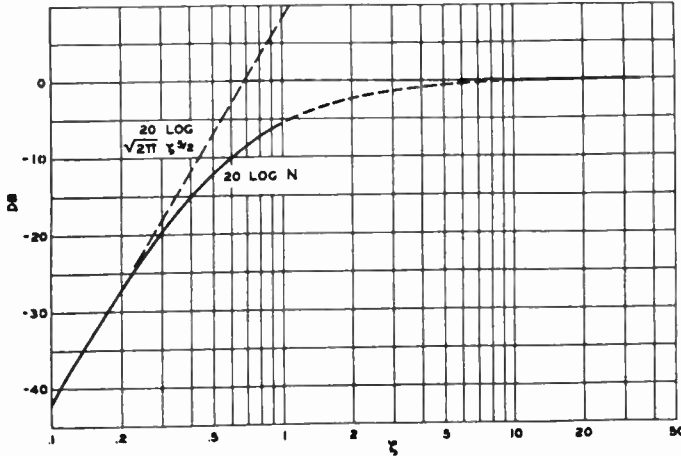


Fig. 14—Values of N .

The factor N is equal to unity when ζ is greater than about 6, but more information about the factor N is required in order that (19) can be used at lower antenna heights. When one antenna is high so that $\zeta_2 > 6$, and the other antenna low ($\zeta_1 < 1$), (19) at line-of-sight reduces to

$$\frac{E}{E_0} = \frac{N_1}{\sqrt{8\pi\zeta_1}}.$$

A solution to this same problem is given by Burrows and Gray (19) which can be shown to be equivalent to

$$\frac{E}{E_0} = \frac{\zeta_1^2}{2}.$$

By setting these two expressions equal it is found that

$$N_1 = \sqrt{2\pi\zeta_1^{5/2}} \quad (20)$$

for low values of ζ_1 .

The asymptotic value of $20 \log \sqrt{2\pi\zeta_1^{5/2}}$ is shown by the dashed line on the left side of Fig. 14, while the other asymptotic value of $20 \log N=0$ for high antenna heights is also shown by a dashed line. The true value of N must be a smooth curve or a family of curves joining these two asymptotic values.

A second method for determining the magnitude of N is to assume a grazing path with two antennas of equal height. This means that $\zeta_1 = \zeta_2$; $N_1 = N_2$; $\zeta_s = 2\zeta_1$. For this case (19) reduces to

$$\frac{E}{E_0} = \frac{N_1^2}{\sqrt{4\pi\zeta_1}}.$$

Another solution to this problem is well known for the case of $\zeta_1 < 1$. It is

$$\frac{E}{E_0} = \frac{4\pi h_1 h_2}{\lambda d} F_s = \frac{\zeta_1^2 \zeta_2^2}{2\zeta_s} F_s.$$

where F_s is the diffraction loss caused by the curvature of the earth when both antennas are near the ground. The value of $20 \log F_s$ is shown on Fig. 13 as a function of ζ_s and is also given by the nomogram in Fig. 5. By setting these two expressions equal, it is found that

$$\frac{N_1^2}{\sqrt{4\pi\zeta_1}} = \frac{\zeta_1^4}{4\zeta_1} F_s$$

$$N_1^2 = \sqrt{\frac{\pi}{4}} \zeta_1^{7/2} F_s.$$

$$\text{or } 20 \log N_1 = -0.5 + 35 \log \zeta_1 + 10 \log F_s \quad (21)$$

where F_s is a function of $2\zeta_1$.

The value of $20 \log N_1$ is shown on Fig. 14, as a function of ζ_1 (or N_2 as a function of ζ_2). The values of N for the range of $0.3 < \zeta < 1$ have been computed from (21). (The quantity ζ_1 is greater than 0.3 whenever the antenna height is greater than 50 feet at 30 megacycles, or greater than 10 feet at 300 megacycles.) The values of N in the range of $1 < \zeta < 6$ have been interpolated, but there seems little chance of serious error in this procedure.

In the nomogram on Fig. 6, the decibel loss

$$L_1 = 20 \log \frac{N_1}{\sqrt{5.656\pi\zeta_1}},$$

the decibel loss $L_2 = 20 \log N_2$, and the decibel loss $L_3 = 20 \log M_3$.

Radio Propagation Above 40 MC Over Irregular Terrain*

JOHN J. EGLI†

Summary—Radio transmissions in the vhf and uhf frequency region over land areas always contend with the irregularities of the terrain and the presence thereon of dispersed quantities of trees, buildings, and other man-made structures, or wave propagation incumbrances. The determination of path attenuation is not easily satisfied by simple, curved, or plane earth calculations. However, quantitative wave propagation data are available in varying degrees which take into account conditions experienced by fixed-to-fixed and fixed-to-moving transmissions over irregular terrain. This available statistical wave propagation information on terrain effects vs frequency, antenna height, polarization, and distance is analyzed, expressed by empirical formulas, and presented in the form of nomographs and correction curves amenable for use by the systems engineer.

INTRODUCTION

RADIO transmissions above 40 mc more often than not take place over irregular terrain so that the ordinary method of calculating propagation attenuation over plane earth, curved earth, and simple diffraction edges becomes unsatisfactory. As one moves about in irregular terrain in a vehicle, the received signal is characterized by a slow variation dependent on the major features of the terrain and on distance, and by a

fast variation about the median in a small sector which is independent of the transmission distance but is dependent on the speed of the vehicle and on the frequency of the transmission.

In the practical sense, the systems engineer is interested in knowing how well his equipment will be able to service an area, or how well his equipment will cover many areas in a very large area. Some of these areas may typify curved earth while other areas may be highly mountainous; all others will be in between these areas in terms of surface irregularity.

This irregular terrain has dotted on it, trees, buildings, and other man-made wave propagation encumbrances. If one could run the entire gamut of terrain conditions in a statistical manner and arrive at the transmission loss which would have to be designed into a system at a given frequency to provide the desired coverage, it would appear that such information would be invaluable to the systems engineer.

Fortunately, such data have been collected and studied by the Federal Communications Commission for use in connection with their studies of the vhf and uhf television allocation problems, and by others in connection with mobile service.

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The majority of the terrain data,¹ on which the following material will be derived, are based on survey data taken by commercial organizations in various parts of the country including New York, N. Y.; Washington, D. C.; Cleveland, and Toledo, Ohio; Harrisburg, Easton, Reading, Pittsburgh, and Scranton, Pa.; Kansas City, Mo.; Cedar Rapids, Iowa; San Francisco, Calif.; Bridgeport, Conn.; Nashville, Tenn.; Fort Wayne, Ind.; Richmond and Norfolk, Va.; and Newark, N. J. In each of these locations, a number of radials were investigated. In all, over the uhf range, 288 to 910 mc, 804 miles on 63 radials are represented in the data. The method of measurement, while not the same at all locations, falls into three categories: continuous mobile recording sampling every 0.2 mile, spot measurements properly weighted so as to be considered unbiased, and clusters of measurements. In the vhf region, 50 to 250 mc, approximately 1400 measurements, consisting of continuous data analyzed over 1-mile and 2-mile sectors, are included in the data.

In discussing service area, we will be concerned with expressing the percentage of locations one could expect to cover statistically at a predescribed distance. Thus, if one arbitrarily divides a 10-mile circle into 100 equal parts with each division represented by a point (location) and superimposes this configuration on the statistically derived landscape represented by the data, then 10 per cent coverage would mean that 10 of the points (locations) would receive satisfactory or better transmissions, while at the balance of the points reception would not be possible. Likewise, when considering 90 per cent coverage, 90 of the 100 points would receive transmissions while the balance would have no reception.

Actually, in dividing the circle into 100 locations, it was assumed that these locations represented the median value of signals in the immediate vicinity of the location, since one finds that in the immediate vicinity of a given location, say a few hundred feet, there will be fine variations in received field strength.

TERRAIN-FREQUENCY, DISTANCE DEPENDENCE

The theoretical plane earth field strength expression is given by

$$E = \frac{h_t h_r f}{95 d^2} \sqrt{P_t}$$

where

E = field intensity in microvolts per meter
 h_t = transmitting antenna height in feet
 h_r = receiving antenna height in feet

¹ H. Fine, "UHF Propagation Within Line of Sight," FCC, TRR Rep. No. 2.4.12; June 1, 1951. Contains material taken from K. A. Norton, M. Schulkin, and R. S. Kirby, "Ground Wave Propagation Over Irregular Terrain at Frequencies Above 50 MC," Ref. C, Rep. of the Ad Hoc Committee of the FCC for the Evaluation of the Radio Propagation Factors Concerning the Television and Frequency Modulation Broadcasting Services in the Frequency Range Between 50 and 250 MC; June 6, 1949.

f = transmission frequency in megacycles
 d = distance from transmitter in miles
 P_t = effective radiated power in watts.

Eq. (1) is limited to those geographical areas which are similar to plane earth, such as relatively short over-water and very flat barren land paths. Even in these areas man has erected bridges, Texas towers, billboards, and so forth, which alter considerably the propagation characteristics as expressed by the theoretical plane earth formula.

While the theoretical received field strength increases with frequency, all other constraints being the same, it is important to note that the voltage across the input to a receiver will be the same at all frequencies when the receiving antenna is a half-wave dipole. However, if the antenna at the higher frequency is constructed so that it presents an effective area equal to that of the half-wave dipole at the lower frequency, then this increased field strength at the higher frequency will be realized as increased voltage at the input to the receiver.

The measured field strength data¹ over irregular terrain were compared with what one could expect over plane earth rather than curved earth, since the best median field strength data fit for distances up to 30 to 40 miles shows that the inverse distance squared trend for plane earth is better than the curved earth field, at least for low antenna heights. Beyond 30 miles to 40 miles the data are sufficiently meager as to be unworthy of analysis as a representative quantity of data. Therefore, the median field at a given frequency can be described by the theoretical plane earth field intensity, less the median deviation therefrom. This median deviation data from the theoretical plane earth field, called terrain factor, is shown in Fig. 1. The straight line on this figure very nearly passes through all the FCC data, and it will be noted that the deviation from the plane earth field strength varies inversely with the frequency and is independent of distance. The intersection of this line with the theoretical plane earth field strength is at 40 mc, so that the variation with frequency is with respect to this frequency.

With this statistical information, (1) becomes empirically for the median field at the 50 percentile locations, E_{50} , independent of frequency

$$E_{50} = \frac{40 h_t h_r}{95 d^2} \sqrt{P_t} \quad (2)$$

This E_{50} field strength may be obtained quickly from the nomograph, Fig. 2.

The theoretical plane earth received power between half-wave dipoles (3) is independent of frequency.

$$P_r = 0.345 \left(\frac{h_t h_r}{d^2} \right)^2 P_t \times 10^{-14} \quad (3)$$

Making use of the power law variation with frequency for the median deviation from the theoretical plane

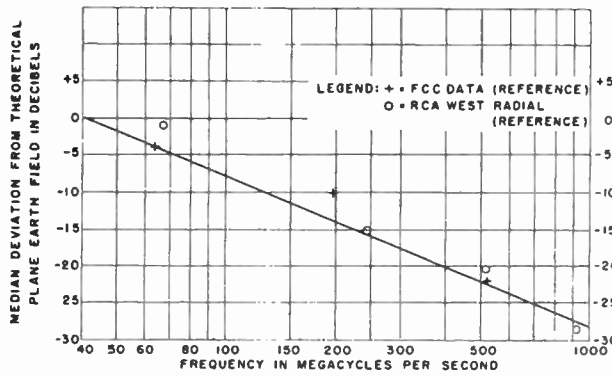


Fig. 1—Median terrain factor for fixed-to-vehicular or mobile service.

earth field, Fig. 1, (3) becomes empirically,

$$P_{50} = 0.345 \left(\frac{h_t h_r}{d^2} \right)^2 \left(\frac{40}{f} \right)^2 P_t \times 10^{-14}. \quad (4)$$

Eqs. (2) and (4) show that nature, by interposing terrain features, has essentially placed in juxtaposition the frequency dependence of the field strength and received power above 40 mc over plane earth. Thus, while the theoretical received field strength over plane earth increases with frequency, the median received field intensity above 40 mc over irregular terrain is independent of frequency, and while the theoretical received power between half-wave dipole antennas is independent of frequency, over irregular terrain the median received power above 40 mc varies inversely as the frequency squared.

For the purpose of the systems engineer, in making irregular terrain calculations it is preferable to use the plane earth received power (3) shown in nomographic form in Fig. 2, in its theoretical form because field strength, median value statistically derived, and received power theoretically derived are, at this point of exploration of irregular terrain propagation, independent of frequency.

It is interesting to note that if one determines from diffraction theory the depth of hills² which will result in the median loss of Fig. 1, the statistical irregular terrain can be conceived as hills with a depth of about 500 feet. It is also interesting to note that the New York west radial terrain over which data are available³ has an irregular depression of about 500 feet, 12 miles in extent and distance from the transmitter. Most of the data were accumulated in this portion of the radial, and the median values below plane earth theory are shown in Fig. 1 as the composite for the entire radial.

At this point in the paper it will be well to assume a rather simple problem and use it as a means of exemplifying the development of the material to be presented.

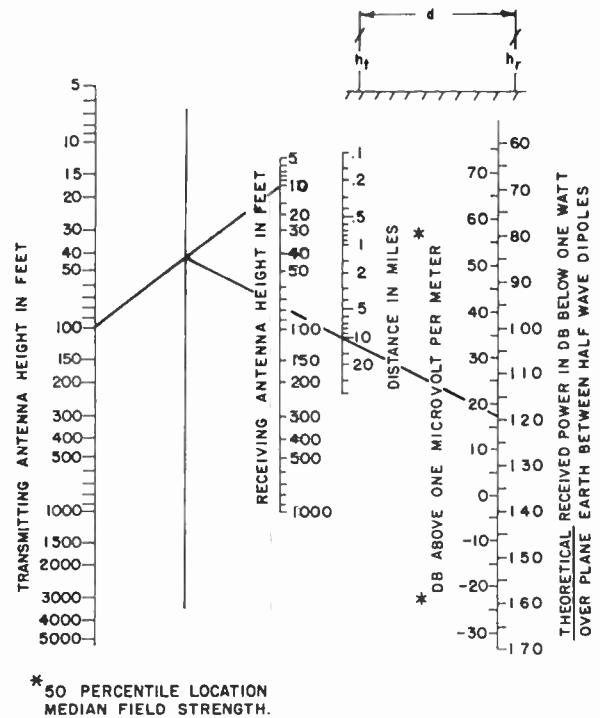


Fig. 2—Received power over plane earth and 50 per cent location median field strength—one watt radiated.

Assume:

- Transmission frequency, 150 mc
- Dipole antennas, half-wave
- Transmitting antenna height, 100 feet
- Receiving antenna height, 10 feet
- Service range, 10 miles
- Service to 90 per cent of locations at 10 miles
- 50 kc IF bandwidth
- Suburban noise
- No transmission line losses.

Required: Transmitter power output.

The theoretical received power in db below one watt will be from Fig. 2, 119 dbw. The field strength at 50 per cent of the locations, Fig. 2, will be 17.5 db above one microvolt per meter, one watt radiated.

TERRAIN-FREQUENCY DEPENDENCE

If one explores the data¹ in terms of the distribution of received field strength over irregular terrain, one finds that the over-all terrain distribution when plotted in decibels above the theoretical plane earth attenuation, is log-normally distributed. Thus, on probability paper, the terrain distribution will appear linear and may be described by its median value and standard deviation, Fig. 3. The terrain distribution of field intensity in the vhf band, taken at a center frequency of 127.5 mc appears to have an over-all standard deviation of 8.3 db, while the terrain distribution of field intensity in the uhf region centered around 510 mc, appears to have an over-all standard deviation of 11.6 db. Of course, the median deviation from theoretical plane earth field is

¹ K. Bullington, "Radio propagation variations at vhf and uhf," *Proc. IRE*, vol. 38, pp. 27-32; January, 1950.

² G. G. Brown, J. Epstein, and D. W. Peterson, "Comparative propagation measurements; television transmitters at 67.25, 288, 510 and 910 megacycles," *RCA Rev.*, vol. 9, pp. 171-201; June, 1948.

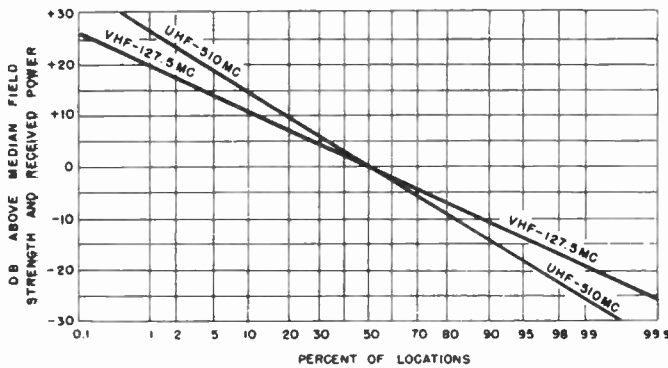


Fig. 3—VHF and uhf terrain distribution.

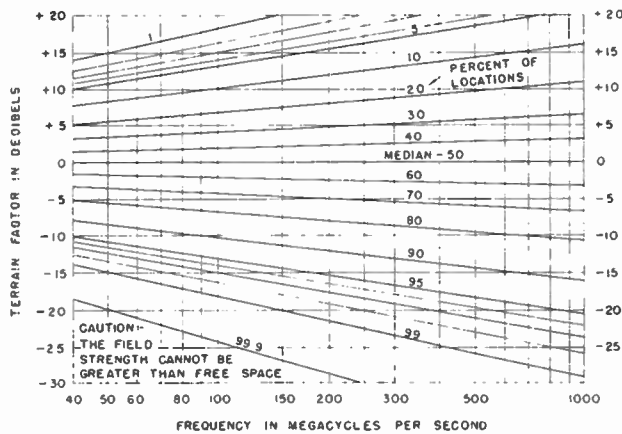


Fig. 4—Fixed-to-vehicular or mobile service field strength terrain factor.

displaced 12 db by the terrain factor for the two frequencies, Fig. 1. From this standard deviation data, Fig. 4 has been prepared which permits the determination of the correction factor to the E_{50} field strength when the received field strength to other than the 50 percentile location is desired. For example, as previously determined, E_{50} was 17.5 db above one microvolt per meter. Applying the terrain correction factor of -11.5 db for the 90 percentile location results in a median received field strength at the 90 percentile location of 6 db above one microvolt per meter, one watt radiated. This value of field strength does not exceed the free space value for 10 miles of 53 db above one microvolt per meter obtained from Fig. 5. Under conditions of greatly increased antenna heights and/or service to a small percentile of locations, the calculated field strength could exceed the free space field. If such is the case, the free space field should be used. It is interesting to note that while the median field strength (2) and terrain factor for 50 per cent of the locations (Fig. 4), are independent of frequency, for percentages of locations less than 50, the field strength increases with frequency, and for $E_{2.3}$ the field strength varies as $f^{1/2}$. Likewise for percentages of locations greater than 50, the field strength decreases with frequency and for $E_{97.7}$ varies inversely as $f^{1/2}$.

Likewise, Fig. 6 has been prepared to reflect the cor-

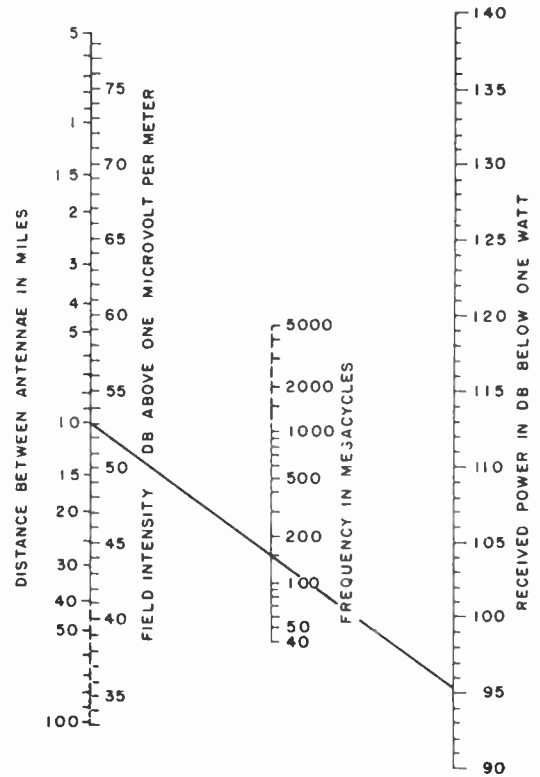


Fig. 5—Free space—one watt radiated between half-wave dipoles.

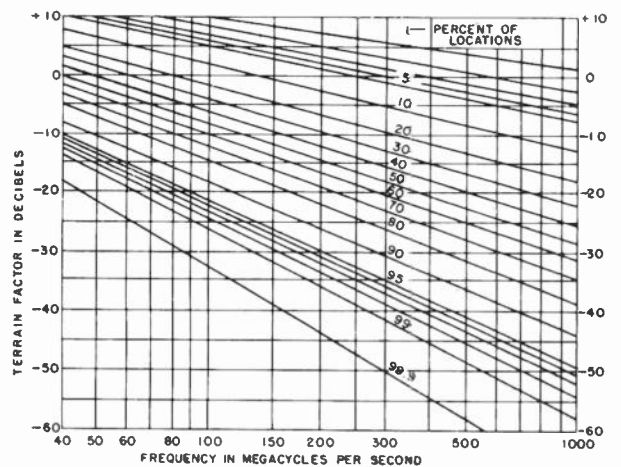


Fig. 6—Received power terrain factor for fixed-to-vehicular or mobile service.

rection factor to the theoretical plane earth received power imposed by irregular terrain. The P_{50} value follows an inverse frequency squared relation as per (4), at $P_{97.7}$ an inverse frequency cubed relation, and at $P_{2.3}$ an inverse frequency relation. As previously determined, the theoretical received power is -119 dbw. The terrain correction factor for the 90 percentile location at 150 mc is -23 db, and the received power at this location will be -142 dbw, or the half-wave dipole-to-half-wave-dipole path attenuation for this degree of service is 142 db. The free space received power is -95.4 dbw from Fig. 3 which exceeds that for the 90 percentile location.

TERRAIN-TRANSMITTING ANTENNA HEIGHT DEPENDENCE

The transmitting antenna height, used in conjunction with the data¹ is defined as the height above the median, 2–10 mile terrain level. This rule has not proven as reliable as one might expect, since it does not take into account the terrain within 2 miles or beyond 10 miles. For purposes of this report the effective height of the antenna will be the height of the antenna above plane earth. In actual practice the transmitting antenna heights could be taken as the effective height above local terrain. For all practical purposes, the data confirmed that the received field strength increased linearly with transmitting antenna height. Transmitter height-gain tests made around the New York area⁴ seem to indicate that in poor service locations the effect of transmitting antenna height increase is somewhat less than one would theoretically predict. In median or 50 percentile locations the height gain would approximate the theoretical expected height gain, and for good service locations the height gain would be somewhat more than the theoretical. For purposes of this paper, the formulas and nomographs reflect a linear high gain for transmitting antenna height.

TERRAIN-RECEIVING ANTENNA HEIGHT DEPENDENCE

Receiving antenna height is the effective height above local terrain. The data do not appear to support any clear-cut variation of field strength with change in receiving antenna height. For receiving antennas which clear surrounding terrain features, the height gain appears to be linear. For receiving antennas which do not clear the surrounding terrain features, no orderly pattern is discernible. However, test results analyzed statistically,¹ show that in the 6 to 30 feet category, the field strength appears to support a square-root height gain variation. Above 30 feet, the height gain is linear. This variation is reflected in the nomograph of Fig. 2.

In practice, when using low antenna heights, as pointed out in the New York tests,⁴ the dependence of field strength upon receiving antenna height is quite variable. When locating in a given area, within the confines of available antenna height, the maximum field strength should be found.

TERRAIN FADING

Both the vhf and uhf studies indicate that the time fading is much smaller for the distances involved than the terrain variation, and may be neglected as a power balance factor in equipment design. In the fear of being misunderstood, suppose equipment is designed for vehicular operation to cover 90 per cent of the locations, at

10 miles from the transmitter. Based on statistical terrain data, the variation in median signal throughout the terrain is far in excess of what the long-time fading would be between two fixed locations. However, fading becomes important for fixed service work. A subscriber land-based for an extended period of time in a poor location, marginal signal, might well compensate for the long-time fading which will ensue by moving to the optimum spot in the small area in which he is to be located, and also by having means for elevating his antenna, which can now be changed to a directional antenna, to the optimum height within the height-raising capability of his antenna system. These two expedients should compensate for time fading and be reflected in a highly reliable transmission circuit.

TERRAIN-ANTENNA POLARIZATION

Theoretically, over plane earth at antenna heights greater than a wavelength and for small angles between the direct and reflected rays, as is the case for irregular terrain transmissions, polarization has negligible effect on the behavior of radio waves above 40 mc. Experimental evidence^{5,6} over irregular terrain of the received characteristics of polarized waves appears in general to verify the above. While it appears that vertical polarization is somewhat better directly behind hills or deep in the shadow area, horizontally polarized waves afford better reception in back of, but away from, the deep shadows of hills. In wooded areas, the attenuation is less for horizontally polarized transmissions than for vertically polarized transmissions below 300 to 500 mc. In total, little difference can be detected in the average propagation characteristics.

There is one exception to the latter statement and it concerns propagation using antenna heights less than one wavelength. In this case the ground wave is dominant and theoretically vertical polarization provides an apparent height gain over horizontal polarization.⁷ This effect is shown in Fig. 7 and pertains only to vertical polarization since for horizontal polarization the effective height is essentially the actual height at frequencies above 40 mc. As shown in Fig. 7, the effective height also depends on the conductivity of the soil over which the transmission will be effective. Unfortunately, as far as the author knows, terrain-statistical data are lacking on the propagation effects resulting from the use of very low vertically polarized antenna heights in the lower vhf region. Until such time as this theoretical information can be placed in dispute statistically by tests, it is

⁵ J. S. McPetrie and J. A. Saxton, "An experimental investigation of the propagation of radiation having wavelengths of 2 and 3 meters," *J. IEE*, vol. 87, pp. 146–153; August, 1940.

⁶ J. A. Saxton and B. N. Harden, "Ground-wave field-strength surveys at 100 and 600 mc/s," *Proc. IEE*, vol. 101, part 3, pp. 215–221; July, 1954.

⁷ K. Bullington, "Radio propagation at frequencies above 30 megacycles," *Proc. IRE*, vol. 35, pp. 1122–1136; October, 1947.

⁴ J. Epstein and D. W. Peterson, "An experimental study of wave propagation at 850 mc," *Proc. IRE*, vol. 41, pp. 595–611; May, 1953.

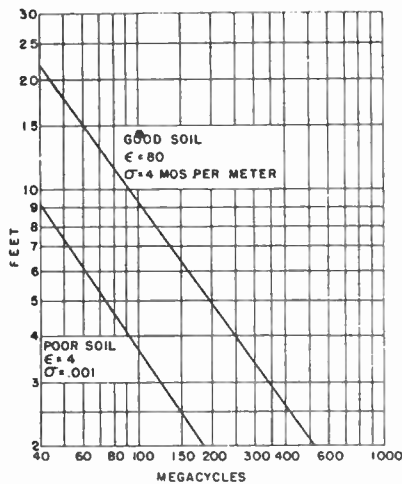


Fig. 7—Minimum effective antenna height for vertical polarization.

proposed that when vertically polarized transmissions are under consideration, Fig. 7 be used in finalizing the effective height of low antennas.

In our problem at 150 mc with an antenna height of 10 feet it can be seen from Fig. 7 that even with vertical polarization this height is also the effective height. If the problem had been one of transmission at 40 mc, then in using Fig. 2 the height would have remained the same for poor soil conditions, but would have to be taken as 23 feet over good soil conditions.

TERRAIN-SMALL SECTOR FIELD STRENGTH VARIATION

As noted earlier, there is a fine amplitude variation about the median in a small distance or area which is independent of the distance from the radiation source. Some studies indicate that these fine variations of field strength have a normal distribution¹ which appears to be independent of frequency with a standard deviation of 5.5 db. Other studies,⁸ indicate a Rayleigh distribution, Fig. 8. The latter appears more likely because the studies which indicate a normal distribution were taken over distances which perhaps exceeded the small sector variation. However the Rayleigh type fading may only occur and be applicable in areas replete with buildings, etc. In open areas the distribution may be log-normal over a small sector. Between the 10 and 90 per cent values of these distributions there is very little difference in the two distributions. The amplitude distribution is the same at all frequencies indicating that the range of constructive and destructive phase interference or standing wave effects is complete. However, the number of constructive and destructive interferences increases in a given distance or area with frequency.

Tests⁹ conducted in the Phoenix, Ariz. area indicate that the average vehicle travel between these fine signal

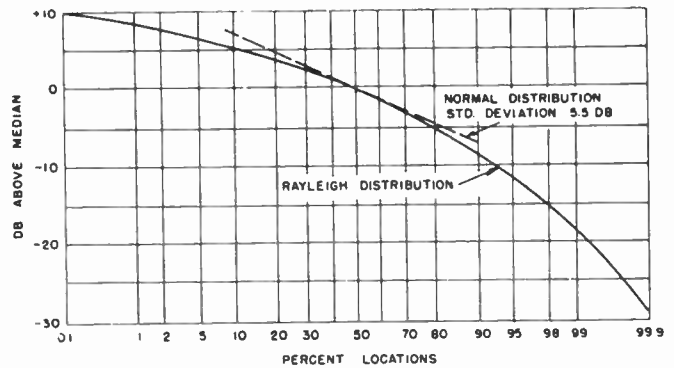


Fig. 8—Terrain-small sector variation.

minima is one wavelength in free space, while in the direction away from or toward the radiation, the distance between signal minima is the free space half-wave distance. With this information, in vehicular service the small sector amplitude fluctuations in received carrier level will increase in rapidity with frequency and the speed of the vehicle, or

$$A = \frac{v}{\lambda/2}, \text{ and in practical terms, } A = 0.003 fv \quad (5)$$

where A is the average amplitude fluctuation rate in cps, f is the radio carrier frequency in mc, and v is the velocity of the vehicle in the direction of transmission in miles per hour. For ready use, (5) has been prepared in the form of a nomograph, Fig. 9. It shows, for example, that at 150 mc the received field in a vehicle traveling at 40 miles per hour in the direction of transmission would have an average fluctuation rate of 18 cps. For vehicular service, this is the rate which would have to be considered in the design of age circuitry with the audio or intelligence pass band designed above this frequency.

The small sector variations at 90 mc¹⁰ appear to be small in open flat country and much greater in built-up areas as might be expected. The variations in built-up and treed areas appear greater for vertically polarized transmissions than for horizontally polarized transmissions.

Another characteristic of these variations which one would expect is that the higher the frequency, the steeper the fall and rise in field strength. In general, the variations appear to be deeper with the time between rise and fall smaller. Maximum envelopes occurring during a test⁹ are shown in Fig. 10. At 15 db down, the "outage time" on 459 mc may be in the order of a few milliseconds at vehicle speeds of 40 miles per hour with perhaps no noticeable effect on speech transmissions, whereas at 156 mc the outage time at this level could cause the loss of voice information.

Unfortunately, data were not found which would permit an expression either quantitatively or qualitatively as to the useful distribution or design point criteria of

¹ W. R. Young, Jr., "Mobile radio transmission compared at 150 to 3700 mc," *Bell Sys. Tech. J.*, vol. 31, pp. 1068-1085; November, 1952.

⁸ C. F. Meyer and D. Soule, "Field Strength Study," Motorola, Inc.; February, 1956. Work performed under Signal Corps Contract DA-36-039-sc-64737.

¹⁰ H. L. Kirke, R. A. Rowden, and G. I. Ross, "A vhf field-strength survey on 90 mc/s," *Proc. IEE*, vol. 98, part 3, pp. 343-359; September, 1951.

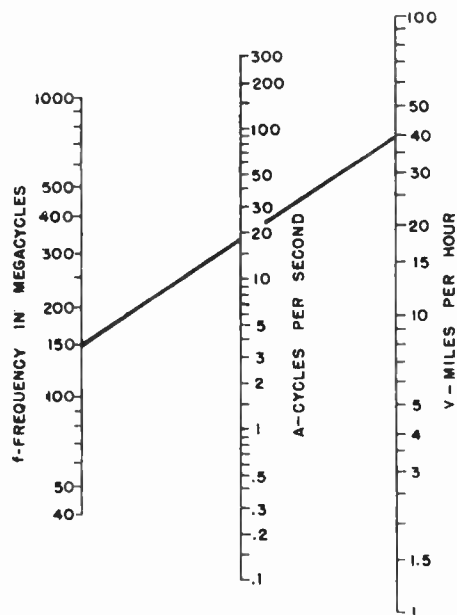


Fig. 9—Fluctuations in vehicles.

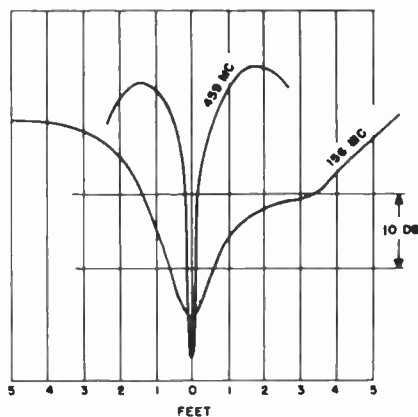


Fig. 10—Maximum small sector variation.

these small sector field strength variations. It may well be, at least for the present, that equipment should be designed to the median value of these fine grain variations for the percentage of locations service desired.

TERRAIN-WIDE MODULATION BANDWIDTH EFFECTS

The field strength variations discussed so far have been those taken over a very narrow bandwidth of the transmission frequency. On wide-band systems distortion effects may be introduced resulting from propagation via more than one path. These distortions may cause cross talk in multichannel voice systems, or shadows in television reception. This subject will be touched on lightly because not very much statistical data are available nor is literature available on the effects of multipath propagation on various types of modulation. The severity of multipath distortion¹¹ ap-

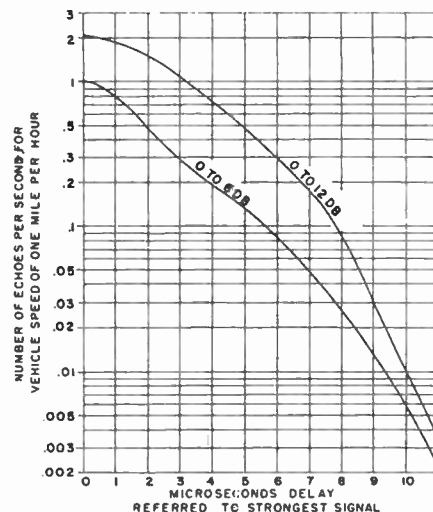


Fig. 11—Echoes in vehicles from a fixed transmission.

pears qualitatively to be independent of frequency and wave polarization, at least within the frequency range of 60 to 3300 mc. The consequences of multipath propagation are not serious for fixed transmission conditions, yet may be very serious in moving situations. For fixed service, movements of the receiving antenna either horizontally or vertically for a distance in the order of a few wavelengths ordinarily cleans up multipath distorted patterns in television reception. More multipath distortion appears in highly built-up and mountainous areas where large off-path reflecting surfaces are present. Directive antennas greatly reduce multipath effects,¹¹ which means that for equal antenna apertures, the use of the higher frequencies will result in less multipath distortion.

The only good statistical results, unfortunately unrelated to all of the terrain data made use of herein and therefore not representative of all the conditions on which this paper is based, are based on tests in the New York area,¹² where one encounters considerable, and perhaps the worst, multipath propagation conditions. In order to understand the difficulties one may encounter in engineering vehicular wide band systems, the New York data,¹² have been altered (Fig. 11) to reflect the number of echoes per second for a vehicle speed of one mile per hour vs delay of these echoes with amplitudes between 0 and 6 db less than the strongest received signal. Thus a remote television transmitter installed in a vehicle patrolling New York at 30 miles per hour would present to the fixed television receiver a picture with thirty, 0- to 6-db echoes per second having $\frac{1}{4}$ - μ sec delay, 9 shadows per second having 3- μ sec delay, and so forth. Besides this ghosting of the picture that is taking place, the synchronous circuit of the television receiver is in essence flip-flopping from the direct signal path amplitude to

¹¹ D. W. Peterson, "Army Television Problems Phase II Tasks 1 and 2 Final Report," January, 1956, RCA. Work performed under a Signal Corps Contract No. DA-36-039-sc-64438.

¹² W. R. Young, Jr. and L. Y. Lacy, "Echoes in transmission at 450 megacycles from land-to-car radio units," *PROC. IRE*, vol. 38, pp. 255-258; March, 1950.

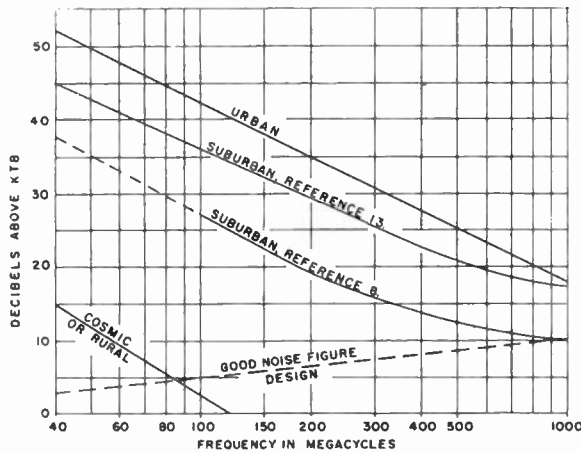


Fig. 12—Median indigenous noise.

the multipath signal amplitude when the ghost signal is the stronger of the two.

INDIGENOUS NOISE

While the relationship between received signal and frequency over irregular terrain has been covered pretty well, another important power balance factor in systems design is the establishment of the noise level of the receiver, or the signal required to assure satisfactory communication. Noise in the frequency range above 40 mc is mainly caused by man-made noise. The general classifications are rural, suburban or small town, and urban noise. Cosmic noise is still present up to 100 mc. Collectively this noise can be termed indigenous noise.

The extent to which this indigenous noise acts upon a receiver is shown in Fig. 12. Two curves have been drawn for suburban noise since the material for these curves have been drawn from two separate references.^{8,12} The lower suburban noise curve is representative of the median indigenous noise experienced in areas suburban to New York, with extrapolated data shown by the dotted portion of the curve. The urban noise data taken from these same two references dovetailed into the same curve. The dotted curve represents the noise figure of a currently well-designed receiver and is shown only to give the figure perspective. The indigenous noise can be referenced with respect to the thermal noise, ktb, of a receiver and is shown in Fig. 12 as the correction factor which must be applied to ktb level, Fig. 13(b).

The difficulty in the use of these curves lies in just what level of noise should be applied in systems design work. Unfortunately indigenous noise data were not collected along with the field strength data. If this had been done a distribution of the magnitude of noise over the areas in which the field strength data were taken would have been available. It would appear that equipment designed for general use should at least consider the lower suburban curve of Fig. 11 with the thought

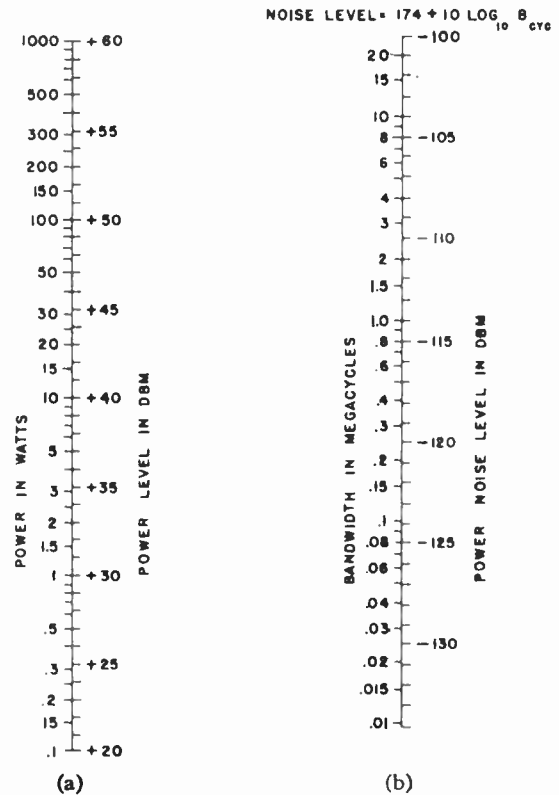


Fig. 13—(a) Conversion of power to dbm. (b) Conversion of bandwidth to thermal noise level.

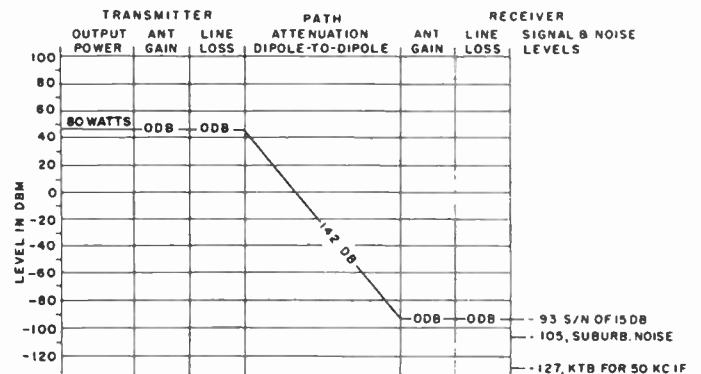


Fig. 14—Power level diagram.

that in urban areas advantage might be taken of the height-gain in these areas.

PROBLEM SOLUTION

The entire problem is reviewed in Fig. 14 in the form of a power level diagram. Working the level diagram from the ktb level of -127 dbm obtained from Fig. 13(b), for a 50 kc IF, suburban noise and not noise figure plus approximately 12 db, establishes the lowest rf signal, -93 dbm, for an acceptable signal-to-noise ratio. Assuming no transmission line losses to the two dipole antennas and with the path attenuation loss over 10 miles of irregular terrain to the 90 percentile location of 142 db, one arrives at a required transmitter power of 49 dbm or 80 watts, Fig. 13(a).

¹² Federal Telephone and Radio Corp., "Reference Data for Radio Engineers," 3rd ed., p. 442; 1949.

VEHICULAR-TO-VEHICULAR TRANSMISSIONS

The entire discussion thus far has dealt with the subject of fixed-to-vehicular, or fixed-to-mobile transmissions over irregular terrain. It is in these subjects that data exist, while in the field of vehicular-to-vehicular transmission good statistical data are nonexistent, at least to the knowledge of the writer.

If one makes the reasonable assumption that the terrain factor will not change whether we deal with the moving-to-moving, fixed-to-fixed, or fixed-to-moving situations, then the median signal received by a vehicle in motion from another vehicle in motion is precisely that given in Fig. 4. However, by statistical theory,¹⁴ it would appear that the standard deviation would be the square root of the sum of the variances of two fixed-to-moving distributions which in this type of transmission can be considered of the same magnitude. Thus the standard deviation for vehicular-to-vehicular transmission is the $\sqrt{2}$ times the standard deviation for the fixed-to-vehicular transmission. This is in essence the correction factor which must be applied to Fig. 6, in order to obtain the vehicular-to-vehicular received power terrain factor shown in Fig. 15. If the given problem were a vehicular-to-vehicular system, fictitiously assuming antenna heights were maintained for this service, the path attenuation at 10 miles to the 90 percentile location would be 119 db, from Fig. 2, plus 32.5 db, from Fig. 15, or 151.5 db compared to a path attenuation of 142 db derived earlier in this paper for the fixed-to-vehicular or mobile transmission. The transmitter power level of 49 dbm, on Fig. 14, must be raised to 58.5 dbm or 700 watts for vehicular-to-vehicular equivalent service.

REMARKS

The statistical method of handling propagation over irregular terrain can be used in frequency assignment studies to determine the number of rf channels which should be designed into equipment for cochannel and adjacent channel field service. It has important usage in vulnerability studies of mutual interference, intentional and unintentional jamming, and countermeasures. It also appears to have application in spectrum allocation studies.

Of course the burning question of how well a particular piece of equipment will act in a given environment

¹⁴ A. Hald, "Statistical Theory with Engineering Applications," John Wiley and Sons, New York, N. Y.; 1952.

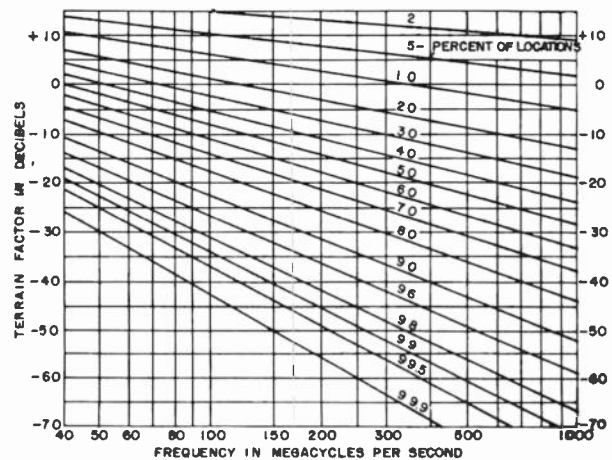


Fig. 15—Vehicular-to-vehicular received power terrain factor.

is difficult to answer. If the terrain is less irregular than the statistical irregular terrain, then better than predicted performance should result. On the other hand, in terrain more irregular than the statistical, a poorer performance should result. However, field operational procedures should be developed which permit a rapid evaluation of the service coverage from a given location. A possible technique for rapid evaluation is one based on a system utilizing the "ground clutter" pattern seen on the radar (PPI) scope.¹⁵

CONCLUSION

This paper is considered a modest start in the direction of supplying irregular terrain propagation information applicable to systems engineering. The author encourages constructive criticism or the supply of data which may be beneficial for deriving better statistical data. For example, much data are required on frequencies above 1000 mc; the nature of the fine variations and their effects upon types of modulation; propagation data on vehicular-to-vehicular transmissions; good statistical small sector variation data; and so forth.

ACKNOWLEDGMENT

The author wishes to express his gratitude to all those referenced authors who have made this paper possible by their efforts in collecting propagation data.

¹⁵ R. E. Lacy and C. E. Sharp, "Radar-type propagation survey experiments for communication systems," 1956 IRE CONVENTION RECORD, part 1, pp. 20-27.

Computer Prediction of Service Areas for VHF and UHF Land Mobile Radio Services

J. DURKIN

Abstract—A computer program written to predict the effective service area of a transmitter in a VHF or UHF mobile radio network is described. The computed results enable field strength contours to be determined, and hence provide more useful information than is possible by reference to standard statistical curves. Present manual methods of calculating the attenuation to be expected over transmission paths rely on the laborious extraction of essential ground profile information along the path joining the transmitter to the receiver. This difficulty may be overcome by using a topographical data base in a computerized method of service area prediction. With this scheme each data base entry represents the effective terrain height above sea level within each 0.5-km square. A high-speed computer can access the necessary information from the data base to reconstruct a close approximation of the radio path profile. The reconstructed profile is then processed to calculate the transmission loss. These computations are repeated for numerous points throughout the area and enable field strength contours to be deduced. The propagation model described forms part of a fully automated frequency assignment procedure for the private land mobile radio services in operation in the Directorate of Radio Technology, Home Office, UK.

I. INTRODUCTION

THE UK land mobile services are currently expanding at the rate of 10 percent per annum and will continue to expand as new applications of mobile radio are introduced. At the present time there are approximately 16 000 base stations using the 800 channels available in the VHF and UHF bands. The demand for mobile radio systems is greatest in the larger conurbations, and more sophisticated techniques to assess potential interference are required.

The prediction of the area of coverage and the potential interference of a radio transmitter is of vital importance in

the planning of any mobile radio communication network. Methods for calculating the attenuation to be expected over transmission paths in point-to-point links have been well developed at both UHF and VHF. Many authors have developed nomograms and charts to permit calculation of expected field strengths from a given transmitter at chosen receiver locations. These calculation aids rely on the laborious extraction of essential ground profile information along the radial joining the transmitter to the receiver.

The prediction of area coverage of a transmitter appears to have received limited attention. This is primarily due to the difficulty of handling area topographical data and to the immense computational task of evaluating field strengths at a large enough number of receiver locations to permit field strengths contours to be determined. However, the modern digital computer with its vast storage capability and speed of calculation has now made area field strength prediction possible.

This paper describes a computer program written to calculate the theoretical field strength contours from a specified transmitter to an accuracy and resolution adequate for VHF and UHF mobile radio network applications. The program executes two main computational tasks. Firstly, from stored geographical data, the ground profile along a radial from the transmitter to a chosen receiver location is reconstructed. Secondly, the path attenuation to be expected along this profile is evaluated. These computations are repeated for a large number of points along 72 equally spaced radials from the transmitter to enable field strength contours to be deduced.

II. GROUND PROFILE RECONSTRUCTION

The data storage requirement, computation time, resolution, and accuracy of the program depend on the following

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factors:

- the density and form of geographical data to be extracted from the proposed service area;
- the number of radials along which the transmission loss has to be calculated (using a large number of radials will improve the accuracy but leads to excessive computation time);
- the interval along the radial at which calculations of signal strength are determined (since the terrain data-base contains a reading every 0.5-km square, it was decided to estimate the transmission loss every 0.5 km along each discrete radial from the transmitter).

For the above reasons considerable attention was given to the problem of ground profile reconstruction and the number of computations required to achieve a reasonable degree of accuracy.

A. Storage of Geographical Data

For use in the United Kingdom, the Ordnance Survey $2\frac{1}{2}$ in/1 m (1:25 000) maps have been divided into 0.5-km squares [1]. A representative height has been deduced from the maps to represent the terrain height over each 0.5-km square. This work, involving the examination of some 1 760 000 squares, was carried out by a specialized contractor using comprehensive error detecting methods. Various procedures for the assignment of a height to each of the 0.5-km squares were compared from the point of view of the preservation of the fidelity of the essential topographic features of the ground profile in the reconstruction process. Comprehensive details have been shown by Edwards and Durkin [1] and Durkin [4] regarding the data format and data base organization.

B. Interpolation for Profile Reconstruction

For a specified transmitter site and each chosen receiver location it is necessary to reconstruct the intervening ground profile from the stored geographical data so that the expected path attenuation can be calculated. The computer program was written to evaluate points on the profile by means of an interpolation routine described in this section and record them in the form of the $2 \times (n + 1)$ matrix; the maximum value of n was set at 200 which represented 200-half-km intervals

$$D = \begin{bmatrix} d_0 & h_0 \\ d_1 & h_1 \\ d_2 & h_2 \\ \vdots & \vdots \\ \vdots & \vdots \\ d_n & h_n \end{bmatrix} \quad (1)$$

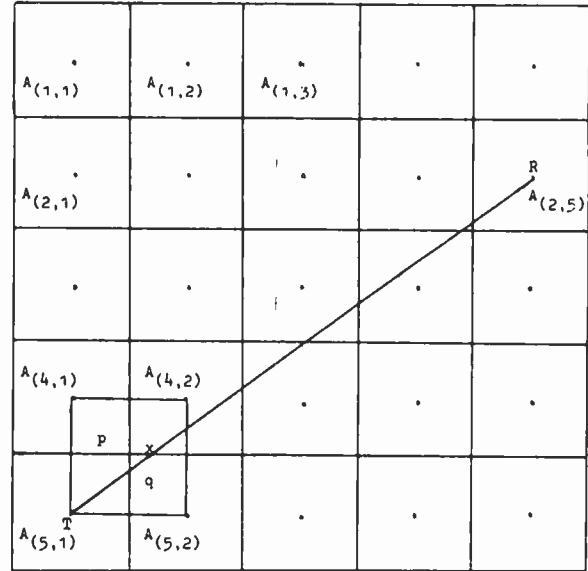
The first column is a list of distances (see nomenclature list) measured from the transmitter such that

$$d_n - d_{n-1} = 0.5 \text{ km}, \quad (2)$$

and the second column is a list of the corresponding calculated heights of the ground profile. The matrix is arranged such that

$$d_{m-1} < d < d_m + 1. \quad (3)$$

The following diagram shows a typical transmission path TR overlaid on the matrix A of stored heights.



$$\sum_{r=1}^2 \sum_{s=1}^2 (h_{rs}, P_r Q_s) \quad (4)$$

where using Lagrange's method for interpolation and the related difference formula

$$P_1 = 1 - p \quad p_2 = p \quad Q_1 = 1 - q \quad Q_2 = q \quad (5)$$

gives the expression for the interpolation height as

$$h_x = h_{5,1}(1-p)(1-q) + h_{5,2}(1-p)q + h_{4,1}(1-q)p + h_{4,2}pq. \quad (6)$$

Thus h_x and 0.5 km became the second entries in the matrix D as given in (1). The computer then steps another half kilometer, and repeats the procedure until it reaches a maximum distance of 100 km from the base station.

Using the above method of storing terrain heights and using the interpolation techniques to derive a path profile enables the attenuation calculations to be reduced to that of the attenuation along a series of equally spaced radials emanating from the base station. In view of the computation time and storage requirements it was decided to use 72 transmission radials spaced at 5 deg intervals around the base station. This gave a compromise between the desired accuracy and the computation time. Also, by interpolating at regular 0.5-km intervals along each transmission radial, the computer pro-

grams were simplified and provided adequate resolution and accuracy as the original topographical data base had at height recordings every 0.5-km interval. However, the computer interpolated profiles were compared with profiles extracted from the original maps, and this showed that no significant topographical features had been lost in the interpolation process. This method of interpolation was compared to the method of linear interpolation as in [1] given by Edwards and Durkin, and no significant differences were apparent.

III. TRANSMISSION PATH ATTENUATION CALCULATIONS

The previous sections have shown that the service area prediction can be reduced to the calculation of the expected attenuation along a series of transmission paths. With this simplification it is possible to make use of well-established techniques which have been successfully applied to point-to-point link calculations. In the USA in recent years, various extensive programs of measurements have been undertaken at VHF over irregular terrain using low-antenna heights and some of the results have been used by the Environmental Science Services Administration (ESSA) to develop a computer method for estimating transmission loss over irregular terrain. This section will describe a modified application of the ESSA method [3] and its adaption to include the use of CCIR smooth-earth propagation curves.

A. Path Parameters

The type of paths encountered will be considered either optical (i.e., when the base station and mobile station antennae are mutually visible or when the angle of diffraction θ is less or equal to zero), or non-optical, whose transmission path is obstructed (i.e., when the angular distance θ is greater than zero (Fig 1)). In both cases the effective base station antenna height is evaluated from the expression

$$h_{eb} = h_b + K \exp(-2h_b/\Delta h(d)) \quad (7)$$

[3, p. 11] where

- h_{eb} effective antenna height;
- h_b actual antenna height;
- $K = 50$ for values of $h_b \geq 100$ m;
- $K = 10$ for values of $h_b \leq 10$ m;
- $\Delta h(d)$ interdecile range of terrain heights above and below a straight line fitted to elevations above sea level.

For values of h_b between 10 m and 100 m the value of K is determined by linear interpolation. The total path loss between the base station transmitter and the mobile receiver is determined as follows:

$$\text{total path loss} = \text{free space loss} + L_{50,50} \quad (8)$$

[3, p. 14] where $L_{50,50}$ represents the smooth earth loss not exceeded at 50 percent of locations for 50 percent of the time on the $L_{50,50}$ contours.

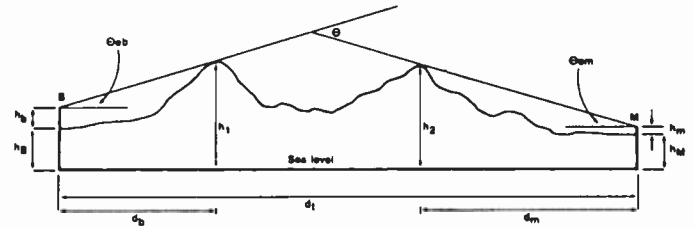


Fig. 1. Geometry of nonoptical radio path.

In (8) the free space loss takes into account the base station transmitter power and the gain of its antenna relative to a dipole. In determining this loss, dipoles have been taken as the reference antennae for both the base station and the mobile. The received signal power is calculated from

received signal power

$$= 32 + 20 \log(f) + 20 \log(d) - 10 \log(P) - \text{antenna gain}, \quad (9)$$

where

- f frequency in megahertz,
- d length of transmission path (kms),
- P base station power in watts.

$L_{50,50}$ is now computed depending on the type of radio path.

B. Optical or Line-of-Sight Paths

A transmission path is considered line of sight if the diffraction angle (θ) is less than zero. This condition is detected by computing the vertical distance between the actual height of the terrain and the height at that point of the straight line between the transmitter and receiver aerials. If a positive value is obtained at any point along the radial then the path is deemed not in line of sight. For line-of-sight paths

$$L_{50,50} = A_r.$$

A_r is defined as the diffraction loss assuming a smooth earth and is obtained from either Fig. 2, 3, or 4 depending on the frequency and effective base station antenna height. These curves are stored in the computer as simple reference tables, are derived from the CCIR Atlas [5] containing theoretical propagation curves for a smooth earth, and assume a mobile station height of 2 m. The total path loss is

$$\text{total path loss} = \text{free space loss} + A_r. \quad (10)$$

C. Non-Line-of-Sight Paths

Fig. 1 illustrates a typical nonoptical path likely to be associated with a specific transmission radial. The total angular distance θ is given by

$$\theta = \theta_{eb} + \theta_{em}$$

where θ_{eb} and θ_{em} are as shown in Fig. 1.

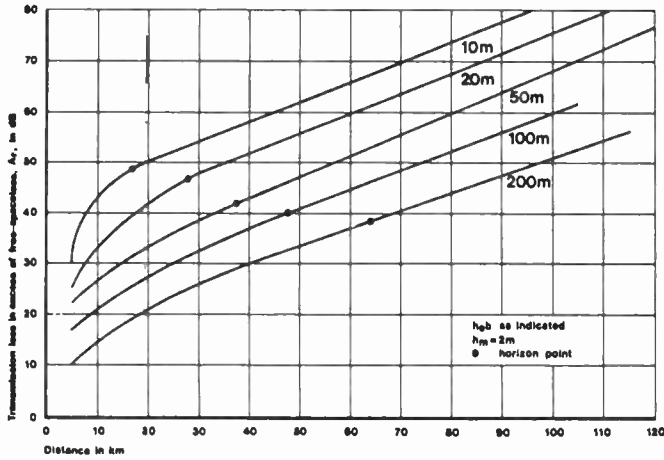


Fig. 2. Theoretical transmission loss over smooth earth at 80 MHz.

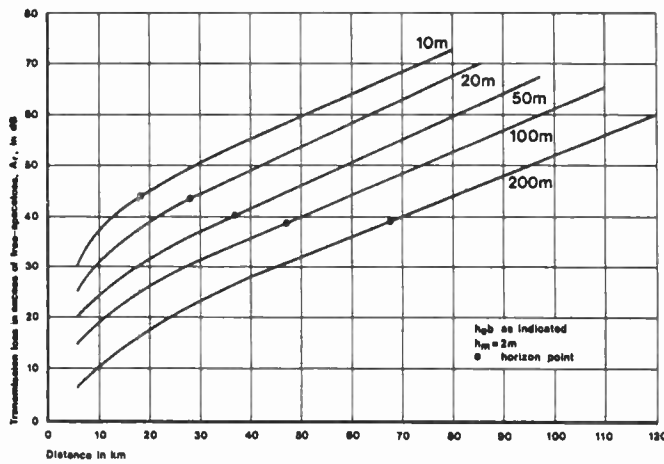


Fig. 3. Theoretical transmission loss over smooth earth at 160 MHz.

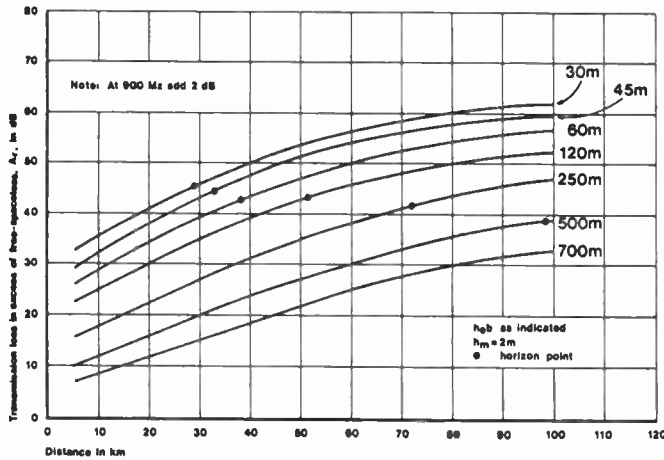


Fig. 4. Median transmission loss due to diffraction over quasi-smooth earth in rural areas (frequency 460 MHz).

In determining $L_{50,50}$ for nonoptical paths it is first necessary to derive A_r as given in Section III-B, and add to this a weighted average of the diffraction loss A_k over a single or double knife edge as applicable, i.e.,

$$L_{50,50} = (1 - w)A_k + wA_r \quad (11)$$

[3, p. 17, (13)]. w is an empirical weighting factor defined by

$$w = \left\{ 1 + 0.1 \left[\frac{\Delta h(d)}{\lambda} \left(\sqrt{\frac{2h_{eb} + 10}{2h_b + 10}} + \frac{a\theta + db + dm}{d_t} \right) \right] \frac{1}{2} \right\} - 1 \quad (12)$$

[3, annex 3, 3.23]. The derivation of A_k is as follows. Having determined the effective height of the base station, it is then necessary to determine the effective aerial height of the mobile station h_{em} , where

$$h_{em} = 2 + 10 \exp(-4/\Delta h(d)). \quad (13)$$

Using (7) and (13), d_{L_s} is computed as

$$d_{L_s} = \sqrt{17h_{eb}} + \sqrt{17h_{em}} \quad (14)$$

where d_{L_s} is the sum of the base station and mobile horizon distances. Having evaluated d_{L_s} , it is now possible to obtain a value for d_z which is used to evaluate the variables V_b and V_m

$$\text{if } d_t \leq d_{L_s}, \quad \text{then } d_z = d_{L_s}$$

$$\text{if } d_t > d_{L_s}, \quad \text{then } d_z = d_t + 0.5(72250000/f)^{1/3}.$$

Having computed the variable d_z , the variables V_b and V_m are calculated to determine the diffraction loss A_k :

$$V_b = 1.2915 \cdot \theta \cdot \sqrt{fd_b(d_z - d_b - d_m)/(d_t - d_m)} \quad (15)$$

[3, annex 3, 3.26(a)] and

$$V_m = 1.2915 \cdot \theta \cdot \sqrt{fd_m(d_z - d_b - d_m)/(d_t - d_b)}. \quad (16)$$

[3, annex 3, 3.26(c)]. A_k is now computed depending on the values of the variables V_b and V_m [3, annex 3, 3.27 (a)].

(i) If $V_b \leq 2.4$ and $V_m \leq 2.4$, then

$$A_k = 12.04 + 9.11(V_b + V_m) - 1.27(V_b)^2 - 1.27(V_m)^2. \quad (17)$$

(ii) If $V_b \leq 2.4$ and $V_m > 2.4$, then

$$A_k = 19 + 9.11V_b - 1.27(V_b)^2 + 20 \log V_m. \quad (18)$$

(iii) If $V_b > 2.4$ and $V_m \leq 2.4$, then

$$A_k = 19 + 20 \log V_b + 9.11V_m - 1.27(V_m)^2. \quad (19)$$

(iv) If $V_b > 2.4$ and $V_m > 2.4$, then

$$A_k = 26 + 20 \log(V_b V_m). \quad (20)$$

Having determined A_k and the weighting factor w , $L_{50,50}$ is computed from (11) and the total transmission loss evaluated by adding the free space loss, i.e.,

$$\text{total loss} = \text{free space loss} + (1 - w)A_k + wA_r. \quad (21)$$

D. Summary of Transmission Loss Calculations

With the development of the transmission loss routines, it was possible to compare the attenuations predicted for an actual profile and its reconstructed counterpart. Examples were chosen to include profiles which were line-of-sight and non-line-of-sight, and in each case the comparisons showed a difference of less than 3 dB. The labor involved in making such comparisons prevented a sufficient number of differences being obtained for statistical conclusions to be drawn. The effect of the earth curvature was also incorporated into the computer program. The radius of the earth was taken to be 4/3 of its true value to allow for atmospheric refraction of the transmitted wave. However, for the relatively short transmission paths (less than 20 km), this correction was found to have negligible influence, but it had a significant effect on the longer transmission radials. It is also possible to include a correction for absorption of the transmitted wave over irregular terrain. Saxton [6] has given an empirical relationship for this additional loss as a function of frequency for "average" irregular terrain; however, at a frequency of 85 MHz used for the experimental verification of the computer program, this correction is negligible. At higher frequencies, however, this additional correction can be readily incorporated. It should be noted that multipath propagation is not included in the present algorithms, but as improved information on the effect of multipath propagation becomes available the algorithms can be improved.

IV. EXPERIMENTAL VERIFICATION

In order to evaluate the accuracy of the computer program, its performance in predicting the area of coverage for an actual mobile radio installation was investigated. A preliminary study of the accuracy of this new method has been made by comparing the predicted values of signal strength set up by a 85 MHz transmitter at Barkway, Hertfordshire, UK, with the values measured along the computed -136 dBW signal strength contour.

The computer program was run with the appropriate engineering parameters to predict the geographical location of the -136 dBW (corresponds to 12 dB SINAD for a receiver input of 0.7 μ V emf) signal strength contour on each of the 72 radials surrounding the base station. In addition, the computer printed out the signal strength level at 0.5-km intervals along each radial up to a maximum distance of 100 km. Practical measurements were made on the transmitter using a test vehicle incorporating a half-wavelength receiving dipole. Test receiver locations were always taken to be on a road, as this is the normal siting for mobile radio working, but otherwise were selected at random. A total of 270 readings was recorded; about half the readings were at locations within line of sight of the transmitter, with the remainder being in shadow. By expressing in decibels the ratio of actual measurements to those predicted by the computer, samples of the estimation error process were obtained. The standard deviation of the errors settled down to a value less than 10 dB.

NOMENCLATURE

D	Height distance matrix.
$A(i, j)$	Matrix of stored terrain heights.
a	Effective radius of the earth in kilometers.
A_k	Total diffraction loss in decibels (dB).
A_r	Smooth earth diffraction loss in decibels (dB).
$L_{50,50}$	Loss not exceeded at 50 percent locations for 50 percent of the time.
d	Length of transmission path in kilometers.
d_b	Distance of the base station from the radio horizon.
d_m	Distance of the mobile station from the radio horizon.
d_{L_s}	Sum of the base station and mobile station horizon distances.
d_z	Variable used in determining V_b and V_m .
f	Frequency of the radio wave in megahertz.
h_{eb}	Effective height in meters of the base station antenna.
h_{em}	Effective height in meters of the mobile station antenna.
h_b	Height above ground level (meters) of the base station antenna.
h_m	Height above ground level (meters) of the mobile station antenna.
h_B	Height of the base station above sea level (m).
h_M	Height of the mobile station above sea level (m).
K	Factor used to determine the effective height of the antenna.
V_B, V_M	Parameters used to determine A_k , the diffraction loss.
$\Delta h(d)$	Difference in height (meters) exceeded by 10 percent and 90 percent of terrain along a given transmission path.
θ	Angular distance (radius) for a nonoptical path.
θ_{eb}	Horizon elevation as seen by the base station antenna.
θ_{em}	Horizon elevation as seen by the mobile station antenna.
λ	Wavelength in meters.
P	Base station transmitter power in watts [ERP].

REFERENCES

- [1] R. Edwards and J. Durkin, "Computer prediction of service areas for VHF mobile radio networks," *Proc. IEE (London)*, vol. 116, no. 9, pp. 1493-1500, 1969.
- [2] C. E. Dadson, J. Durkin, and R. E. Martin, "Computer prediction of field strength in the planning of radio systems," *IEEE Trans. Veh. Technol.*, vol. VT-24, no. 1, Feb. 1975.
- [3] A. G. Longley and P. L. Rice, "Prediction of tropospheric radio transmission loss over irregular terrain, a computer method," ESSA Tech. Rep., ERL-79-ITS 67, Institute for Telecommunications Sciences, Boulder, CO.
- [4] J. Durkin, "A Study of Computer Methods in Mobile Radio Planning," Ph.D. thesis, Victoria University of Manchester, Sept 1969.
- [5] Atlas of Ground-Wave Propagation Curves for Frequencies between 30 MHz and 300 MHz. CCIR Resolution no. 11, Geneva, 1955.
- [6] J. A. Saxton, "Basic ground-wave propagation characteristics in the frequency band 50-800 Mc/s," in *Proc. IEE*, vol. 101, pt. III, pp. 211-224, 1954.

An Approach to Estimating Land Mobile Radio Coverage

EDWARD A. NEHAM, MEMBER, IEEE

Abstract—This paper reports some propagation and coverage prediction results using various models provided to the Federal Communications Commission, Spectrum Management Task Force.

INTRODUCTION

DURING the period July–December 1972, Kelly Scientific Corporation (KSC), under contract to the Federal Communications Commission, provided technical assistance to the Spectrum Management Task Force (SMTF) in implementing the first phase of the National Spectrum Management Program in Chicago, as established under Docket 19150—Notice of Proposed Rule Making, February 5, 1971. KSC activities involved three tasks with the following objectives:

Task 1: To provide technical support to the SMTF Systems Engineering Group in evaluating the engineering techniques and parameters to be used in the Automated Frequency Assignment Model (AFAM).

Task 2: To provide technical support to the SMTF Data Systems Group in determining the final AFAM design to be implemented in the Chicago Regional Center.

Task 3: To provide effort for the preliminary development of methodology for spectrum impact forecasting.

This paper reports on some of the work KSC performed in responding to the first task and addresses propagation and coverage predictions in particular.

THE AUTOMATED FREQUENCY ASSIGNMENT MODEL

AFAM consists of the seven major elements identified in Fig. 1, of which five are sequential routines and two are supporting data bases. As illustrated, the completed FCC Form 425 serves as the input to the AFAM program and the output consists of a listing of acceptable frequencies from an interference and channel loading standpoint. In order to meet the needs of the land mobile radio user community, AFAM has been constructed with the following attributes in mind:

identification of those frequencies, the use of which by the applicant's system results in minimal mutual interference between the applicant's system and the environment;

enhancement of spectrum management through the careful selection and reservation of individual or groups of frequencies, and

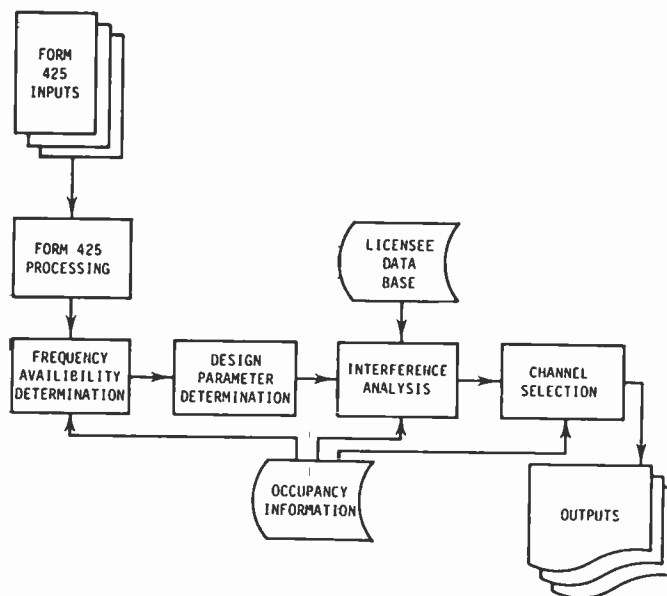


Fig. 1. Major AFAM elements.

development and use of channel loading models to forecast spectrum crowding problems and thus provide sufficient lead-time during which to find alternative solutions.

PROPAGATION CONSIDERATIONS IN AFAM

The propagation models utilized in AFAM serve as some of the most important elements of the program because their results are used to determine desired and undesired signal levels at various locations, which eventually affect the assignment and reassignability of frequencies. Two basic models are used in AFAM; the first is a modified plane earth model used in calculating desired signal strength at mobile receivers, and the other is a free space model used to compute interference levels between base stations. Propagation results affect desired signal, adjacent channel, intermodulation, and co-channel signal computations, and are of particular importance in the establishment of suitable applicant system parameters.

The establishment of appropriate applicant design parameters is certainly one of the major positive approaches toward efficient spectrum management of the land mobile radio services. Previous experience in examining land mobile radio operations has led to the conclusion that a large number of base stations are radiating more power than is required to cover their operational area.

The advantages to the applicant of establishing appropriate design parameters prior to licensing are twofold. It ensures adequate system performance on behalf of the

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TABLE I
SYSTEM PARAMETERS USED IN PROPAGATION MODEL COMPARISONS

Parameter	Value
Operating Frequency	150 MHz
Transmitter Power	100 W
Transmit Antenna Gain	6 dB
Receive Antenna Height	6 ft.
Receive Antenna Gain	0 dB
Receiver Sensitivity	-150 dBW
Indigenous Noise Factor	5 dB
System Loss Factor	0 dB
Location Factor	Various *

* Different reliability factors, dependent upon 50 percent and 90 percent of locations receiving a usable signal, where specified for each model.

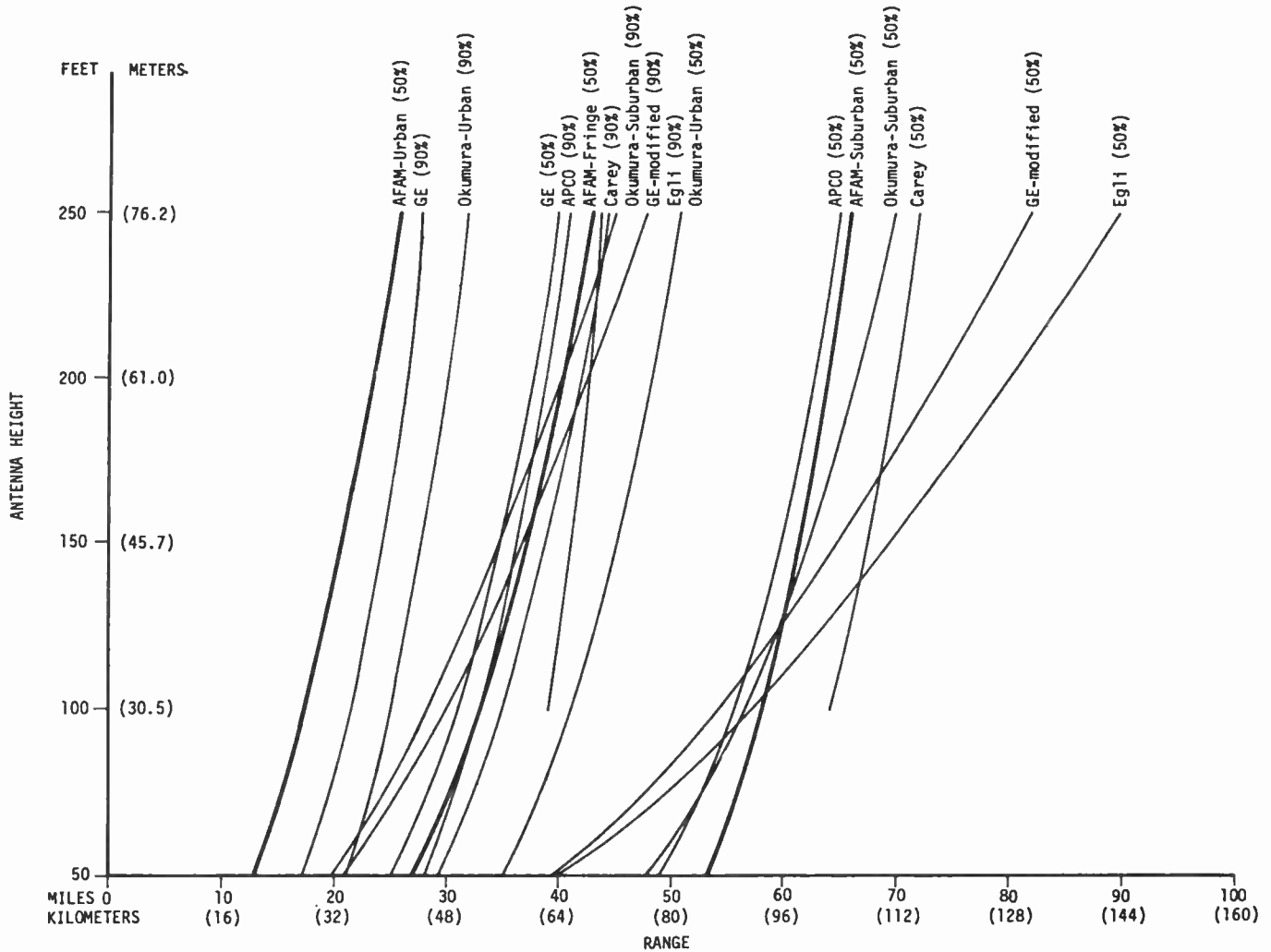


Fig. 2. Comparison of propagation model results in high band.

TABLE II
DESIGN VALUES FOR REQUIRED RECEIVED POWER
Table 2

DESIGN VALUES FOR REQUIRED RECEIVED POWER

Frequency	Required Received Power (dBW)		Comment
	Mobile	Base Station	
Low Band (25-50 MHz)	-127	-131 (High noise) -139 (Avg. noise) -143 (Low noise)	Mobile stations require substantially stronger signals than base stations in this band. Mobile transmitters will usually have enough power to reach their base, provided transmission requirements are met in the base to mobile direction.
High Band (150-170 MHz)	-137	-132 (High noise) -141 (Avg. noise) -148* (Low noise)	Available data indicates that base station receivers in this band may be subject to more degradation than mobile receivers depending upon the man-made noise environment. Note also that a noise environment (high, average, low) of a base receiver may be associated with its fixed location. Even in a single location, the automotive ignition noise affecting mobiles is highly variable.
UHF Band (450-470 MHz)	-146*	-138 (High noise) -145 (Avg. noise) -146* (Low noise)	The effects of man-made noise are relatively small in UHF and range is consequently more dependent upon transmitter power. The mobile to base requirement is most critical since mobiles usually have less power.

*Minimum receiver input power is approximately the same as receiver sensitivity and this implies negligible degradation from man-made noise.

applicant, and it makes more efficient use of the spectrum by reducing the harmful interference effects of over-powered stations thereby enabling efficient geographic reuse of the land mobile frequencies.

The important factors in the design parameter determination portion of the program are ambient noise levels, antenna gains, propagation loss, system losses, and transmitter power. Each of these factors is evaluated with respect to the applicant's radio coverage requirements and, in the case of an overpowered system, the applicant will be notified to take corrective action.

MODEL COMPARISONS

In examining the effects of propagation on radio system coverage, various plane earth propagation models have been tested and compared with the FCC's model which was developed based upon data measured in the UHF TV bands. In particular, some results using this model have been compared with results using the several models listed below:

Egli [1]
APCO [2]

GE [3]
Carey [4]
Okumura [5].

All of these models, including the one used in AFAM, are based upon median location data; i.e., signal levels exceeded 50 percent of the time. However, in planning communications systems, 90-percent data are often used. Where applicable, both 50- and 90-percent results are used in the comparisons.

As a basis for comparison, a set of system parameters was selected and applied to each model. These parameters and their values are listed in Table I. For each model, the radio range (miles) was computed for various base station antenna heights (h_t between 50 and 250 ft, and where applicable, for reception at 50 percent and 90 percent of the receiver locations. The results of these computations are shown pictorially in Fig. 2. In this illustration, two data groupings are observed. One is the set of 50-percent location data at ranges above 50 mi and the other is the set of 90-percent data grouped between 25 and 40 mi. This grouping can be more clearly seen in Fig. 3 which

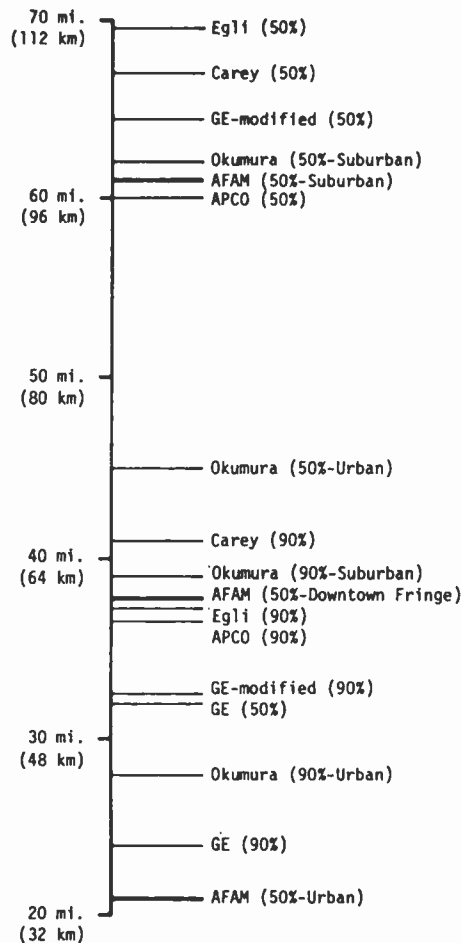


Fig. 3. Various propagation range predictions, transmit antenna height at 150 ft.

illustrates the ranges provided by the various models for 150-ft transmit antenna heights.

The AFAM propagation computations used in this comparison involved the use of median (50-percent) data with Urban (25-dB), downtown fringe (12.5-dB), and suburban (0-dB) correction factors added to the calculated losses as required.

In examining these results more closely, it was determined that the AFAM median data without any correction for "urbaness," could be modified by some amount resulting in 90-percent data in line with the predictions of other models. This modification, termed the Location Variability Factor (LVF), was estimated to be:

$$LVF = \begin{cases} 11 \text{ dB—low band} \\ 14 \text{ dB—high band} \\ 17 \text{ dB—UHF band.} \end{cases}$$

The LVF presented above is in close agreement with the literature [1], [4], [5] although several decibels have been added to provide a somewhat more conservative estimate of received signal strength.

COVERAGE PREDICTIONS

The closeness of the 90-percent grouping (see Fig. 3) implies that these models may be considered equivalent. The development presented by Egli [1] allows the direct

computation of distance based upon plane earth theory. Modifying this approach to include the effects of ambient noise, location factor, and other losses, results in the following equation for coverage prediction:

$$d = \left[\frac{3.5 \times 10^{-15} h_T^2 h_R^2 P_T G_T G_R}{L_N L_L L_S S} \right]^{1/4}, \quad \text{mi}$$

where

- d the range (in miles);
- h_T the transmitter antenna height above average terrain (in feet);
- h_R the receiver antenna height (in feet);
- P_T the transmitter output power (in watts);
- G_T the gain of the transmitter antenna;
- G_R the gain of the receiver antenna;
- L_N the indigenous noise loss factor;
- L_L the location variability factor;
- L_S the system cable loss factor;
- S the sensitivity of the receiver (in watts).

The product of the noise factor L_N and the receiver sensitivity S is the minimum required received power (RRP) in the receiver. Based upon other work performed in this contract, Table II presents typical values which may be used in making coverage predictions.

When the loss characteristics of the cable to be used at the base station are not known, the following data may be used to estimate these losses:

system cable loss per 100 ft	1.0 dB—low band
	2.7 dB—high band
	5.5 dB—UHF band.

SUMMARY

In summary, the equation presented above leads to the rapid computation of radio system coverage and, with a 90-percent location factor, yields results comparable to those of other models. When used with the FCC's eight-radial procedure, the results can easily be plotted on a map to more clearly illustrate the system's coverage and also expose potential "dead spots."

ACKNOWLEDGMENT

The extensive work performed by P. Walcoff, which in part resulted in this paper, is gratefully acknowledged, as are the basic engineering and programming efforts of the SMTF staff, which was instrumental in implementing the spectrum management program.

REFERENCES

- [1] J. J. Egli, "Radio propagation above 40 Mc over irregular terrain," *Proc. IRE*, vol. 45, pp. 1383-1391, Oct. 1957.
- [2] *The Public Safety Communications Standard Frequency Coordination Manual*, Associated Public Safety Communications Officers, Inc., May 15, 1971.
- [3] "VHF and UHF propagation," GE Data File Bulletin No. 10003-1, July 1962.
- [4] R. Carey, "Technical factors affecting the assignment of facilities in the domestic public land mobile radio service," FCC Rep. R-6406, Washington, D. C., June 24, 1964.
- [5] Y. Okumura *et al.*, *Field Strength and Its Variability in VHF and UHF Land-Mobile Radio Service* (Review of the Electrical Communication Laboratory), vol. 10, nos. 9-10, Sept.-Oct. 1968.

Selection of intermodulation-free frequencies for multiple-channel mobile radio systems

R. Edwards, M.Sc., Ph.D., J. Durkin, M.Sc., and D. H. Green, M.Sc., Ph.D.

Abstract

The paper presents results which enable the designer of a mobile radio network to allocate channel frequencies which give freedom from interfering third- or fifth-order intermodulation products. The general rules for the selection of third- and fifth-order mutually compatible channels are developed, and Tables of channel-difference sequences are presented for direct use in channel allocation. An extension of the theory for immunity to higher-order products is also given.

1 Introduction

The number of private mobile radio installations in service in the United Kingdom has maintained a high rate of growth in recent years. The number of mobile radio stations in service rose from 22000 in 1964 to 50000 in 1967. Present information indicates that this rate of increase is now being exceeded. Such an expansion in mobile radio traffic puts an ever-increasing strain on the spectrum available for this form of communication. This is reflected in the recent recommendations that channel bandwidths be reduced further to 12·4 kHz.

Hooper^{1,2} has shown that economies in radio-frequency-spectrum utilisation can result from the 'trunking advantage' due to the introduction of multiple-channel systems with channel selection rather than a multiplicity of independent single-channel systems. A statistical examination of mobile radio traffic properties indicates^{1,2,3} that there is a maximum number of mobiles which can be provided with a reasonably good service by a single channel. When a greater number of mobiles is involved, the probability of the individual user suffering an unacceptably long waiting time rises rapidly. In making more channels available, it is much more valuable to enable each mobile to have access to each frequency, through multiple-channel working, than to have the same number of channels used on separate systems.

From the practical and economic standpoints, the introduction of a number of frequency channels into a single service area inevitably leads to the co-siting of transmitters. This is true whether channel switching is used or not, and the location of the transmitters at a common site leads to a number of interference problems.^{4,5,6} Apart from co-channel interference, which must receive similar attention to that encountered in single-channel working, the most severe interference effect^{4,5,6} results from the intermodulation products generated in the receiver. This interference occurs when two or more high-level unwanted signals, on certain frequencies, are received simultaneously. The interference effects of intermodulation products, however, will be shown to be minimised by the correct choice of frequencies for a given service area. The paper provides the necessary information for the selection of channel frequencies which are mutually compatible, in the sense that they will give freedom from interfering third-order intermodulation products. In addition, it is shown that freedom from the troublesome fifth- and even higher-order products is also possible. The results developed for the selection of mutually compatible channels will find application in the design of mobile radio networks where the number of mobiles, existing or projected, necessitates the allocation of multiple channels to given service areas.

2 Source of intermodulation products

The intermodulation products generated in the mixer of a radio receiver can be predicted^{5,6} by defining the input-

output relationship of the mixer, and treating its input as a group of sine waves. The mixer characteristic can be approximated, by an exponential expression⁵ representing the diode characteristic, as

$$i = i_0(e^{aE} - 1) \quad (1)$$

where a is a temperature-dependent constant, or by expressing the input-output voltage relationship in terms of the power series⁶

$$E_{out} = k_1 E_{in} + k_2 E_{in}^2 + k_3 E_{in}^3 + \dots \quad (2)$$

In either case, the intermodulation frequencies are identical, but their relative amplitudes are expressed in terms of the different coefficients. By representing the input as the sum of sine waves,

$$E_{in} = \sum_{i=1}^n e_i \sin \omega_i t \quad (3)$$

it can be shown that the output of the mixer can be expressed either as⁵

$$E_{out} = \sum_{\alpha_1 \alpha_2 \alpha_3 \dots} A(e_1, e_2, e_3, \dots, \alpha_1, \alpha_2, \alpha_3, \dots, a) \cos(\alpha_1 \omega_1 + \alpha_2 \omega_2 + \alpha_3 \omega_3 \dots) t \quad (4)$$

or as⁶

$$E_{out} = \sum_{\alpha_1 \alpha_2 \alpha_3 \dots} A(e_1, e_2, e_3, \dots, \alpha_1, \alpha_2, \alpha_3, \dots, k_1, k_2, k_3) \cos(\alpha_1 \omega_1 + \alpha_2 \omega_2 + \alpha_3 \omega_3 + \dots) t \quad (5)$$

where A is the amplitude of the intermodulation product, and α_i are integers such that

$$\alpha_{1,2,3 \dots} = 0, \pm 1, \pm 2, \dots \quad (6)$$

The frequency of a typical product f_x is, therefore,

$$f_x = \alpha_1 f_1 + \alpha_2 f_2 + \alpha_3 f_3 + \dots \quad (7)$$

and the order of this response is given by⁵

$$K = |\alpha_1| + |\alpha_2| + |\alpha_3| + \dots \quad (8)$$

However, the majority of the intermodulation products of eqns. 4 and 5 are not troublesome, because they are removed by the filtering action of the networks which follow the mixer. The terms which do cause interference lie in the frequency band occupied by the desired signal. Under the normal conditions, with the bandwidth of the communication channels very much less than the carrier frequencies $f_1, f_2, f_3, \dots$, it is easily shown* that the intermodulation product f_x in eqn. 7 can lie in the frequency band occupied by a desired signal only if the following equation is satisfied:

$$\alpha_1 + \alpha_2 + \alpha_3 + \dots = 1 \quad (9)$$

This equation is seen to be correct, intuitively, by noting that the carrier frequencies $f_1, f_2, f_3, \dots$ are relatively close together; i.e.

$$|(f_i - f_j)/f_i| \ll 1 \quad (10)$$

for all carriers in the group under consideration.

* Interference due to intermodulation products in the land mobile service between 25 and 300 MHz: CCIR 12th plenary assembly, draft report of study program 7C/X111

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Eqs. 8 and 9 form the basis of the following analysis, which provides rules by which channel frequencies which are free from third- or fifth-order intermodulation interference products can be selected. One immediate consequence of the diophantine equations, eqns. 8 and 9, is that they cannot be satisfied if K is even. This corresponds to the well known result that intermodulation products of even order do not generally give rise to interference effects.

3 Third-order intermodulation products

The dominant intermodulation products giving rise to interference are those of the third order.⁴ These terms may be associated⁶ with the coefficient k_3 in the power series of eqn. 2. In this case, the conditions for troublesome intermodulation products are given by eqns. 8 and 9 as

$$|\alpha_1| + |\alpha_2| + |\alpha_3| = 3 \quad (11)$$

$$\alpha_1 + \alpha_2 + \alpha_3 = 1 \quad (12)$$

Evidently, these equations have only two solutions, as follows:

$$\alpha_i = 1, \alpha_j = 1, \alpha_k = -1 \quad \text{for } i, j, k = 1, 2, 3 \quad (13)$$

$$\alpha_i = 2, \alpha_j = -1 \quad \text{and } i \neq j \neq k \quad (14)$$

These equations are significant because a third-order intermodulation product will give rise to interference if either of the following two equations is satisfied:

$$f_x = f_i + f_j - f_k \quad (15)$$

$$f_x = 2f_i - f_j \quad (16)$$

where f_x, f_i, f_j and f_k are any of the frequencies associated with the channels allocated to a single service area. Eqns. 15 and 16 can be expressed in terms of the channel numbers. Assuming that the frequency band under consideration is split up into channels of equal width, with no intervals between them, then

$$f_m = f_0 + bC_m \quad (17)$$

where f_0 is an initial frequency, b is the channel bandwidth and C_m are the channel numbers. Using the notation of eqn. 17, eqns. 15 and 16 become

$$C_x = C_i + C_j - C_k \quad (18)$$

$$C_x = 2C_i - C_j \quad (19)$$

In turn, these equations can be rewritten as

$$C_x - C_i = C_j - C_k \quad (20)$$

$$C_x - C_i = C_i - C_j \quad (21)$$

so that eqn. 21 is really just a special case of the general equation, eqn. 20. The interpretation of eqns. 20 and 21 is simply that third-order intermodulation products are troublesome if any two of the differences between pairs of channel numbers are identical.

For generality, it is convenient to derive the results in terms of the differences between consecutive pairs of channel numbers, rather than in terms of the channel numbers themselves. For this purpose, these single differences d_i are defined by

$$d_i = C_2 - C_1; d_2 = C_3 - C_2 \dots; d_{n-1} = C_n - C_{n-1} \quad (22)$$

where the sequence of the n channel numbers

$$C_1, C_2, C_3, \dots, C_n \quad (23)$$

is written in ascending order. As a result, the difference between any pair of channel numbers can be expressed as the sum of the single differences

$$d_{xi} = C_x - C_i = \sum_{m=x-1}^i d_m \quad (24)$$

To avoid ambiguity in the terminology, single differences

between consecutive pairs of channel numbers will be given a single subscript, i.e.

$$d_i = C_{i+1} - C_i \quad (25)$$

but the sum differences, which are the differences between all other channel-number pairs, will be given double subscripts, i.e.

$$d_{xi} = C_x - C_i = d_{x-2} + d_{x-2} + \dots + d_i \quad (26)$$

The general condition for interfering third-order intermodulation products is now given, by eqn. 20, as

$$\sum_{m=x-1}^i d_m = \sum_{m=j-1}^k d_m \quad (27)$$

or $d_{xi} = d_{jk}$

for all x, i, j and k , but excluding the identity for which $x = j$ and $i = k$.

The conditions contained in eqn. 27 can be illustrated by means of Fig. 1, which has been drawn for the particular case

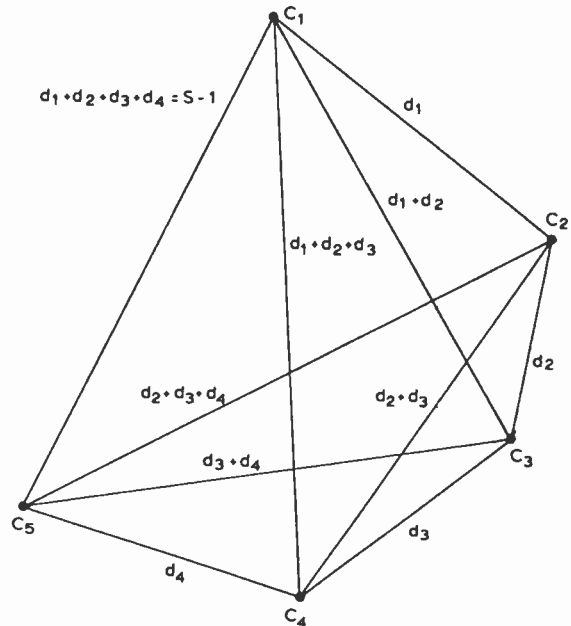


Fig. 1
Graphical representation of channel numbers and all possible differences for $n = 5$

of $n = 5$. The nodes represent the channel numbers, and the distance between the nodes are the differences between the channel numbers. For the channels C_1, C_2, C_3, C_4 and C_5 to be free from interfering third-order intermodulation products, no two edges in the figure should represent the same distance.

It is further necessary to define the switching range S of a series of mutually compatible channels. The n channels $C_1, C_2, \dots, C_n$, arranged in ascending numerical order, have a switching range S defined by

$$S = C_n - C_1 + 1 \text{ channels} \quad (28)$$

Clearly, S is the sum of all the single differences plus unity, so that

$$S = d_1 + d_2 + d_3 + \dots + d_{n-1} + 1 \quad (29)$$

Evidently, from a receiver-design point of view, the parameter S should be kept to a minimum.

4 Calculation of channel sequences which are free from interfering third-order intermodulation products

The results derived in the previous section were used to obtain permissible sequences of single differences between consecutive channel numbers, which give freedom from third-order intermodulation interference. The sequences were calculated with the aid of a computer program. Two parameters were required to initiate the computation; the switching range S and the number of channels n . It is clear from

eqn. 29 that the sum of the $n - 1$ single differences is equal to $S - 1$. A contender for a permissible difference sequence is therefore a partition of $S - 1$, into $n - 1$ components. Partitions which have nondistinct elements were not considered, since they immediately satisfy eqn. 27. Furthermore, elements of unity were not permitted, so as to avoid the use of adjacent channels. Each remaining partition was expressed in all the possible permutations of the order of its elements. Each of the sequences so formed represents a possible list of single differences between consecutive channel numbers. It only remains to decide which of these sequences have the property of noninterfering third-order intermodulation products. This decision was implemented by determining whether or not a given sequence satisfied eqn. 27.

A graphical interpretation of eqn. 27 was given in Fig. 1. However, this technique is not suited to computer calculation, and, for this reason, the equivalent tubular method illustrated in Table 1 was devised. A triangular matrix is set up, the left-hand column being the single-difference sequence under test. Each remaining element is a sum difference, formed by adding together two previous entries, one from the preceding column and one from the first column, as shown in Table 1. The array then displays every possible difference between pairs of channel numbers. For the difference sequence $d_1 d_2 \dots d_{n-1}$ to give rise to n mutually compatible channels, in the sense of freedom from unwanted third-order products, no two entries in the array of Table 1 should have the same value.

An example will illustrate the foregoing test procedure. It is required to allocate five channels which are free from third-order intermodulation interference to a single service area. The switching range of the receiver is limited to 20 channels. From this information, $n = 5$ and $S = 20$. Taking $S = 20$ as an example, all the possible partitions of 19 ($= S - 1$) into four ($= n - 1$) distinct elements not equal

to unity are

$$\left. \begin{array}{l} 2 \ 3 \ 4 \ 10 \\ 2 \ 3 \ 5 \ 9 \\ 2 \ 3 \ 6 \ 8 \\ 2 \ 4 \ 5 \ 8 \\ 2 \ 4 \ 6 \ 7 \\ 3 \ 4 \ 5 \ 7 \end{array} \right\} \dots \dots \dots (30)$$

By permutating the elements of these partitions, 144 ($= 6 \times 4!$) difference sequences are to be subjected to the third-order intermodulation test. For example, the sequence 2359 generates the array

$$\left. \begin{array}{l} 2 \\ 3 \ 5 \\ 5 \ 8 \ 10 \\ 9 \ 14 \ 17 \ 19 \end{array} \right\} \dots \dots \dots (31)$$

Since there are two 5s in the array, this difference sequence gives rise to an interfering third-order product, namely

$$C_4 - C_3 = C_3 - C_1 = 5 \dots \dots \dots (32)$$

which is a realisation of eqn. 21. The permutation 2539, however, does provide mutually compatible channels, because the array generated from it has distinct elements:

$$\left. \begin{array}{l} 2 \\ 5 \ 7 \\ 3 \ 8 \ 10 \\ 9 \ 12 \ 17 \ 19 \end{array} \right\} \dots \dots \dots (33)$$

Thus, one possible channel allocation is

$$C_1 = 1, C_2 = 3, C_3 = 8, C_4 = 11, C_5 = 20 \quad (34)$$

In fact, as can be seen from Table 4, 96 of the 144 possible difference sequences for this example give rise to valid solutions.

Because single differences should be distinct and not equal to unity, it is evident that a lower bound on the permissible switching range for n channels is

$$S \geq 1 + \sum_{i=2}^n i \dots \dots \dots (35)$$

However, this lower bound is not always attained, and Table 3 shows the computed minimum switching ranges for channel numbers in the range $3 \leq n \leq 8$. Table 4 lists the computed valid difference sequences for a range of n and S . It should be noted that the reverse of each of the sequences in Table 4 is also a valid sequence.

The use of Tables 3 and 4 is illustrated by an example. It is required to allocate seven 12.5 kHz speech channels to a single service area using cosited transmitters. From Table 3, the smallest possible switching range for seven compatible channels is 29. This corresponds to a spectrum bandwidth of 362.5 kHz. A valid difference sequence for this minimum range is obtained from Table 4 as

$$2 \ 8 \ 6 \ 5 \ 4 \ 3 \dots \dots \dots (36)$$

for which one set of channel numbers is

$$\left. \begin{array}{l} C_1 = 1, C_2 = 3, C_3 = 11, C_4 = 17 \\ C_5 = 22, C_6 = 26, C_7 = 29 \end{array} \right\} \dots \dots \dots (37)$$

Table 1

CONSTRUCTION OF ARRAY TO TEST THIRD-ORDER COMPATIBILITY

d_1				
d_2	$d_1 + d_2$			
d_3	$d_2 + d_3$	$d_1 + d_2 + d_3$		
d_4	$d_3 + d_4$	$d_2 + d_3 + d_4$	$d_1 + d_2 + d_3 + d_4$	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_{n-1}	$\vdots$	$\vdots$	$\vdots$	$d_1 + d_2 + \dots + d_{n-1}$

EQUIVALENT ARRAY USING THE NOTATION OF EQN. 26

d_1				
d_2	d_{31}			
d_3	d_{42}	d_{41}		
d_4	d_{53}	d_{52}	d_{51}	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_{n-1}	$\vdots$	$\vdots$	$\vdots$	d_{n1}

Table 2

CONSTRUCTION OF ARRAY TO TEST FIFTH-ORDER COMPATIBILITY

	d_1	d_2	$d_3 \dots d_{n-1}$	d_{31}	d_{42}	$d_{53} \dots$
d_1	$2d_1$					
d_2	$d_1 + d_2$	$2d_2$				
d_3	$d_1 + d_3$	$d_2 + d_3$	$2d_3$			
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_{n-1}	$d_1 + d_{n-1}$	$d_2 + d_{n-1}$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_{31}	$d_1 + d_{31}$	$d_2 + d_{31}$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_{42}	$d_1 + d_{42}$	$d_2 + d_{42}$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_{41}	$d_1 + d_{41}$	$d_2 + d_{41}$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_{52}	$d_1 + d_{52}$	$d_2 + d_{52}$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_{51}	$d_1 + d_{51}$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_{62}	$d_1 + d_{62}$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_{n1}	$d_1 + d_{n1}$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$2d_{n1}$

Table 3

MINIMUM SWITCHING RANGES FOR THIRD-ORDER COMPATIBILITY

Number of channels	Minimum switching range for third-order compatibility
3	6
4	10
5	15
6	21
7	29
8	40

Table 4

CHANNEL DIFFERENCE SEQUENCES FREE FROM THIRD-ORDER INTERFERING INTERMODULATION PRODUCTS

Number of channels	Switching range	Difference sequences giving third-order compatibility
3	6	2 3
	7	2 4
	8	2 5 3 4
	9	2 6 3 5
	10	2 7 3 6 4 5
4	11	2 8 3 7 4 6
	10	2 3 4 3 2 4 3 4 2
	11	2 5 3
	12	2 3 6 3 2 6 3 6 2 2 4 5 4 2 5 4 5 2
	13	2 3 7 3 2 7 3 7 2 2 6 4 3 4 5 4 3 5 4 5 3
5	14	2 3 8 3 2 8 3 8 2 2 4 7 4 2 7 4 7 2 2 5 6
	15	5 2 6 5 6 2 3 4 6 4 3 6 4 6 3
	15	2 3 9 3 2 9 3 9 2 2 4 8 4 2 8 4 8 2 2 7 5
	16	3 7 4 3 5 6 5 3 6 5 6 3
	16	2 4 3 5 2 4 5 3 4 2 5 3
6	17	2 3 4 6 4 3 2 6 4 6 2 3 2 6 4 3 2 6 3 4 2 3 6 4
	18	3 2 4 7 4 2 3 7 2 4 7 3 4 2 7 3 4 7 2 3 2 3 7 4
	18	2 5 3 6 2 5 6 3 5 2 6 3
	18	2 3 4 8 3 2 4 8 3 4 2 8 4 3 2 8 4 2 8 3 4 2 3 8
	18	2 4 8 3 4 2 8 3 4 8 2 3 2 8 4 3 2 8 3 4 2 3 9 4
7	19	2 7 5 3 2 7 3 5 4 5 2 6 2 5 4 6 2 5 6 4 5 2 6 4
	19	2 6 5 4 2 6 4 5
	19	2 4 9 3 4 2 9 3 4 9 2 3 2 9 4 3 2 9 3 4 2 3 9 4
	19	2 5 8 3 5 2 8 3 2 3 6 7 3 2 6 7 6 2 3 7 6 2 6 3 7
	19	2 6 7 3 6 2 7 3 6 7 2 3 2 3 7 6 2 4 5 7 5 7 2 4
8	20	2 4 7 5 3 4 5 6 4 3 5 6 5 3 4 6 3 5 4 6 3 5 6 4
	20	5 3 6 4 5 6 3 4 3 4 6 5
	20	2 4 3 10 2 3 4 10 3 2 4 10 3 4 2 10 4 3 2 10 4 2 3 10 4 2 3 10 3
	20	4 10 2 3 4 2 10 3 2 10 4 3 2 10 3 4 2 3 10 4 2 3 10 4 2 4 10 3
	20	3 5 2 9 2 5 3 9 2 5 9 3 5 2 9 3 2 9 5 3 2 9 3 5
9	21	2 3 6 8 6 3 2 8 6 8 2 3 2 8 6 3 2 8 3 6 2 3 8 6
	21	2 4 5 8 4 2 5 8 4 5 2 8 5 4 2 8 5 2 4 8 2 5 4 8
	21	2 5 8 4 5 2 8 4 5 8 2 4 2 8 5 4 2 8 4 5 2 4 8 5
	21	4 6 2 7 2 6 4 7 2 6 7 4 6 2 7 4 2 7 6 4 2 7 4 6
	21	4 5 3 7 3 5 4 7 3 5 7 4 5 3 7 4 3 7 5 4 3 7 4 5
10	22	3 4 5 6 2
	22	2 4 5 3 7 3 5 7 4 2 5 3 7 4 2 3 7 5 4 2 5 3 7 2 4
	23	3 5 7 2 4
	23	5 4 3 8 2 3 4 5 8 2 5 8 3 4 2 5 8 2 4 3 3 2 7 6 4
	23	3 5 7 2 4
11	24	5 4 3 8 2 3 4 5 8 2 5 8 3 4 2 5 8 2 4 3 3 2 7 6 4
	24	6 4 7 2 3
	24	4 2 5 3 9 3 5 2 4 9 5 3 4 9 2 4 3 5 9 2 4 9 3 5 2
	24	3 5 9 4 2 5 3 9 4 2 3 9 5 2 4 5 3 9 2 4 3 5 9 2 4
	24	3 5 2 9 4 5 2 4 9 3 2 3 4 6 8 2 3 6 4 8 6 3 4 8 2
12	25	4 3 6 8 2 4 8 6 3 2 6 4 8 3 2 4 6 8 3 2 6 8 4 3 2
	25	6 3 2 8 4 6 8 2 3 4 6 5 3 7 2 3 5 6 7 2 3 7 5 6 2
	25	5 7 3 6 2 3 7 2 6 5
	25	2 4 3 5 10 2 4 5 3 10 3 10 4 5 2 5 10 3 4 2 3 5 10 4 2
	25	5 3 10 4 2 3 10 5 4 2 3 10 5 2 4 5 3 10 2 4 3 5 10 2 4
13	26	3 10 2 5 4 5 10 2 4 3 5 4 2 10 3 5 2 4 10 3 3 2 6 4 9
	26	3 4 6 2 9 6 4 3 9 2 3 4 6 9 2 4 3 9 6 2 3 4 9 6 2
	26	6 4 9 3 2 4 6 9 3 2 6 2 3 9 4 3 2 6 9 4 3 2 9 6 4
	26	6 2 9 3 4 6 2 9 4 3 6 4 9 2 3 3 2 4 7 8 4 2 3 7 8
	26	4 2 7 3 8 3 7 8 4 2 7 3 8 4 2 3 8 7 2 4 7 8 3 2 4
14	27	3 2 8 7 4 7 8 4 2 3 7 4 8 2 3 7 2 4 8 3 3 6 5 2 8
	27	3 6 5 8 2 3 6 8 5 2 6 3 8 5 2 6 3 8 2 5 3 6 8 2 5
	27	4 6 5 7 2 5 4 7 6 2 4 5 7 6 2
	27	2 4 3 5 11 5 3 4 2 11 4 5 3 11 2 5 4 3 11 2
	27	5 3 4 11 2 3 5 4 11 2 3 4 5 11 2 4 3 4 11 2
15	28	4 11 3 5 2 5 11 3 4 2 3 5 11 4 2 5 3 11 4 2
	28	5 3 11 2 4 3 5 11 2 4 3 5 2 11 4 5 11 2 4 3
	28	4 3 2 6 10 2 6 3 4 10 6 2 3 4 10 4 3 6 2 10
	28	6 3 4 10 2 4 3 6 10 2 4 3 10 6 2 3 4 10 6 2
	28	4 10 3 6 2 4 10 6 3 2 6 10 4 3 2 3 6 2 10 4
16	29	6 3 2 10 4 6 2 3 10 4 3 2 6 10 4 6 10 2 3 4
	29	6 2 10 3 4 6 2 10 4 3 2 4 7 3 9 2 3 7 4 9
	29	4 9 7 3 2 7 4 9 3 2 4 7 9 3 2 3 7 9 4 2
	29	7 3 9 4 2 3 9 7 4 2 7 3 9 2 4 3 7 9 2 4
	29	7 3 2 9 4 3 9 5 6 2 6 9 3 5 2 3 9 6 5 2
17	30	3 9 6 2 5 6 9 2 5 3 3 8 5 7 2 5 8 3 7 2
	30	3 8 2 7 5 2 5 4 6 8 2 5 6 4 8 6 5 4 8 2
	30	4 5 6 8 2 6 8 4 5 2 4 6 8 5 2 6 4 8 5 2
	30	4 8 6 5 2 6 8 2 5 4 6 5 2 8 4 3 5 4 6 7
	30	5 3 6 4 7 4 6 3 5 7 4 5 6 7 3 5 7 4 6 3
18	31	6 7 4 5 3 4 6 7 5 3 6 4 7 5 3 4 7 6 3 5
	31	6 7 3 5 4 6 3 5 7 4 6 2 5 9 3
	31	4 2 5 3 12 3 5 2 4 12 3 12 4 5 2 4 12 3 5 2
	31	5 12 3 4 2 3 5 12 4 2 5 3 12 4 2 3 12 5 4 2
	31	3 12 5 2 4 5 3 12 2 4 3 5 12 2 4 3 5 2 12 4
19	32	3 12 2 5 4 5 12 2 4 3 5 4 2 12 3 5 2 4 12 3
	32	2 3 4 6 11 2 6 4 3 11 4 3 11 6 2 3 4 11 6 2
	32	3 11 4 6 2 6 4 11 3 2 4 6 11 3 2 6 11 4 3 2
	32	3 2 11 6 4 3 11 2 6 4 6 11 2 3 4 6 2 11 3 4
	32	6 2 11 4 3 6 4 11 2 3 3 2 4 7 10 3 2 7 4 10
20	33	7 4 10 3 2 4 7 10 3 2 7 10 3 2 4 7 2 3 10 4
	33	3 2 7 10 4 3 2 10 7 4 7 10 4 2 3 7 4 10 2 3
	33	4 2 8 3 9 3 4 8 2 9 3 4 8 9 2 4 3 9 8 2
	33	3 4 9 8 2 3 8 9 4 2 8 3 9 4 2 3 9 8 2 4
	33	3 2 9 8 4 8 2 9 3 4 8 2 9 4 3 8 4 9 2 3

Table 4—continued

Number of channels	Switching range	Difference sequences giving third-order compatibility			
7	29	8 2 4 9 3	3 6 2 5 10	3 6 5 2 10	5 6 3 10 2
		6 5 3 10 2	6 3 5 10 2	3 6 5 10 2	3 5 6 10 2
		5 3 6 10 2	5 10 3 6 2	3 6 10 5 2	6 3 10 5 2
		6 3 10 2 5	3 6 10 2 5	3 6 2 10 5	7 3 5 9 2
		3 7 5 9 2	3 5 7 9 2	2 3 6 7 8	3 2 7 6 8
		2 3 7 6 8	3 6 7 8 2	3 8 6 7 2	6 8 3 7 2
		6 8 7 3 2	7 8 6 3 2	7 2 3 8 6	3 2 7 8 6
		7 8 2 3 6	4 6 2 5 9	5 9 4 6 2	4 6 9 5 2
		6 4 9 5 2	6 4 9 2 5	4 6 9 2 5	4 6 2 9 5
		2 4 5 7 8	7 5 4 2 8	5 7 4 2 8	7 4 5 8 2
7	30	4 7 5 8 2	4 5 7 8 2	5 4 7 8 2	7 8 5 4 2
		4 2 8 7 5	7 8 2 4 5	7 5 8 2 4	3 4 5 6 8
		5 6 3 4 8	6 4 5 8 3	5 4 6 8 3	4 8 5 6 3
		6 5 8 4 3	5 6 8 4 3	6 8 5 4 3	6 8 3 4 5
		5 3 7 9 2			
		2 8 6 5 4 3			
		3 4 6 2 9 5	2 9 6 4 3 5	2 9 5 3 4 6	2 6 5 9 3 4
		2 4 5 8 7 3			
		2 6 10 3 4 5	3 4 10 2 6 5	3 6 2 5 10 4	2 10 5 6 3 4
		2 6 5 10 4 3	2 6 10 5 4 3	2 4 7 9 3 5	2 4 7 9 5 3
7	31	3 2 7 4 6 8	4 6 8 3 2 7	2 3 6 7 8 4	3 2 7 8 6 4
		2 8 4 7 6 3			
		2 6 4 3 11 5	3 11 4 6 2 5	3 11 2 6 4 5	2 6 11 3 4 5
		6 2 11 3 4 5	4 11 2 5 3 6	3 4 5 11 2 6	2 11 3 5 4 6
		2 5 11 3 6 4	3 11 5 2 6 4	2 5 3 6 11 4	2 6 11 5 4 3
		2 11 6 4 5 3	2 5 11 4 6 3	2 4 10 3 5 7	2 4 5 3 10 7
		3 5 10 4 2 7	3 5 10 2 4 7	3 5 10 2 7 4	3 5 10 7 2 4
		2 7 4 10 5 3	2 4 7 10 5 3	2 4 10 7 5 3	2 4 5 7 10 3
		4 3 9 2 8 5	3 9 8 5 2 4	2 8 5 9 3 4	2 9 5 8 4 3
		2 5 9 4 8 3	2 3 7 4 9 6	4 9 7 3 2 6	2 3 9 7 4 6
7	32	4 9 6 2 3 7	3 2 6 4 9 7	2 3 9 6 4 7	2 6 9 3 7 4
		2 3 9 6 7 4	2 3 9 7 6 4	3 2 9 7 6 4	2 6 9 4 7 3
		2 8 7 5 6 3	2 6 4 5 11 3		
		2 6 3 4 12 5	4 3 6 2 12 5	4 6 3 12 2 5	3 6 4 12 2 5
		3 4 12 2 6 5	4 3 12 2 6 5	3 12 4 5 2 6	2 5 12 3 6 4
		3 12 6 2 5 4	2 6 5 12 3 4	2 6 5 12 4 3	2 12 5 6 4 3
		2 5 12 4 6 3	7 2 4 11 3 5	4 2 7 11 3 5	4 2 11 7 3 5
		4 2 11 3 7 5	4 2 11 3 5 7	4 2 11 5 3 7	3 5 11 4 2 7
		3 7 5 11 2 4	3 5 7 11 2 4	3 5 11 7 2 4	2 11 7 3 5 4
		3 10 8 4 2 5	3 4 2 10 8 5	3 4 2 10 5 8	3 10 5 2 4 8
7	33	2 5 4 8 10 3	3 2 10 4 7 6	3 2 10 6 7 4	3 2 6 7 10 4
		2 3 6 7 10 4	3 2 7 6 10 4	3 2 9 8 4 6	3 2 9 6 4 8
		2 3 8 9 6 4	2 9 8 6 4 3	3 7 5 9 2 6	2 6 5 9 3 7
		2 6 7 3 9 5	2 6 5 9 7 3	2 8 4 5 6 7	4 8 2 7 6 5
		2 6 13 3 4 5	6 2 13 3 4 5	2 13 4 3 5 6	4 13 2 5 3 6
		3 4 5 13 2 6	2 5 3 6 13 4	2 13 6 5 3 4	2 6 13 5 4 3
		2 6 4 5 13 3	2 5 4 6 13 3	2 4 7 3 5 12	2 4 7 3 12 5
		7 3 12 2 4 5	3 7 12 2 4 5	7 4 2 12 3 5	4 7 2 12 3 5
		2 7 4 12 3 5	7 2 4 12 3 5	4 2 7 12 3 5	2 4 7 12 3 5
		2 4 12 7 3 5	2 4 5 12 3 7	4 2 12 5 3 7	2 4 12 5 3 7
7	34	3 5 12 4 2 7	3 5 12 2 4 7	3 5 12 2 7 4	2 7 4 12 5 3
		2 4 7 12 5 3	4 2 7 12 5 3	2 4 5 12 7 3	2 8 5 4 3 11
		3 4 2 8 5 11	3 4 2 8 11 5	3 4 8 2 11 5	2 8 11 3 4 5
		8 2 11 3 4 5	2 4 3 11 8 5	2 4 3 11 5 8	3 4 5 11 2 8
		2 8 5 11 3 4	2 8 11 5 4 3	3 5 9 4 2 10	4 2 5 9 3 10
		4 2 9 5 3 10	3 9 10 4 2 5	9 3 10 4 2 5	2 9 10 4 3 5
		9 2 4 10 3 5	4 2 9 10 3 5	2 4 10 9 3 5	4 3 10 2 9 5
		4 2 10 3 5 9	4 2 5 10 3 9	2 4 10 5 3 9	3 10 9 5 2 4
		3 9 10 5 2 4	3 5 9 10 2 4	2 9 10 5 3 4	2 9 5 10 3 4
		2 10 5 9 4 3	2 5 10 4 9 3	4 6 7 2 3 11	7 2 3 11 4 6
7	35	3 2 7 11 4 6	2 3 11 4 6 7	4 6 11 3 2 7	2 3 7 6 11 4
		3 11 7 2 6 4	3 2 7 11 6 4	2 3 11 7 6 4	2 3 4 8 6 10
		2 3 4 8 10 6	2 3 8 4 10 6	4 3 2 10 8 6	4 3 2 10 6 8
		2 3 6 10 4 8	2 3 6 10 8 4	2 3 10 6 8 4	2 10 6 8 3 4
		2 10 8 6 3 4	2 4 7 3 9 8	2 3 7 4 9 8	4 7 9 3 2 8
		3 9 7 4 2 8	3 7 9 2 4 8	2 4 9 7 3 8	2 3 9 4 7 8
		3 9 8 2 4 7	2 4 9 8 3 7	4 2 8 3 9 7	2 4 8 3 7 9
		3 2 8 4 7 9	4 7 8 2 3 9	2 3 7 8 9 4	3 2 9 7 8 4
		3 9 7 8 2 4	2 3 9 8 7 4	3 2 8 9 7 4	2 4 8 9 7 3
		2 8 7 4 9 3	2 4 7 8 9 3	3 5 6 7 2 10	2 7 5 3 10 6
7	35	2 7 10 3 5 6	7 2 10 3 5 6	2 10 5 3 6 7	3 5 6 10 2 7
		2 6 3 10 5 7	2 6 3 10 7 5	3 10 6 2 7 5	2 10 7 6 3 5
		2 10 7 6 5 3	2 7 10 6 5 3	2 7 5 6 10 3	3 9 8 2 5 6
		2 5 6 8 9 3	2 6 9 4 7 5	2 6 4 7 9 5	2 9 5 7 6 4
		2 6 9 5 7 4	3 7 6 5 4 8	4 5 7 3 8 6	5 8 4 7 3 6
		5 4 8 3 7 6	4 8 5 6 3 7	3 8 6 4 5 7	4 6 3 8 7 5
		4 8 7 3 6 5	3 7 6 8 4 5	3 8 6 7 5 4	3 6 8 5 7 4
		3 4 5 6 2 14	2 6 4 3 14 5	2 6 3 4 14 5	4 3 6 2 14 5
		3 4 6 2 14 5	4 6 3 14 2 5	3 6 4 14 2 5	4 14 3 6 2 5
		2 6 14 3 4 5	6 2 14 3 4 5	2 14 6 4 3 5	2 14 3 4 6 5
7	35	3 4 14 2 6 5	4 3 14 2 6 5	2 14 3 4 5 6	3 4 5 14 2 6
		2 14 5 3 4 6	2 14 3 5 4 6	2 5 14 3 6 4	3 6 2 5 14 4
		2 6 5 14 3 4	2 6 5 14 4 3	2 14 5 6 4 3	2 14 6 5 4 3
		2 6 14 5 4 3	2 14 6 4 5 3	2 5 14 4 6 3	2 4 5 3 7 13
		7 3 13 2 4 5	3 7 13 2 4 5	2 4 13 7 3 5	2 4 13 3 7 5
		2 4 13 3 5 7	2 4 5 13 3 7	2 4 13 5 3 7	3 5 4 2 13 7
		2 4 5 3 13 7	2 4 13 7 5 3	2 13 7 4 5 3	2 13 5 4 7 3
		2 4 5 13 7 3	2 4 13 5 7 3	5 8 3 4 2 12	3 12 8 2 4 5
		3 8 2 12 4 5	2 8 3 12 4 5	4 2 12 3 8 5	3 4 12 2 8 5
		3 4 2 12 8 5	2 4 3 12 8 5	3 4 2 12 5 8	2 4 3 12 5 8
7	35	3 12 5 4 2 8	3 8 2 5 12 4	3 8 5 12 2 4	3 8 2 12 5 4
		2 8 3 12 5 4	2 12 5 8 3 4	2 8 5 12 4 3	2 4 5 8 12 3

Table 4—continued

Number of channels	Switching range	Difference sequences giving third-order compatibility			
8	40	2 5 3 9 4 11	2 4 9 11 3 5	2 5 3 11 4 9	2 5 3 11 9 4
		2 5 3 9 11 4	2 11 9 5 3 4	2 4 9 11 5 3	2 3 5 4 12 7
		4 6 3 2 12 7	2 6 12 3 7 4	3 2 6 7 12 4	2 12 7 4 6 3
		2 6 12 4 7 3	2 7 4 6 12 3	2 3 4 6 8 11	6 8 4 3 2 11
		2 8 6 3 4 11	6 8 2 3 4 11	3 2 11 8 4 6	2 3 11 8 4 6
		2 8 11 4 3 6	3 2 11 4 8 6	3 4 11 2 8 6	4 3 2 11 8 6
		2 3 4 11 8 6	2 3 4 11 6 8	4 3 2 11 6 8	3 2 11 4 6 8
		2 3 4 6 11 8	2 3 11 6 4 8	3 2 11 6 4 8	3 2 11 6 8 4
		3 6 11 2 8 4	3 2 8 6 11 4	3 2 11 8 6 4	2 8 11 6 3 4
		2 8 6 11 4 3	2 11 6 8 4 3	2 8 4 11 6 3	3 4 9 6 2 10
		3 2 6 9 4 10	3 4 9 10 2 6	3 2 6 10 4 9	3 2 6 10 9 4
		3 2 6 9 10 4	3 2 4 7 8 10	3 8 7 2 4 10	7 8 3 2 4 10
		4 10 8 3 2 7	3 8 10 4 2 7	2 3 10 8 4 7	2 4 10 3 8 7
		3 2 4 10 8 7	3 2 4 10 7 8	4 10 7 2 3 8	3 2 7 4 10 8
		2 3 10 7 4 8	3 2 4 7 10 8	2 7 10 3 8 4	3 8 7 2 10 4
		3 2 7 8 10 4	2 3 8 7 10 4	3 8 10 7 2 4	3 8 7 10 2 4
		2 7 10 4 8 3	2 4 10 7 8 3	2 4 8 7 10 3	5 7 3 11 2 6
		3 7 5 11 2 6	5 11 3 7 2 6	2 11 7 5 3 6	2 11 6 3 5 7
		2 6 11 3 7 5	2 11 6 3 7 5	3 7 2 6 11 5	2 7 6 11 3 5
		2 7 6 11 5 3	2 6 11 5 7 3	2 6 7 5 11 3	3 6 5 2 10 8
		3 6 10 2 5 8	2 5 8 10 6 3	2 10 8 5 6 3	2 9 3 7 8 5
		2 9 5 8 7 3	2 9 8 5 7 3	5 4 7 6 2 10	2 6 7 5 4 10
		7 4 5 10 2 6	5 4 7 10 2 6	2 10 4 5 6 7	5 4 10 2 6 7
		4 10 7 2 6 5	4 10 2 7 6 5	2 6 7 10 4 5	2 10 7 6 5 4
		2 6 5 7 10 4	4 6 8 5 2 9	6 4 8 5 2 9	2 5 9 8 4 6
		5 2 9 8 4 6	2 9 5 8 4 6	5 2 9 4 8 6	5 2 9 4 6 8
		5 2 9 6 4 8	2 5 9 6 4 8	4 8 6 9 2 5	4 6 8 9 2 5
		2 8 4 9 6 5	2 5 6 9 8 4	4 9 7 3 5 6	3 5 7 9 4 6
		4 6 5 3 9 7	3 5 6 4 9 7		
		3 5 6 4 12 7 2	5 3 12 6 4 7 2	3 7 12 4 5 6 2	
		3 7 4 5 12 6 2	5 4 7 3 12 6 2	4 5 12 2 6 7 3	
		4 5 6 2 12 7 3	4 8 2 5 11 6 3	4 3 9 10 5 6 2	
		9 3 4 10 5 6 2	5 7 8 3 10 4 2	6 9 7 4 8 2 3	
		3 5 6 4 13 7 2	4 6 5 3 13 7 2	4 6 13 3 5 7 2	
		6 2 13 5 4 7 3	5 6 3 4 12 8 2	4 3 6 5 12 8 2	
		5 2 12 8 3 6 4	8 3 6 4 12 2 5	5 4 8 7 3 11 2	
		3 7 11 5 8 4 2	2 4 7 9 3 5 10	3 5 10 9 7 4 2	
		7 4 2 10 9 5 3	2 3 6 7 8 4 10	6 8 4 7 10 3 2	
		8 4 10 7 6 3 2	4 7 6 8 10 2 3		

If the carrier frequency of the first channel is to be 105 MHz, seven carriers (in megahertz) which have freedom from interfering third-order intermodulation products are

$$\left. \begin{array}{llll} 105.0000 & 105.0250 & 105.1250 & 105.2000 \\ 105.2625 & 105.3125 & 105.3500 & \end{array} \right\} \quad (38)$$

5 Fifth-order intermodulation products

Techniques similar to those of the previous sections can be used to determine the channel groupings which are free from interfering fifth-order intermodulation products. It can be seen from eqns. 11 and 12 that troublesome fifth-order products arise when both the following equations are satisfied:

$$|\alpha_1| + |\alpha_2| + |\alpha_3| + |\alpha_4| + |\alpha_5| = 5 \quad (39)$$

$$\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 = 1 \quad (40)$$

These equations have the following six solutions:

$$\left. \begin{array}{l} \alpha_i = 1, \alpha_j = 1, \alpha_k = 1, \alpha_l = -1, \alpha_m = -1 \\ \alpha_i = 1, \alpha_j = 1, \alpha_k = 1, \alpha_l = -2, \\ \alpha_i = 2, \alpha_j = 1, \alpha_k = -1, \alpha_l = -1, \\ \alpha_i = 2, \alpha_j = -2, \alpha_k = 1, \\ \alpha_i = 3, \alpha_j = -1, \alpha_k = -1, \\ \alpha_i = 3, \alpha_j = -2, \end{array} \right\} \quad (41)$$

for $i, j, k, l, m = 1, 2, 3, 4, 5$ and $i \neq j \neq k \neq l \neq m$.

The first equation in this set is the most general, and it gives rise to the following condition, in terms of channel numbers:

$$C_x = C_i + C_j + C_k - C_l - C_m \quad (42)$$

which can be written

$$(C_x - C_l) = (C_j - C_i) + (C_k - C_m) \quad (43)$$

By removing the implied condition in eqn. 43, that no channel number should appear more than once, the other degenerate members of eqns. 41 are realised. For example, if we let

$$C_l = C_m \quad (44)$$

eqn. 43 reduces to

$$(C_x - C_l) = (C_j - C_l) + (C_k - C_l) \quad (45)$$

which in turn gives

$$\alpha_1 = 1, \alpha_2 = 1, \alpha_3 = 1, \alpha_4 = -2 \quad (46)$$

which is a realisation of the second member of eqn. 41. All the restrictions, such as eqn. 44, give rise to a solution of one member of eqn. 41. For this reason, the first member is the general generic condition for interfering fifth-order intermodulation products. One exception to the above is to permit

$$C_j = C_x, C_k = C_l, C_m = C_i \quad (47)$$

which gives the condition

$$(C_x - C_l) = (C_x - C_k) + (C_k - C_l) \quad (48)$$

Eqn. 48 is merely an identity, and it is automatically satisfied for any values given to the channel numbers. Eqn. 48 does not arise from any solution of eqns. 41, and it is therefore excluded as a possible contraction of eqn. 43.

The significance of eqn. 43 can be expressed as the following simple result: for the channels $C_1, C_2, \dots, C_n$ to be free from interfering fifth-order intermodulation products, the difference between any two channel numbers should not equal the sum of any other two such differences. This, of course, includes the case where a given difference is added to itself. It should also be noted that channels which are free from

Table 5

MINIMUM SWITCHING RANGES FOR FIFTH-ORDER COMPATIBILITY

Number of channels	Minimum switching range for fifth-order compatibility
4	13
5	26
6	>40

Table 6

CHANNEL DIFFERENCE SEQUENCES FREE FROM FIFTH- AND THIRD-ORDER INTERFERING INTERMODULATION PRODUCTS

Number of channels	Switching range	Difference sequences giving fifth-order compatibility									
4	13	3 7 2	3 4 5								
	14	3 8 2	2 5 6	5 2 6	5 6 2						
	15	2 3 9	3 2 9	3 9 2							
	16	3 10 2	2 5 8	2 6 7	6 2 7	6 7 2	3 5 7	4 5 6			
	17	2 3 11	3 2 11	3 11 2	5 9 2	3 4 9	4 3 9	4 9 3			
		4 5 7	5 4 7	5 7 4							
	18	2 3 12	3 2 12	3 12 2	2 6 9	6 2 9	6 9 2	2 7 8			
		7 2 8	7 8 2	4 10 3	3 5 9	5 3 9	5 9 3	4 6 7			
		6 4 7	6 7 4								
	19	2 3 13	3 2 13	3 13 2	2 5 11	5 2 11	5 11 2	4 11 3			
		3 7 8	7 3 8	7 8 3	5 6 7						
	20	2 3 14	3 2 14	3 14 2	5 12 2	2 6 11	6 2 11	6 11 2			
		2 7 10	7 2 10	7 10 2	2 8 9	8 2 9	8 9 2	3 4 12			
		4 3 12	4 12 3	5 11 3	3 7 9	7 3 9	7 9 3	4 6 9			
		6 4 9	6 9 4	5 6 8	6 5 8	6 8 5					
	21	2 3 15	3 2 15	3 15 2	2 5 13	5 2 13	5 13 2	7 11 2			
		3 4 13	4 3 13	4 13 3	3 5 12	5 3 12	5 12 3	3 8 9			
		8 3 9	8 9 3	4 5 11	5 4 11	5 11 4	4 7 9	7 4 9			
		7 9 4	5 6 9	6 5 9	6 9 5	5 7 8	7 5 8	7 8 5			
5	26	5 13 3 4	5 13 4 3								
	27	2 6 11 7	3 9 10 4								
	28	2 8 14 3	2 3 9 13	2 12 8 5	2 12 5 8	2 9 6 10					
		2 9 10 6	5 15 3 4	3 4 15 5	4 9 3 11	3 11 9 4					
	29	2 16 7 3	2 16 3 7	2 15 8 3	2 15 3 8	3 2 11 12					
		2 3 12 11	2 6 15 5	6 2 15 5	6 15 2 5	2 5 15 6					
		2 9 12 5	5 16 3 4	3 16 5 4	3 16 4 5	3 4 16 5					
		3 10 11 4	3 13 7 5	3 13 5 7	3 9 11 5	8 5 6 9					
		5 8 9 6									
	30	2 7 17 3	7 2 17 3	3 2 9 15	9 15 2 3	6 16 2 5					
		2 5 16 6	2 13 9 5	2 11 10 6	2 11 6 10	2 7 8 12					
		2 7 12 8	5 17 3 4	3 17 5 4	3 17 4 5	3 4 17 5					
		4 10 3 12	3 12 10 4	3 12 4 10	4 14 6 5	4 14 5 6					
	31	2 9 16 3	2 3 16 9	3 2 12 13	2 3 13 12	5 2 6 17					
		6 2 5 17	2 6 17 5	6 2 17 5	6 17 2 5	2 5 17 6					
		2 11 5 12	2 11 12 5	11 2 12 5	2 6 13 9	7 2 8 13					
		2 7 13 8	7 10 2 11	2 10 7 11	2 10 11 7	2 11 10 7					
		5 18 3 4	3 4 18 5	3 11 12 4	5 9 3 13	3 13 9 5					
		3 10 9 8	4 7 10 9								
	32	2 7 19 3	7 2 19 3	2 19 7 3	2 19 3 7	2 18 8 3					
		2 18 3 8	9 17 2 3	2 17 9 3	2 17 3 9	2 3 17 9					
		2 10 16 3	10 2 16 3	2 3 11 15	11 15 2 3	2 3 15 11					
		2 6 18 5	6 2 18 5	6 18 2 5	2 18 6 5	2 18 5 6					
		2 5 18 6	5 9 2 15	2 15 9 5	2 15 5 9	2 16 7 6					
		2 16 6 7	6 9 2 14	2 14 9 6	2 14 6 9	2 13 10 6					
		2 13 6 10	8 9 2 12	2 12 9 8	2 12 8 9	5 19 3 4					
		3 19 5 4	3 19 4 5	3 4 19 5	3 4 9 15	3 4 15 9					
		4 11 3 13	3 13 11 4	3 13 4 11	5 11 3 12	3 12 11 5					
		3 12 5 11	3 8 7 13	3 8 13 7	6 16 4 5	4 5 16 6					
		4 5 7 15	7 15 4 5	4 5 15 7	6 7 8 10	6 7 10 8					

fifth-order interference are automatically free from third-order interference.

6 Calculation of channel sequences which are free from interfering fifth-order intermodulation products

The simple condition for fifth-order compatibility, derived in Section 5, was used as the basis of a computer program which was written for the evaluation of permissible channel difference sequences. The test condition was again reduced to tabular form.

As for the third-order products, the contenders for a valid fifth-order sequence are all element permutations of the partition of $S - 1$ into $n - 1$ components, and only the test procedure on these sequences is changed. As an intermediate step, the triangular array of Table 1 previously used for third-order compatibility assessment, is constructed for the single difference sequence under test. By rewriting this array column by column, a new complete sequence of differences is formed. This sequence now forms both the first row and the first column of a new array, as shown in Table 2. Further elements are formed by adding together the leading row term and the leading column term. The array now contains all the possible differences between channel numbers, and all the possible sums of these differences taken two at a time. As the array is symmetrical, only the lower triangle need be evaluated.

Before applying the test for a valid fifth-order solution, certain degenerative terms, illustrated by eqns. 47 and 48,

must be eliminated from the array. These are the encircled terms in Table 2. With the removal of these entries, the conditions expressed by eqns. 41 can now be stated simply: for a valid fifth-order solution, each remaining element in the array should not be equal to any element in the generating sequence (the first row or column).

An example will illustrate the foregoing test procedures. Consider the simple difference sequence 2, 3, 9 under test: the third-order array becomes

$$\begin{array}{ccc} 2 & & \\ 3 & 5 & \\ 9 & 12 & 14 \end{array} \quad \dots \quad (49)$$

This array is now written, column by column, to form the generating sequence

$$2 \ 3 \ 9 \ 5 \ 12 \ 14 \quad \dots \quad (50)$$

This sequence forms the generating row and column for the fifth-order array

$$\begin{array}{cccccc} 2 & 3 & 9 & 5 & 12 & 14 \\ 2 & 4 & & & & \\ 3 & \textcircled{5} & 6 & & & \\ 9 & 11 & \textcircled{12} & 18 & & \\ 5 & 7 & 8 & \textcircled{14} & 10 & \\ 12 & \textcircled{14} & 15 & 21 & 17 & 24 \\ 14 & 16 & 17 & 23 & 19 & 26 & 28 \end{array} \quad \dots \quad (51)$$

The encircled terms are removed, as they correspond to identities in the manner of eqns. 47 and 48. As every remaining element in the array is different from each element in the generating row and column, the sequence 2, 3, 9 is a valid fifth-order solution. As an example, channel numbers

$$C_1 = 1, C_2 = 3, C_3 = 6, C_4 = 15 \dots \dots (52)$$

exhibit both third- and fifth-order compatibility.

The computer program written to calculate all the possible valid fifth-order difference sequences was run for a range of switching range S and number of channels n . The minimum possible calculated switching range for a given number of channels is given in Table 5, and the full results are given in Table 6. Again, only one half of the valid sequences are shown, because a sequence reversal also represents a valid solution. From the results, it is clear that considerably more switching ranges are required to give freedom from fifth-order effects. Because of the large number of partitions generated as S is increased, excessive computation time has limited the number of results obtained for the fifth-order case.

7 Freedom from higher-order intermodulation products

Similar techniques can be applied to investigate higher-order intermodulation products. The general result can be stated as follows: for freedom from interfering $(2m + 1)$ th-order intermodulation products, the difference in any pair

of channel numbers should not be equal to the sum of any other such differences taken m at a time. In view of the excessive switching ranges implied and the diminishing importance of higher-order terms, it was considered that such calculations would have negligible practical value.

8 Conclusions

The paper has presented results which enable the designer of a mobile radio network to select channel frequencies which are free from interfering third- or fifth-order intermodulation products.

9 References

- 1 HOOPER, J.: 'The probability of excessive delay in a communication channel'. Central Electricity Research Laboratories Report RD/L/N132/66, 1967
- 2 HOOPER, J.: 'Traffic-handling capacity and numbers of mobiles in mobile radio networks', *Proc. IEE*, 1968, 115, (8), pp. 1120-1122
- 3 MARTIN, R. E.: 'Trends in the field of mobile radio communication with particular reference to the fuel and power industries'. Central Electricity Research Laboratories Report RD/L/M814, 1968
- 4 'Characteristics of equipment and principles governing the allocation of frequency channels in the land mobile services between 25 and 500 MHz'. CCIR 12th plenary assembly, Report GPC/CP.71, 1968
- 5 GRETSCH, W. R.: 'The spectrum of intermodulation generated in a semiconductor-diode junction', *Proc. Inst. Elect. Electron. Engrs.*, 54, 1966, pp. 1528-1535
- 6 STEINER, J. W.: 'An analysis of radio frequency interference due to mixer intermodulation products', *IEEE Trans.*, 1964, EC-4, pp. 62-68

Examples of Signals and Noise in the Radio-Frequency Spectrum

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Abstract—Many types of signals and noise inhabit the radio-frequency (RF) spectrum. This paper presents selected examples of the electromagnetic energy occupying blocks of this spectrum as observed on a real-time 3-axis (amplitude versus frequency and time) display connected to the output of a scanning receiver. These examples provide some insight into spectrum utilization.

I. INTRODUCTION

THE ABILITY of radio receivers to detect and reproduce accurately, intelligence carried by radio signals is often limited by other (undesired) signals or by unintentionally generated man-made radio noise [1], [2]. Numerous studies and measurements of man-made radio noise have been made in an attempt to characterize properties of noise for the detailed analysis of receiver detection processes [3]–[5]. However, the often erratic and variable properties of some signals [6] and of man-made radio noise have made all-inclusive measurements, definitions, and analyses very difficult [2]. The large number of diverse sources of signals and radio noise suggests that a great variety of amplitude-frequency-time structures can be significant at any given receiving site. This variety of signal structure has raised numerous questions such as: 1) what are the spectral properties of signals, ignition noise, powerline noise, industrial noise, etc.; 2) what is the predominate noise affecting HF, VHF, and UHF receivers; 3) can noise be adequately characterized by amplitude probability distributions, peak measurements, average measurements; 4) can noise and signals always be easily separated; and, 5) why is the issue so complicated?

In an effort to understand better the gross properties of man-made noise and its relationship to the signals occupying the spectrum, a series of observations and measurements have been made of noise and signals in blocks of frequencies. These measurements were made at typical urban and suburban receiver locations. A scanning receiver and a 3-axis display were employed to measure and portray noise and signals existing in a selected block of frequencies for brief periods of time [7]–[11]. These observations and measurements have provided considerable insight into the erratic and often unpredictable impact of man-made noise on desired radio signals. Selected examples of 3-axis displays are presented in this paper to illustrate what electromagnetic energy is actually inhabiting the RF spectrum.

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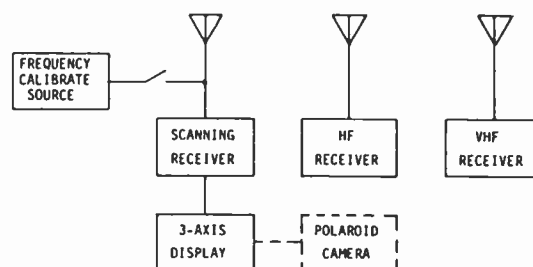


Fig. 1. Block diagram of measurement system.

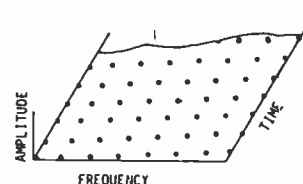


Fig. 2. Data sampling process.

II. DESCRIPTION OF INSTRUMENTATION

The instrumentation used to acquire the data presented in this paper is shown in the block diagram in Fig. 1. A Hewlett Packard 140/141 Spectrum Analyzer was used as a scanning receiver to drive an EMTEL Model 7200B 3-Axis Display System. The 3-axis display provided a moving real-time visual representation of signals and noise received by the scanning receiver.

The display system converts the output of each scan of the spectrum analyzer from analog to digital data; these are stored in a digital memory. The output of the memory is rapidly scanned at a rate exceeding the flicker detection of the eye, with the data in the memory being formatted and shown on a CRT in a convenient and easy-to-interpret 3-axis presentation. If desired, digital data flowing into the memory can be recorded on digital magnetic tape in computer-compatible formats for use in statistical computation of spectrum occupancy. The 3-axis presentations can be photographed by still cameras (including Polaroid), and moving-frame cameras.

Fig. 2 illustrates the process used to convert the analog output of the spectrum analyzer into a 3-axis pictorial view. As the spectrum analyzer scans through a selected block of spectrum space, its output is divided into equally-spaced data points which are indicated by the black dots in the figure. The signal amplitude at each data point is represented by an 8-bit computer word which provides an amplitude resolution of 256 levels for each data point. When a scan is com-

pleted, it is stored in the memory and presented as line 1 on the pictorial view. When the second scan is completed, its data are stored in the memory, line 1 on the view moves to line 2, and the new scan is presented on line 1. Subsequent scans move the earlier data lines step-by-step along the time axis until the entire memory is filled. When the memory is full, each new scan causes the oldest scan to be discarded. The resulting animated moving view of signals and noise within the spectrum block under observation provides a unique and easy-to-interpret visual picture of the noise and signal population in the spectrum.

The 3-axis display system has a number of controls to assist the operator in interpreting the signals. Among these controls are: a stop-action control to freeze any desired view for detailed observation; geometry controls to vary the viewing aspect; display mode controls to select any segment of the total view for detailed examination and; a threshold control to vary the background noise level.

The 3-axis views presented in this paper were obtained by photographing the display in its stop-action mode. In interpreting the data, consideration must be given to situations where repetitive impulsive signals are observed by the repetitive scanning process. The relative repetition rates of impulsive signals and the scan rate of the receiver produces distinctive bands that slant across the CRT.

III. EXAMPLES OF MAN-MADE NOISE AND SIGNALS

A number of examples of man-made radio noise and radio signals sharing portions of the radio spectrum are provided in subsequent 3-axis views. These examples are representative of the variety and types of man-made radio noise found in most urban and suburban areas. Care was taken not to emphasize unusual or rare cases of noise.

1) *Land-Mobile Transmissions and Automobile Ignition Noise (155 MHz)*: Fig. 3 shows an example of land-mobile transmissions observed in Menlo Park, CA during an interval when an automobile was idling near the scanning receiver. The vehicle was turned off for about 30 s, starting at 60 s, and then turned on again for another 30 s. The noise produced was broadband as observed on this display, which was generated using a spectrum analyzer, a magnetic tape recorder, and non-real-time computer processing as described in [7].¹ A nearby land-mobile base station (the Menlo Park police) is shown on the left of Fig. 3, and a weaker simulated desired signal is indicated at a level that might be adversely affected by the ignition noise when both are present.

Table I provides pertinent measurement-system parameters for each of the following views. These parameters are useful for the reader who wishes to carefully scale detail from the

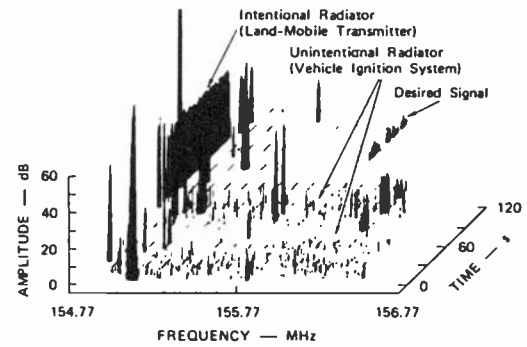


Fig. 3. Land mobile transmissions and automobile ignition noise.

TABLE I
MEASUREMENT SYSTEM PARAMETERS

Fig	Time/Scan (ms)	Blanking Time (ms)	Amplitude Cal (dB/cm)	IF Bandwidth (kHz)
4	50	5	40	3
5	20	5	20	10
6	50	5	20	30
7	50	5	20	10
8	100	~80	20	10
9	100	80	>40	3
10	200	80	20	0.1
11	20	5	40	0.1
12	200	80	>40	3
13	100	80	>40	3
14	100	80	40	3
15	20	5	20	3
16	200	80	20	300
17a	50	5	>60	10
17b, c, d	100	80	>60	10
18	200	80	10	300

3-axis views or to relate noise and signal parameters to other data.

2) *Auto Ignition Noise (30-50 MHz)*: Radiation from auto ignition is a major source of radio noise in the upper HF and VHF parts of the radio spectrum. Fig. 3 shows automobile noise ignition on a relatively compressed amplitude scale. The 3-axis signature of ignition noise shown in Fig. 4, where the distinctive curved lines are caused by the changing interval between ignition impulses as engine speed varies, shows considerable time resolution. The noise impulses originated from an auto several hundred yards from the receiving site, and represent the occasional noisy automobile [12]. The noise peaked in amplitude at about 40 MHz and affected the reception of signals in the land-mobile service over the range of about 32 MHz to 47 MHz.

3) *Land-Mobile Transmissions and Powerline Noise (30-50 MHz)*: Fig. 5(a) shows a 3-axis view of land-mobile signals and radiated noise originating at a power line. Signals from the land-mobile service can be seen which are parallel to the time axis and at fixed frequencies. Two large slanting areas of noise can be seen in the view occupying the band from 30 MHz upward to about 42 MHz with a minimum in noise amplitude at about 33 MHz. These distinctive slanting areas are caused by the interaction of the scanning receiver measurement process and the 120 Hz peaks in noise power from the alternating voltage producing the noise. The peaks in observed noise are slightly more than 8 ms apart which agree with the

¹ The instrumentation which produced Fig. 3 was a predecessor to the system used to obtain the subsequent examples. It consisted of a Hewlett Packard 140/141 Spectrum Analyzer whose output was recorded on analog magnetic tape. The tape was digitized and processed by a general-purpose computer with associated graphics. The resulting 3-axis views were produced by the Stanford Research Institute in a marching time format on 16-mm film for a motion picture projector in 1969. The movie was presented to the FCC as a part of their efforts under Dockets 18261 and 18262.

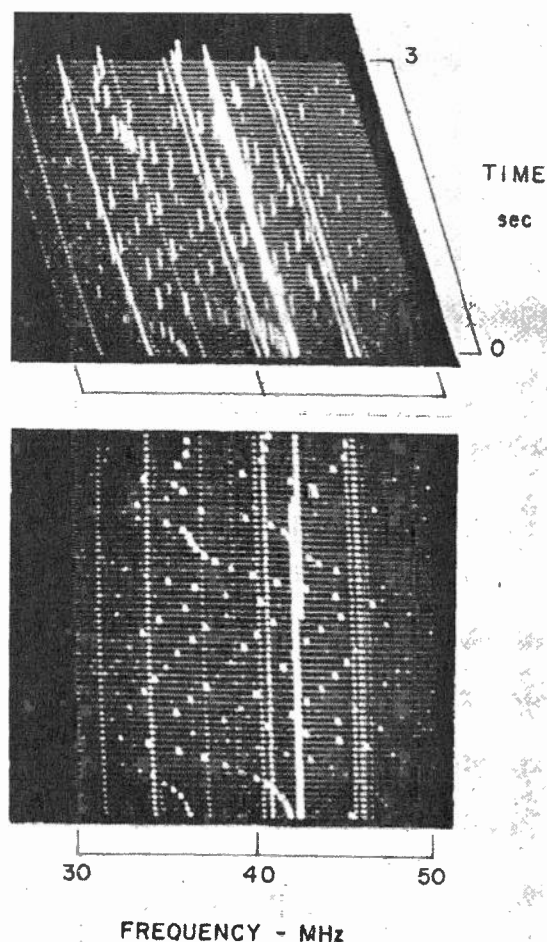


Fig. 4. Automobile ignition noise during engine speed variation (30-50 MHz).

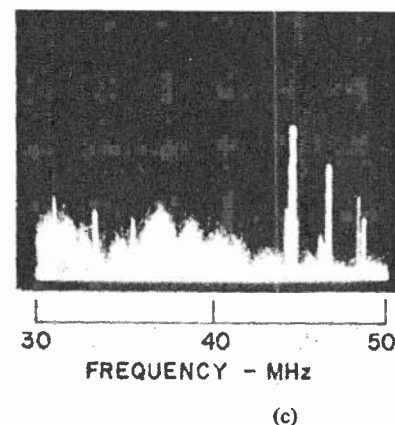
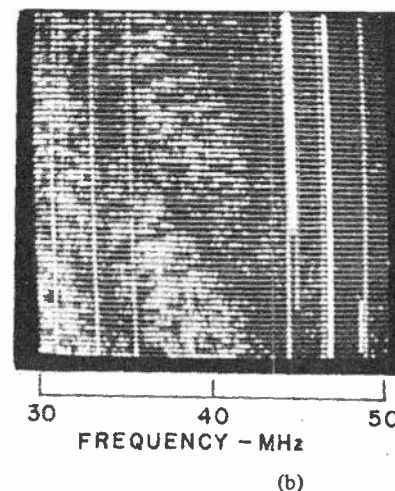
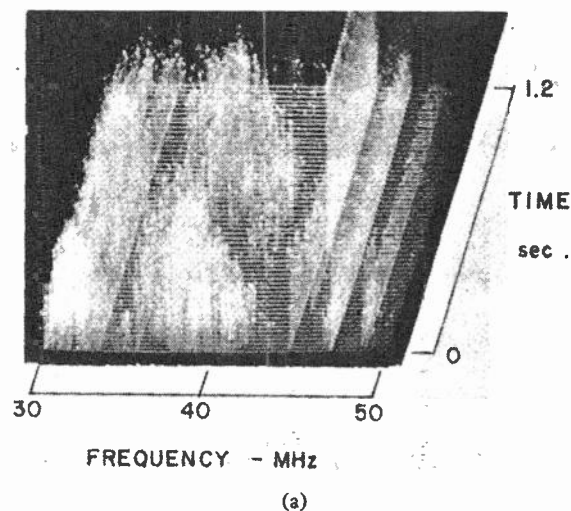


Fig. 5. Land mobile transmissions and powerline noise (30-50 MHz).

interval between maxima of powerline voltage. Fig. 5(b) shows the same data as Fig. 5(a) but with amplitude fully compressed and the horizontal aspect of the view changed to 0° . Fig. 5(c) shows the same data with the amplitude uncompressed, the horizontal aspect at 0° , and the vertical axis tilted downward to 0° to give a display like a standard spectrum analyzer with a memory oscilloscope.

Signals below about 43 MHz were largely covered by the received noise. A land-mobile receiver at the same location experienced considerable difficulty in receiving signals due to the man-made noise. Above 43 MHz very little noise degradation of receiver performance was experienced.

4) Calculator Noise (30-50 MHz): During the measurement of noise and signals, a new and very strong but intermittent noise source was observed. The noise signature is shown in Fig. 6, and it prevented the reception of signals in the 30 to 50 MHz band at the measurement site. The source was traced to an ancient but still running motor-driven mechanical calculator located in the accounting department of a small company which was several-hundred feet from the measurement-system antenna. However, a common electrical-power distribution system provided a combination radiation/conduction path for the noise to enter the receiving-system antenna and severely limit the reception of signals in the lower part of the VHF band.

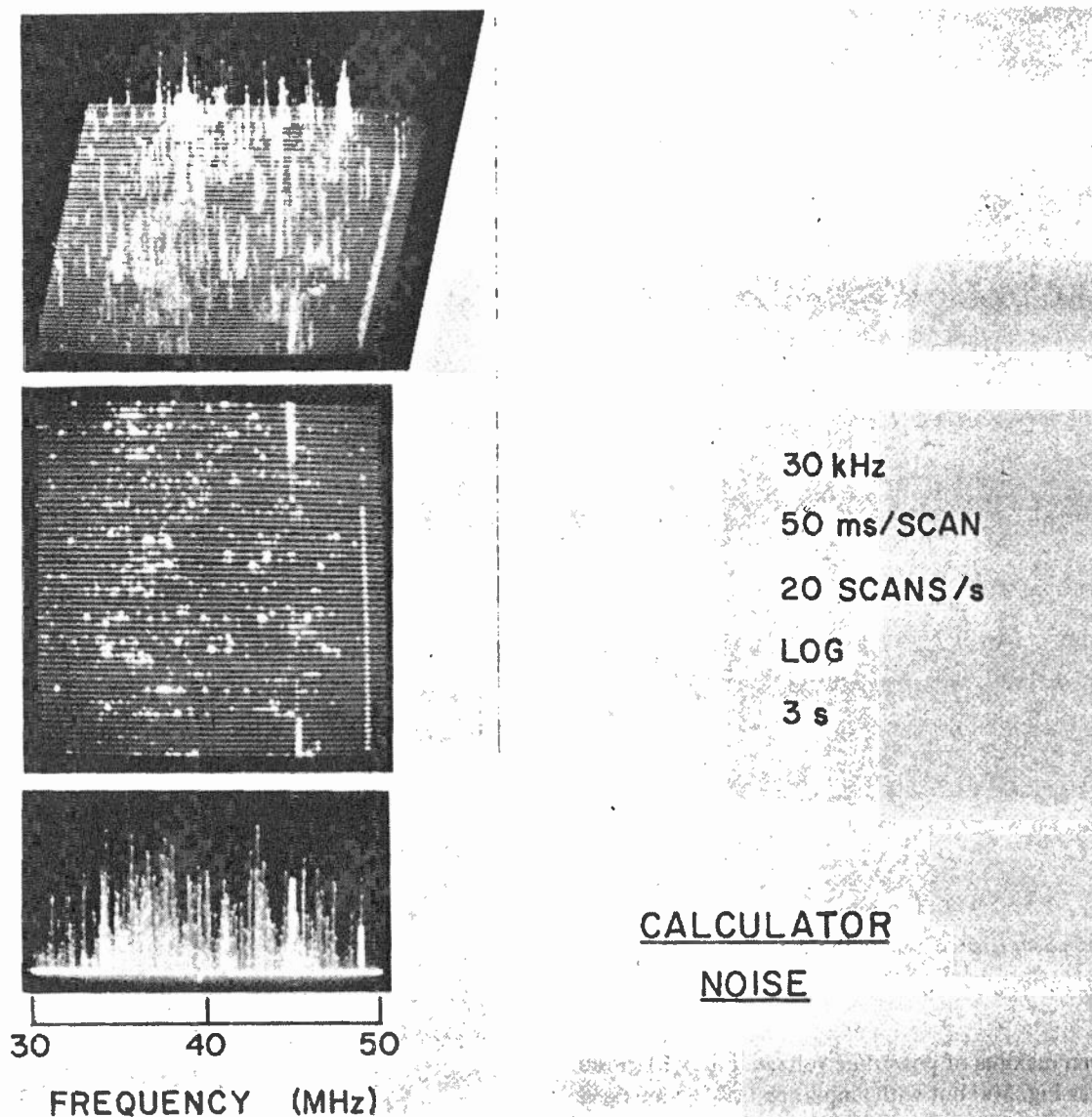


Fig. 6. Calculator noise (30-50 MHz). IF bandwidth is 30 kHz, sweep time is 50 ms/scan, sweep rate is 20 scans/s, amplitude is log, and time axis is 3s.

5) *Random Noise Bursts (30-50 MHz)*: Random bursts of radio noise from an unknown source along with VHF signals from the land-mobile service are shown in Figs. 7(a) and 7(b). Distinct noise maxima occurred near 34 and 40 MHz with little noise above 45 MHz. Maximum noise occurred for about one second near the center of the time scale.

The random bursts of noise seriously degraded reception of two weak signals near 35 MHz during the maximum period of the noise and somewhat degraded reception of the two signals immediately below and above 40 MHz. Signals above 43 MHz were not affected either because their strength was significantly above the noise peak amplitude or at the higher frequencies there was no noise.

6) *Electric-Train Noise (1.5-8 MHz)*: Man-made radio noise originating from a modern rapid-transit system was examined with the objective of obtaining initial data on the gross characteristics of such noise [9].

Radio noise emanating from trains of a rapid-transit system was examined by parking a van containing a spectrum measurement system on a city street parallel and adjacent to ground level tracks of the transit system. The van was parked about 400 yards from a station to allow observation of arriving and departing trains. An 8-foot vertical antenna was used as a pick-up antenna for all measurements. The antenna was about 60 feet from the tracks.

Radio noise levels in the 0.5 to 8.5-MHz region increased substantially above the background noise environment each time a commuter train was in the vicinity of the measurement van. Noise from trains arriving at the station was largely impulsive in nature. Strong bursts of noise appeared to be correlated with track switching operations. Bright arcing observed in the wheel area of the cars was associated with radio-noise bursts on the 3-axis display. Noise bursts from arriving trains exceeded the receiver threshold by 20 to 30 dB.

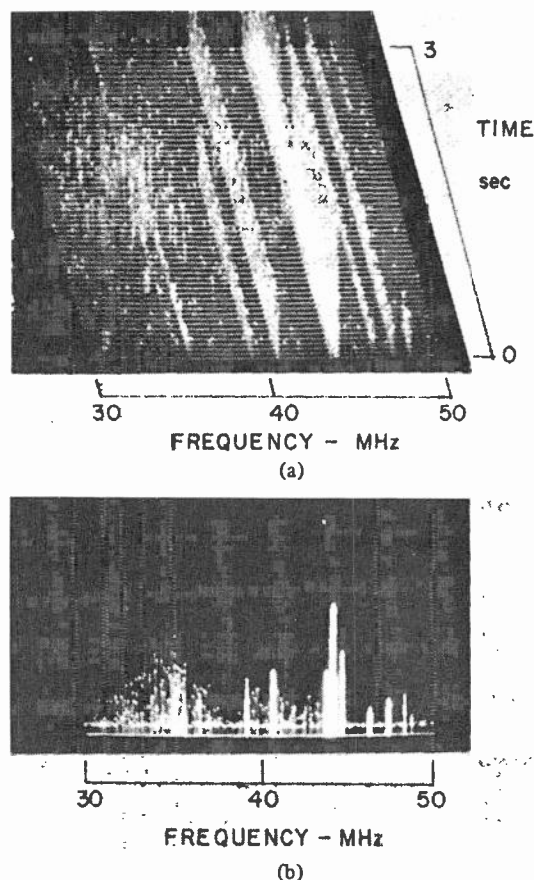


Fig. 7. Random noise bursts (30-50 MHz).

Repetitive impulsive noise from departing trains was observed for a 20-to 30-s period each time a train passed the measurement van. The observed signals appeared to represent HF switching transients and are probably associated with the driver-motor control circuitry. Fig. 8 shows four sets of typical data from departing trains. Each 3-axis data frame is shown with two viewing aspects to aid in visual interpretation of the noise spectrum signature.

Fig. 8(a) shows a typical view of time and spectral variations of the repetitive noise in a 1-MHz block of spectrum space centered at 2 MHz. Noise at the top of the view occurred as the train approached the measurement van. Noise energy was concentrated in the 1.7 to 2.4-MHz region for several seconds. The noise then disappeared for about 2 s. Observation of the nearby train indicated that the motor control propulsion system was turned off during the period of minimum noise. When the propulsion system was turned on, strong noise impulses were observed over the entire 1-MHz band. Signals from two broadcast stations can be observed near the left edge of Fig. 8(a). The noise spikes are about equal in amplitude to the station near 1.6 MHz and less in amplitude than the local station near 1.55 MHz.

Fig. 8(b) shows noise observed in a 5-MHz block of spectrum space which is centered at 4 MHz. Areas of maximum noise energy and areas of minimum noise energy can be observed. These areas move in the frequency-time space shown in the 3-axis view. Reasons for the time variations of the noise

spectrum signature were not pursued; however, they may be associated with the changing orientation of the train with respect to the measurement van (radiation-pattern effects), variations in the noise source as propulsion is changed, or a combination of these factors.

Figs. 8(c) and 8(d) show noise observed in a 5-MHz block of spectrum which space is centered at 6 MHz. These views also show areas of maximum and minimum noise energy. In Fig. 8(c) the minimum noise near the center of the time scale was associated with propulsion-system power reduction. Other maxima and minima move throughout the views and produce distinctive noise spectrum-signature patterns. The maximum observed frequency of the noise was about 8.5 MHz.

The spacing between noise impulses along the frequency axis provides a measure of the impulse repetition rate. About twenty-two impulses occur during the 100-millisecond scan period. This suggests an impulse period of about 4.5 milliseconds and a repetition rate of about 220 pulses per second. Minor variations in repetition rate occurred from train to train and during propulsion changes of each train.

7) *Radiation from a Color-TV Receiver (7 MHz):* Some color-TV sets radiate sufficient energy to adversely affect HF communications over a radius of several city blocks. An example of the signature of TV-receiver radiation is shown in Fig. 9. The fairly narrow-band TV noise (from 7.210 to 7.214 MHz) suddenly appeared between two amateur-service signals, at 7.209 and 7.215 MHz, and it terminated amateur com-

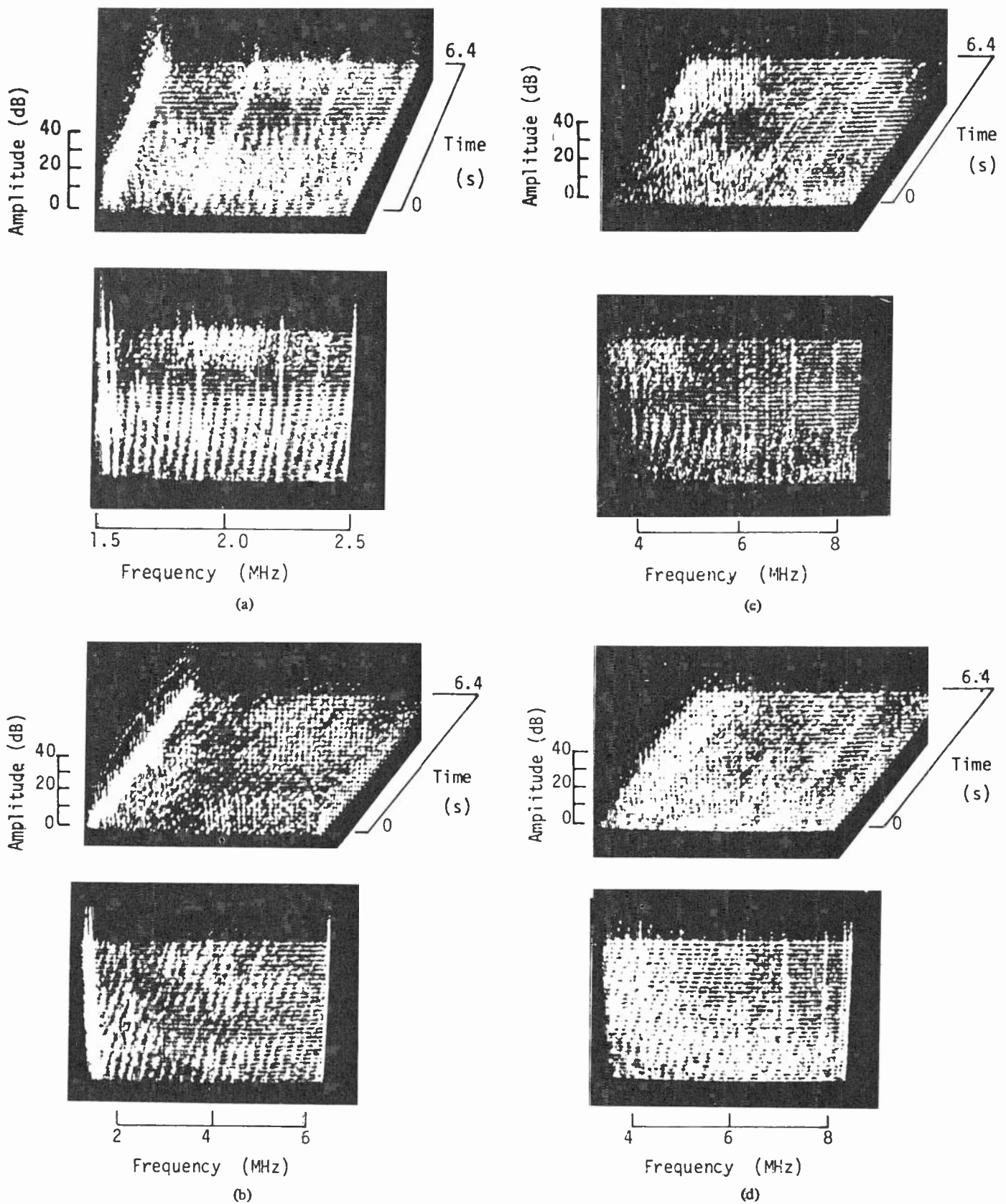


Fig. 8. Repetitive impulsive noise from departing trains (1.5-8 MHz).

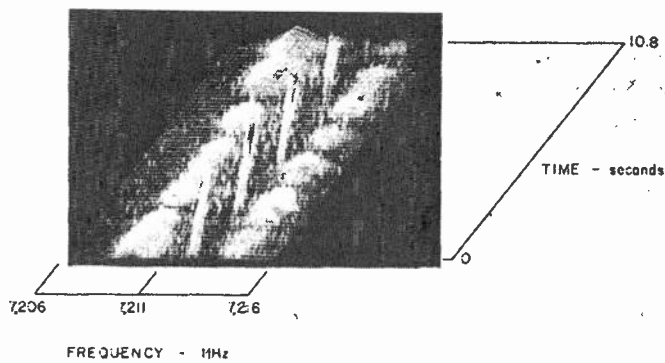


Fig. 9. Radiation from a color TV receiver (7MHz).

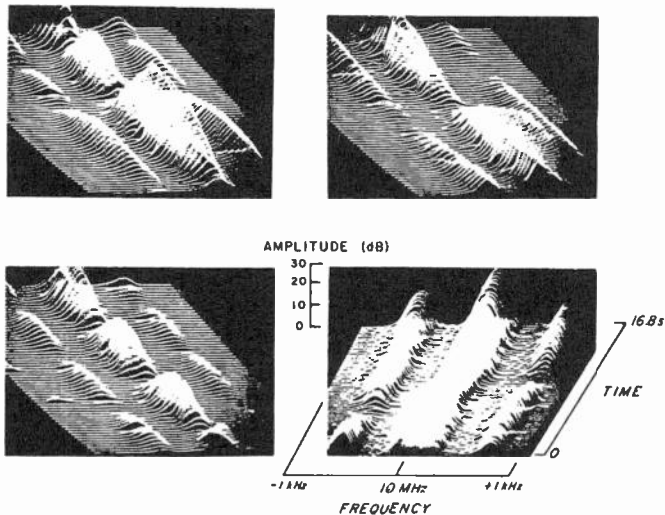


Fig. 10. Selective fading on WWV (10 MHz).

munications operations on 7.212 MHz because of an amateur operator's inability to receive weak single-sideband voice communications in the presence of the noise.

The primary frequency of the noise pulses is 60 Hz. Additional pulse structure can be seen which suggests that the primary signal consisted of a sequence of three close-spaced pulses or a pulse with 3 primary components.

8) *3-Axis Views of Selective Fading on WWV (10 MHz):* Time- and frequency-standard transmissions are among the occupants of the spectrum. Selective fading on an HF, ionospherically-propagated path are shown in Fig. 10. The signal originated at WWV, Ft. Collins, CO, and was received at Mountain View, CA, at 1400 h (PDST). The 10-MHz carrier and the upper and lower sidebands of the amplitude-modulated tone are shown in the views below. Signal amplitude changes with time are shown in each 3-axis view. Note the time displacement of the signal minima and maxima of the carrier and the sidebands. Distinctive patterns of selective fading are formed across the bandwidth of the WWV signal from phase cancellation of signals arriving from multiple propagation paths.

9) *Frequency-Sweeping Signal (14 MHz):* The author was communicating with a fellow radio amateur on 14.239 MHz when an unusual signal was noted crossing the frequency. The sweeping signal was observed on the display as shown in Fig.

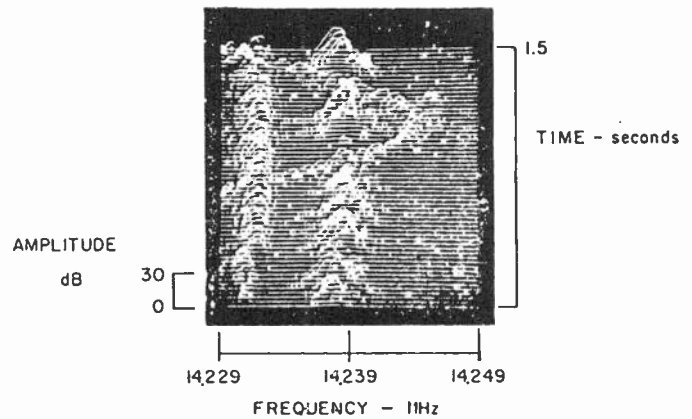


Fig. 11. Frequency sweeping signal in amateur band (14 MHz).

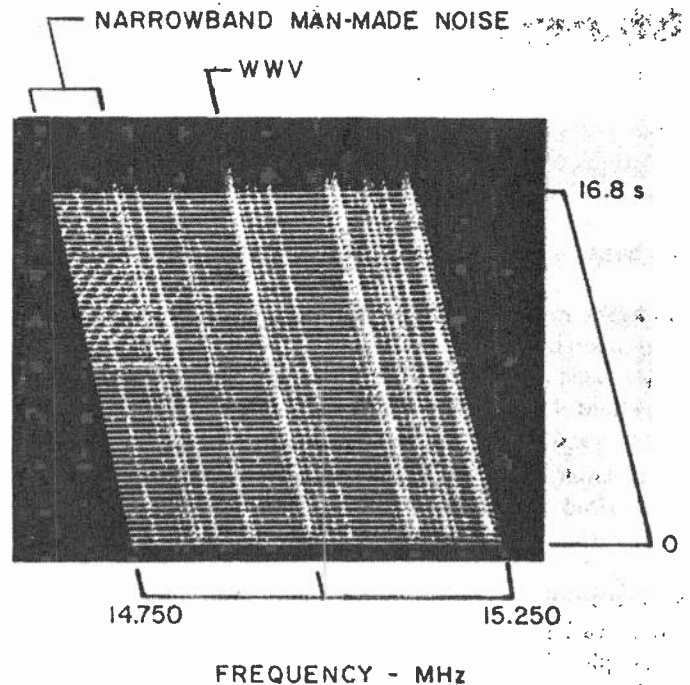


Fig. 12. Noise from SCR device (15 MHz).

11 where it can be seen sweeping smoothly upward and then downward in frequency. The sweeping signal produced two distinctive noise bursts in the receiver output as it passed across the receiver frequency. Since the sweeping signal entered the receiver bandpass during speech pauses in the received SSB signal, only minimal disruption occurred for the example shown. Such signals have been regularly observed in the amateur bands, and they seem to be of nonamateur origin.

10) *Noise from SCR Device (15 MHz):* High-power silicon-controlled rectifier (SCR) devices can radiate noise in the HF and VHF portions of the radio spectrum. An example of SCR noise is shown in Fig. 12. The noise occurred in the 14.750 to 14.850 MHz frequencies for an 8 s duration near the upper left portion of the view. Reception of signals in this frequency and time region was degraded while other signals outside this region were not affected. Reception of WWV, at 15 MHz, was not affected by the noise. Careful scaling of the time between

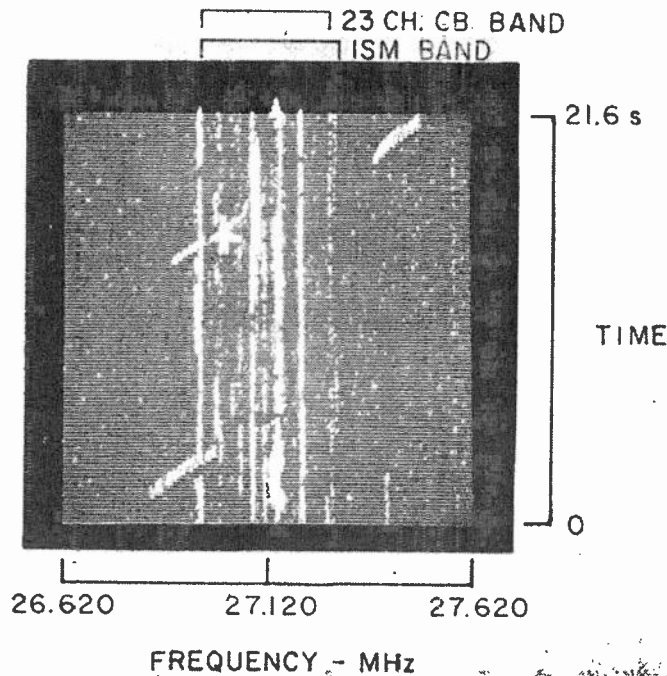


Fig. 13. ISM emissions in and out of the 27 MHz citizens band.

noise bursts indicates that the SCR was triggering at a 120-Hz rate.

11) ISM Emissions (27 MHz): Many plastic-moulding and sealing operations employ RF dielectric-heating devices which radiate. Such devices are authorized by the Federal Communications Commission (FCC) under the ISM (Industrial, Scientific, and Medical) service in certain bands. For example, ISM radiation, as well as Citizens Band (CB) communications, is authorized in the 27.120 ± 0.160 -MHz band. Since most contemporary ISM signals consist of brief bursts of signals sweeping 50 to 200 kHz across the band, only minimal interference is experienced by urban and suburban CB communications.

Examples of ISM radiation and CB signals are shown in Fig. 13. The examples were taken prior to the 40-channel CB authorization and hence represents conditions experienced by the older 23-channel CB operation. Numerous cases of ISM signals crossing the fixed-frequency CB signals are shown, and at such times the ISM signal produced a brief burst of noise in a CB receiver. For the case shown, the ISM signals originated at a plastic-moulding plant about 8 miles from the measurement location. The CB signals originated from a variety of sources estimated to be from 1 to 10 miles from the site. Several of the ISM signals are outside the 27.120 ± 0.160 MHz authorization which implies poor frequency control of the units whose signals were observed. Also, a few CB signals can be seen outside authorized channels. The ISM signals also radiated considerable energy at harmonics of their primary frequency (not shown).

12) Unidentified Repetitive Signal (27 MHz): An unidentified repetitive signal was observed in Mountain View, California at the lower edge of the 27-MHz Citizens Band (see Fig. 14).

13) Random Noise Bursts from Electrical Arc (42-48 MHz): Another example of random noise bursts at VHF is shown in Fig. 15 where a 3-axis view of intermittent noise from a rapid succession of electrical arcs and signals in the VHF land-mobile service are shown. Reception of the weak signal at 42 MHz was seriously degraded by the strong intermittent bursts of noise. Note that individual broadband noise bursts show up as narrowband spikes on the 3-axis display due to the limited number of scans displayed (see also Fig. 2). However, broadband impulsive random noise does appear to be broadband when many successive scans are displayed (see Fig. 3).

14) Spectrum Signature of a Radar (218 MHz): An example of a radar spectrum signature was observed at Mountain View, CA using a tilted monopole antenna 25' above ground driving an HP140 spectrum analyzer. The general properties of the radar signal are shown in Fig. 16(a) where the skewed presentation shows two signals emitted by the radar which are centered at about 217.49 MHz and 219.5 MHz. This same view is shown with alternate control settings in Figs. 16(b), (c), and (d) (operator adjustment of AZIMUTH, ELEVATION, and COMPRESSION controls to enhance aspects of the signal). Fig. 16(b) is a full-amplitude, rising-raster presentation while Fig. 16(c) is a conventional rising-raster presentation with amplitude fully compressed. In Fig. 16(d), the ELEVATION control was set at 0° to observe the radiated spectral shape of the two signals produced by 60 successive receiver scans. Fig. 16(c) shows two signal-blanking sectors during each revolution of the radar's antenna, where the large blanking sector, near the center of the time axis, known locally as the San Jose blanking sector, minimizes radio interference from main-beam radiation in nearby highly-populated areas. The brief blanking sector at about 5 s on the time axis minimizes interference to a nearby TV and FM broadcast site.

The signals in Fig. 16(b) and (c) appear to form pairs of lines slanting across the view. This is an indication that the radar operates with a two-step stagger-pulse repetition interval (PRI).

Side- and back-lobe antenna radiation is shown in Fig. 16(e), where the scanning receiver was tuned to the center of the 218-MHz signal and the frequency scan width was reduced to 200 kHz to examine signal strength vs. time near the signal center frequency. The scan time was also changed to 10 ms/scan.

The two-step stagger PRI can be seen in this view, and the PRI values were scaled as 3.2 and 4.5 ms. Since the time axis also represents received signal level during rotation of the radar antenna, antenna-pattern detail is shown along the time axis. The time axis can be calibrated in degrees of antenna rotation by measuring the antenna rotation period and calculating the angular sector represented by the time axis as follows:

Degrees along time axis

$$= \frac{360 \times \text{time-axis duration (in seconds)}}{\text{radar antenna rotation period (in seconds)}}$$

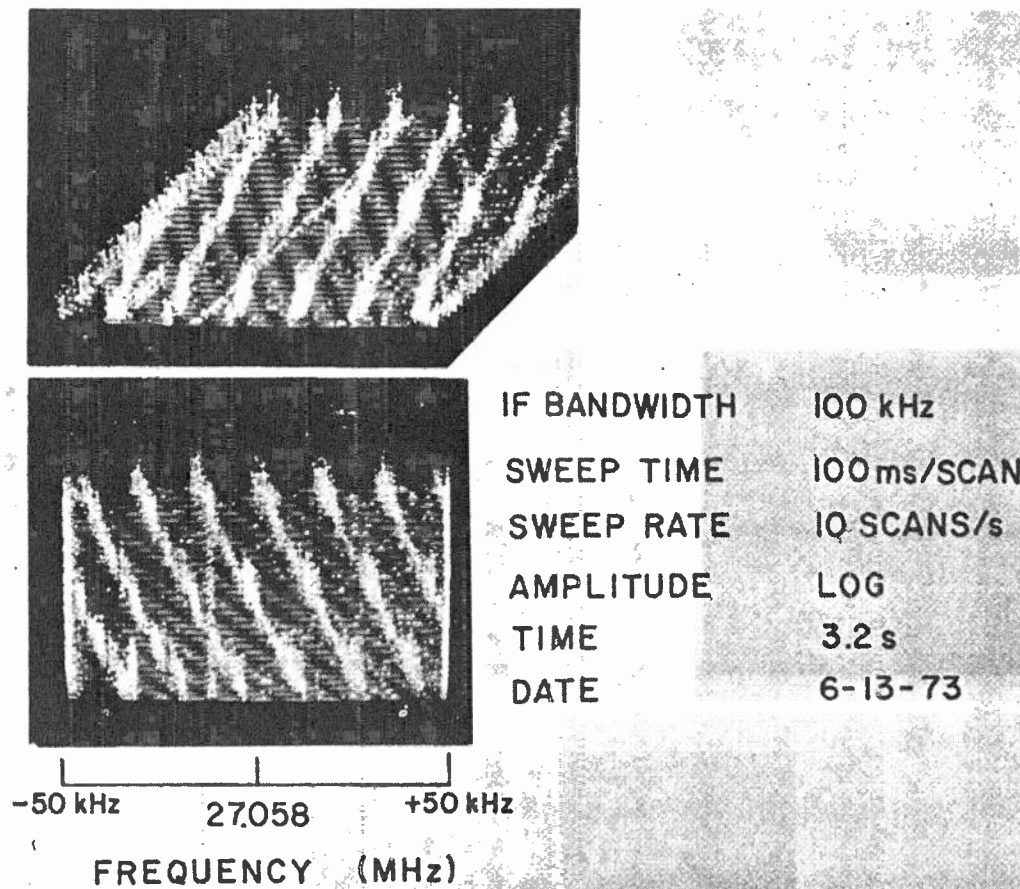


Fig. 14. Unidentified repetitive signal (27 MHz). IF bandwidth is 100 kHz, sweep time is 100 ms/scan, sweep rate is 10 scans/s, amplitude is log, time is 3.2 s, date 6/13/73.

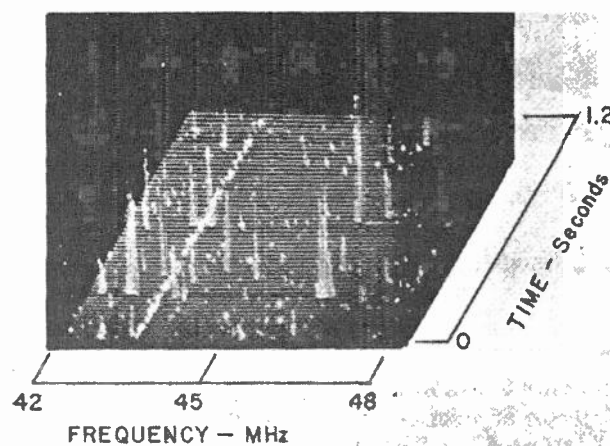
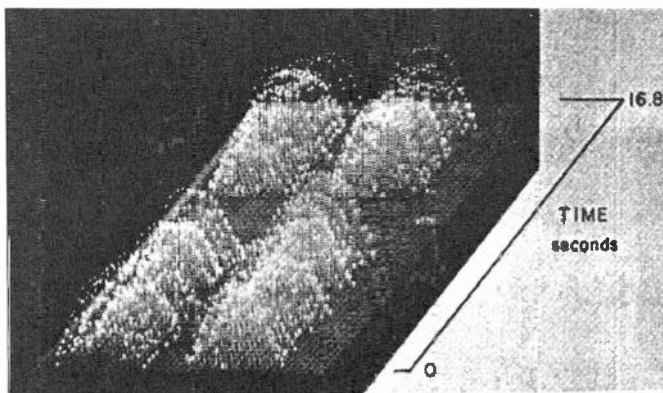
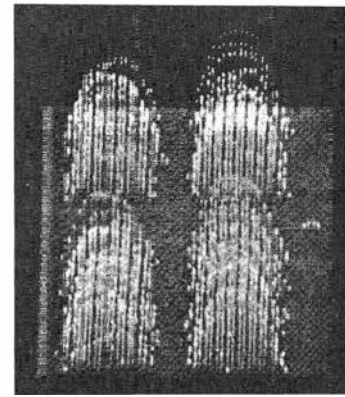


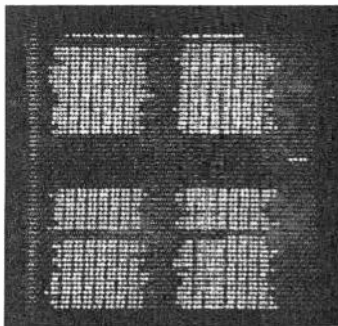
Fig. 15. Random impulsive noise (42-48 MHz).



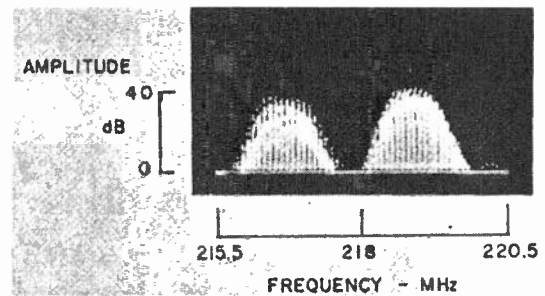
(a)



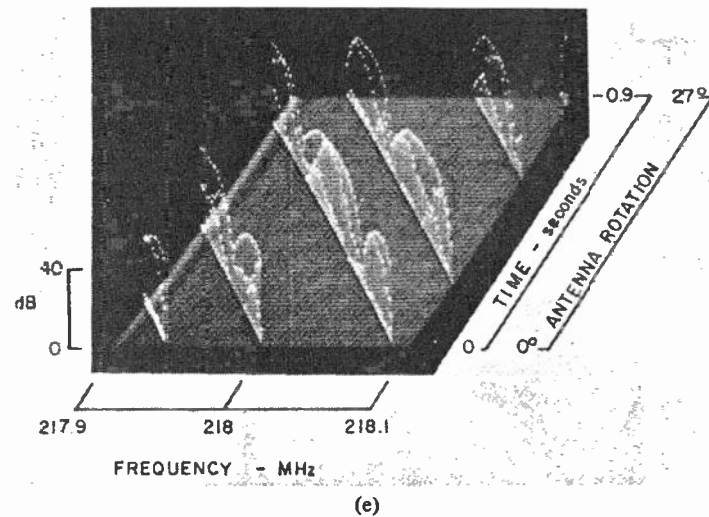
(b)



(c)



(d)



(e)

Fig. 16. Spectrum signature of a radar (218 MHz).

The radar antenna period, as measured from one prominent feature in its pattern to the next occurrence of the same feature, was 12.0 s. This results in a 27° sector of antenna rotation as shown in Fig. 16(e). Main antenna-lobe radiation was not observed since the measurement site was located in the San Jose blanking sector.

A small burst of four pulses can be seen in Figs. 16(a), (b), and (c) near 220 MHz about halfway along the time axis. These pulses originated from a distant radar, and the signal occurred each time the main antenna beam of that radar passed over the measurement site. The time-axis memory of the

display allowed the operator to easily detect these weak bursts of radar signal as well as to scale pertinent signal parameters from the 3-axis view.

15) Frequency-Agile Signals (400 MHz): The signals shown in Fig. 17 were recorded in Mountain View, CA, in May of 1975. A vertical whip antenna was used with an HP 141 spectrum analyzer.

The two views in Fig. 17(a) show the signal moving in frequency across a 0.5 MHz block of spectrum space. Full amplitude-compression was used in the left view along with a signal threshold setting which allowed some receiver noise to

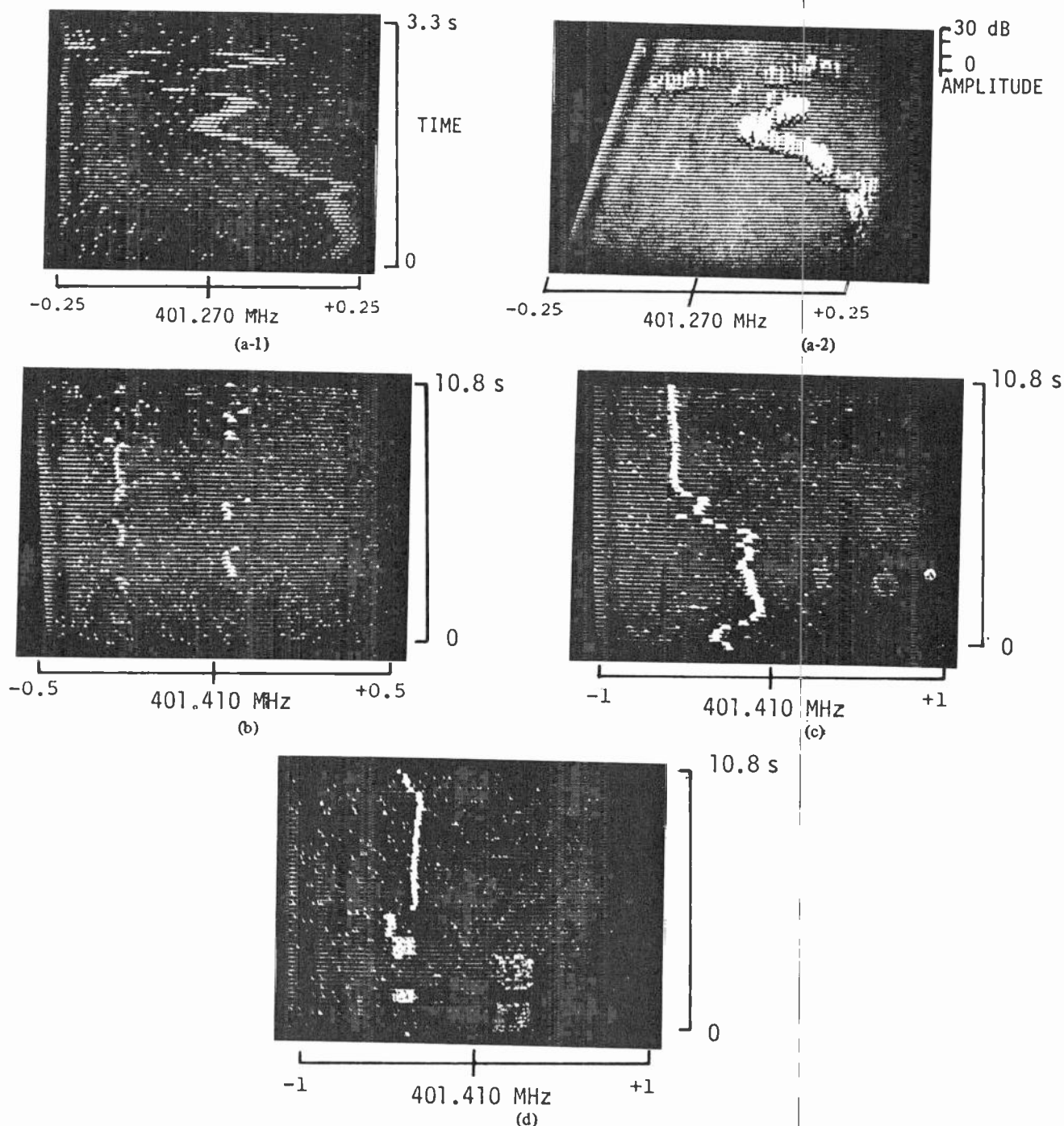


Fig. 17. Example of a frequency-agile signal in the UHF band (401 MHz).

appear as data, randomly scattered throughout the minimum-signal-threshold plane. In the right view, the threshold control was adjusted to remove background noise, the amplitude compression was removed and the view perspective changed.

Fig. 17(b) was taken about one minute after Fig. 17(a). The scan width of the scanning receiver was increased to 1 MHz to follow discrete frequency shifts of 300 to 400 kHz. Fig. 17(c) was taken a few seconds later to show a period of low frequency change followed by an erratic upward movement of the frequency of about 500 kHz.

Fig. 17(d) was taken about one minute after Fig. 17(c) and

shows a period of stable frequency followed by a sequence of frequency shifts of about 0.65 MHz. A high pulse-rate modulation appeared on the carrier during each shift with an upper-frequency signal bandwidth of about 0.2 MHz and a lower-frequency signal band-width of about 0.11 MHz.

16) Spectrum Signature of a Radar (1250 MHz): Another example of a radar spectrum signature is given in Fig. 18. It was obtained with the same instrumentation as described in the 218-MHz example.

Fig. 18(a) shows the general properties of the signal where

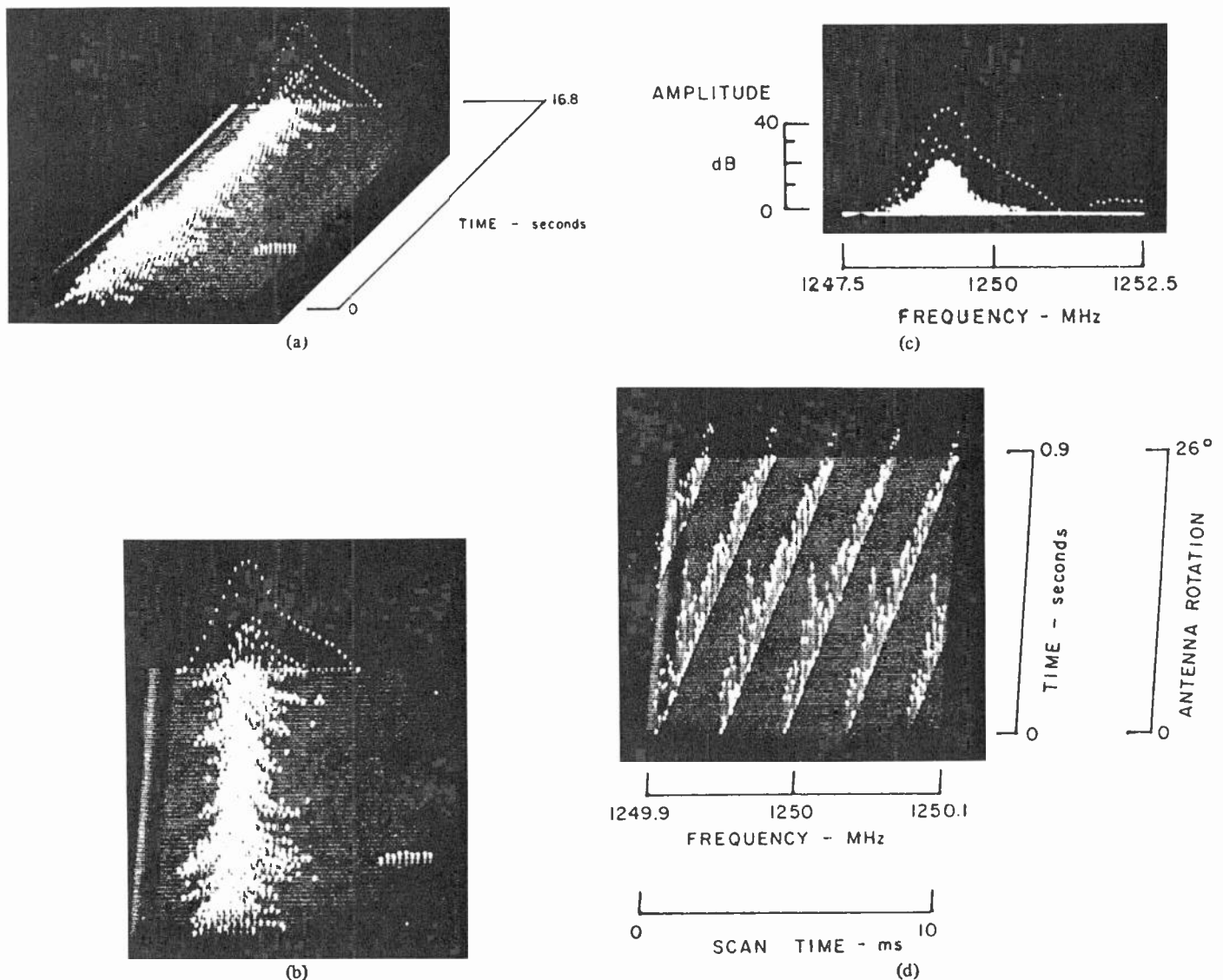


Fig. 18. Spectrum signature of a radar (1250 MHz).

the skewed presentation depicts radar antenna side- and back-lobe radiation from 0 to 16.7 s along the time axis. At 16.8 s on the time axis, the radar's main antenna lobe signal passed over the measurement site, causing the increased level at the upper end of the time axis.

Figs. 18(b) and (c) shows the radar signal with different 3-axis view aspects (in elevation and azimuth) from that shown in Fig. 18(a). Note the unsymmetrical spectral shape of the radar main-lobe signal. This unsymmetrical spectral shape occurred on most main-lobe signal intercepts; however, occasionally the spectral shape of the received signal was severely distorted, implying some form of occasional intermittent operation of the radar. The distinctive spectral shape of the main-lobe signal in Figs. 18(a), (b), and (c), along with the intermittent spectral distortion, provide unique signal properties useful in radar identification and fingerprinting tasks.

In Fig. 18(c), the display ELEVATION control was set at 0°, and the resulting integrated A-scope presentation provides a convenient measurement of main-lobe signal strength and

average side- and back-lobe signal strength. The main-lobe signal is about 20 dB above the average side- and back-lobe signal.

A signal from the main antenna-lobe of a distant radar can be seen at 1252 MHz about 3 s along the time axis. The received signal consists of nine successive pulses at the same PRI and antenna rotation period as the primary signal. However, the main-lobe spectral shape of this signal is considerably different from the spectral shape of the primary signal.

Antenna-pattern detail of the primary signal is shown in Fig. 18(d) where the scanning receiver was tuned to the center of the radar signal, the frequency scan width was changed to 200 kHz and the scan time was changed to 10 ms. The time axis can be calibrated in degrees of antenna rotation by measuring the intervals between main-lobe signals with a stop watch and calculating the angular sector (26°) represented on the display using the equation given in the previous radar example.

The main antenna-lobe signal can be seen along any PRI line in Fig. 18(d) at about 0.35 s on the time axis. Nulls and

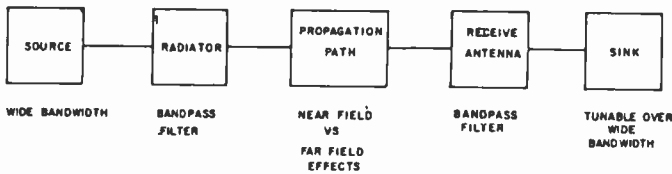


Fig. 19. Source-to-sink model.

peaks of the side lobes can be seen before and after the main-lobe signal. These nulls and peaks are not symmetrical around the main-lobe signal. This unsymmetrical side-lobe pattern was found to be consistent from one antenna rotation period to the next period, suggesting that this feature can also be used in radar fingerprinting tasks.

IV. DISCUSSION

The scanning receiver and 3-axis display have been of considerable value in the general investigation of signals occupying the RF spectrum and of the types and sources of man-made noise which affect communications-system performance. The viewer sees a real-time running visual history or parade of noise and signals which share and occupy blocks of the radio spectrum. The examples shown provide a realistic and accurate description of the ever-changing and often erratic noise states that affect communication-system performance. The distinctive visual signature allows the viewer to immediately determine the type of noise which aides in subsequent source-location tasks.

No single dominate source of man-made radio noise has been found in urban and suburban areas. The noise signatures frequently change over periods of seconds or minutes as implied by the 3-axis views. Occasionally a persistent type will be observed for several hours. The highly erratic and changing noise states complicate the modeling and definition of noise effects on communications systems. Most man-made radio noise exhibits distinctive spectral peaks and nulls and spectral limits, as shown in many of the 3-axis views. These peaks and nulls are generally consistent and stable while a specific noise source is active. However, the spectral properties change as sources change. The noise properties observed suggest that noise-source radiating elements probably control the spectral properties of noise energy sharing the spectrum with communications signals. The observed properties suggest that an appropriate model for the noise is as described in Fig. 19 where the source itself is coupled to a radiating element. The resonant properties and radiation patterns of the radiating element must be considered, as well as the source, propagation-path and receiving-system characteristics. This source-to-sink

model has been discussed in much greater detail by Middleton [5], [13].

V. CONCLUSIONS

Many kinds of signals and noise inhabit the RF spectrum. The instrumentation used to produce the 3-axis views has provided a number of examples representative of urban- and suburban-area spectrum conditions. These examples show the complexity and diversity of signals and noises that must be considered in radio-system design and in radio-spectrum management tasks.

REFERENCES

- [1] G. H. Hagn, "Definitions and fundamentals of electromagnetic noise, interference, and compatibility," in *NATO Advisory Group Aerospace Res. Dev. Conf. Proc.*, AGARD-CP-159, Nevilly-Sur-Seine, France, Nov. 1975. (Available NTIS, Springfield, VA as AD-A-018 980.)
- [2] A. D. Spaulding, "Man-made noise: The problem and recommended steps toward solution," OT Rep. 76-85, U.S. Department of Commerce, Office of Telecommunications, Boulder, CO, Apr. 1976.
- [3] A. D. Spaulding and R. T. Disney, "Man-made noise, Part I: Estimates for business, residential, and rural areas," OT Rep. 74-38, U.S. Department of Commerce, Office of Telecommunications, Boulder, CO, 1974.
- [4] A. D. Spaulding, R. T. Disney, and A. G. Hubbard, "Man-made radio noise, Part II: Bibliography of measurement data, applications, and measurement methods," OT Rep. 75-63, Office of Telecommunications, U.S. Department of Commerce, Boulder, CO, 1975.
- [5] D. Middleton, "Statistical-physical models of urban radio-noise environments—Part I: Foundations," *IEEE Trans. Electromagn. Compat.*, vol. EMC-14, pp. 38–56, May 1972.
- [6] N. C. Gerson and W. H. Gossard, "Sweepers," *J. Atmos. Terr. Phys.*, vol. 17, pp. 82–85, 1959.
- [7] W. R. Vincent and T. I. Dayharsh, "A study of land mobile spectrum utilization, Part B: Analysis of the spectrum management problem," Final Rep., FCC Contract RC-10056, SRI Project 7379, Stanford Research Institute, Menlo Park, CA, July 1969. (Available NTIS, Springfield, VA as PB 182 918.)
- [8] W. R. Vincent and T. I. Dayharsh, "Observations of man-made noise and RFI in urban and suburban areas," in *Conf. Rec., IEEE Mountain West, Electromagnetic Compatibility*, Tucson, AZ, Nov. 1971.
- [9] W. R. Vincent and R. W. Ellison, "RF noise radiated by a rapid transit system," in *1974 IEEE Electromagn. Compat. Symp. Rec.*, pp. 288–289, pp. 385–387, July 1974. (IEEE Cat. No. 74CH0803-7EMC.)
- [10] W. R. Vincent and R. S. Rich, "QRN and QRM in amateur bands," to be published in QST.
- [11] W. R. Vincent, "Poor operating practices and deliberate QRM," to be published in QST.
- [12] R. A. Shepherd, J. W. Engles, and G. H. Hagn, "Automobile ignition noise and the supernoisy vehicle," *IEEE 1976 Int. Symp. Electromagn. Compat. Record*, pp. 403–412, July 1976. (IEEE Cat. No. 76-CH-1104-9EMC.)
- [13] D. Middleton, "Statistical-physical models of electromagnetic interference," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, Part 1, Aug. 1977.

Appendix

ARTICLE 1 of the ITU Radio Regulations presents the terms and definitions used in spectrum management. Many of these definitions and terms have been adopted by the United States and other nations and appear in their national rules and regulations. Article 1 is presented here in its entirety.

Article 8 of the ITU Radio Regulations presents the frequency allocations. The parts of Article 8 containing

the introduction, regions and areas, categories of services and allocations, and a description of the table of frequency allocations are presented herein.

Article 8 also contains the table of frequency allocations. The portion of the table covering 470–890 MHz and associated footnotes are presented here as an example to illustrate the regional divisions, allocation heirarchy typefaces, etc.

Terms and Definitions

ARTICLE 1

Introduction

- 2 For the purposes of these Regulations, the following terms shall have the meanings defined below. These terms and definitions do not, however, necessarily apply for other purposes. Definitions identical to those contained in the International Telecommunication Convention (Malaga-Torremolinos, 1973) are marked "(CONV.)".

Note: If, in the text of a definition below, a term is printed in italics, this means that the term itself is defined in this Article.

Section I. General Terms

- 3 1.1 *Administration:* Any governmental department or service responsible for discharging the obligations undertaken in the Convention of the International Telecommunication Union and the Regulations (CONV.).
- 4 1.2 *Telecommunication:* Any transmission, *emission* or reception of signs, signals, writing, images and sounds or intelligence of any nature by wire, *radio*, optical or other electromagnetic systems (CONV.).
- 5 1.3 *Radio:* A general term applied to the use of *radio waves* (CONV.).
- 6 1.4 *Radio Waves* or *Hertzian Waves:* Electromagnetic waves of frequencies arbitrarily lower than 3 000 GHz, propagated in space without artificial guide.
- 7 1.5 *Radiocommunication:* *Telecommunication* by means of *radio waves* (CONV.).
- 8 1.6 *Terrestrial Radiocommunication:* Any *radiocommunication* other than *space radiocommunication* or *radio astronomy*.
- 9 1.7 *Space Radiocommunication:* Any *radiocommunication* involving the use of one or more *space stations* or the use of one or more *reflecting satellites* or other objects in space.
- 10 1.8 *Radiodetermination:* The determination of the position, velocity and/or other characteristics of an object, or the obtaining of information relating to these parameters, by means of the propagation properties of *radio waves*.
- 11 1.9 *Radionavigation:* *Radiodetermination* used for the purposes of navigation, including obstruction warning.
- 12 1.10 *Radiolocation:* *Radiodetermination* used for purposes other than those of *radionavigation*.
- 13 1.11 *Radio Direction-Finding:* *Radiodetermination* using the reception of *radio waves* for the purpose of determining the direction of a *station* or object.

- 14 1.12 *Radio Astronomy*: Astronomy based on the reception of *radio waves* of cosmic origin.
- 15 1.13 *Coordinated Universal Time (UTC)*: Time scale, based on the second (SI), as defined and recommended by the CCIR¹, and maintained by the International Time Bureau (BIH).
- For most practical purposes associated with the Radio Regulations, UTC is equivalent to mean solar time at the prime meridian (0° longitude), formerly expressed in GMT.
- 16 1.14 *Industrial, Scientific and Medical (ISM) Applications* (of radio frequency energy): Operation of equipment or appliances designed to generate and use locally radio frequency energy for industrial, scientific, medical, domestic or similar purposes, excluding applications in the field of *telecommunications*.

Section II. Specific Terms Related to Frequency Management

- 17 2.1 *Allocation* (of a frequency band): Entry in the Table of Frequency Allocations of a given frequency band for the purpose of its use by one or more terrestrial or space *radiocommunication services* or the *radio astronomy service* under specified conditions. This term shall also be applied to the frequency band concerned.
- 18 2.2 *Allotment* (of a radio frequency or radio frequency channel): Entry of a designated frequency channel in an agreed plan, adopted by a competent conference, for use by one or more administrations for a terrestrial or space *radiocommunication service* in one or more identified countries or geographical areas and under specified conditions.
- 19 2.3 *Assignment* (of a radio frequency or radio frequency channel): Authorization given by an administration for a radio *station* to use a radio frequency or radio frequency channel under specified conditions.

Section III. Radio Services

- 20 3.1 *Radiocommunication Service*: A service as defined in this Section involving the transmission, *emission* and/or reception of *radio waves* for specific *telecommunication* purposes.
- In these Regulations, unless otherwise stated, any radiocommunication service relates to *terrestrial radiocommunication*.
- 21 3.2 *Fixed Service*: A *radiocommunication service* between specified fixed points.
- 22 3.3 *Fixed-Satellite Service*: A *radiocommunication service* between *earth stations* at specified fixed points when one or more *satellites* are used; in some cases this service includes satellite-to-satellite links, which may also be effected in the *inter-satellite service*; the fixed-satellite service may also include *feeder links* for other *space radiocommunication services*.
- 23 3.4 *Aeronautical Fixed Service*: A *radiocommunication service* between specified fixed points provided primarily for the safety of air navigation and for the regular, efficient and economical operation of air transport.

15.1 ¹ The full definition is contained in CCIR Recommendation 460-2.

- 24 3.5 *Inter-Satellite Service: A radiocommunication service providing links between artificial earth satellites.*
- 25 3.6 *Space Operation Service: A radiocommunication service concerned exclusively with the operation of spacecraft, in particular space tracking, space telemetry and space telecommand.*
These functions will normally be provided within the service in which the *space station* is operating.
- 26 3.7 *Mobile Service: A radiocommunication service between mobile and land stations, or between mobile stations (CONV.).*
- 27 3.8 *Mobile-Satellite Service: A radiocommunication service:*
— between *mobile earth stations* and one or more *space stations*, or between *space stations* used by this service; or
— between *mobile earth stations* by means of one or more *space stations*.
This service may also include *feeder links* necessary for its operation.
- 28 3.9 *Land Mobile Service: A mobile service between base stations and land mobile stations, or between land mobile stations.*
- 29 3.10 *Land Mobile-Satellite Service: A mobile-satellite service in which mobile earth stations are located on land.*
- 30 3.11 *Maritime Mobile Service: A mobile service between coast stations and ship stations, or between ship stations, or between associated on-board communication stations; survival craft stations and emergency position-indicating radiobeacon stations may also participate in this service.*
- 31 3.12 *Maritime Mobile-Satellite Service: A mobile-satellite service in which mobile earth stations are located on board ships; survival craft stations and emergency position-indicating radiobeacon stations may also participate in this service.*
- 32 3.13 *Port Operations Service: A maritime mobile service in or near a port, between coast stations and ship stations, or between ship stations, in which messages are restricted to those relating to the operational handling, the movement and the safety of ships and, in emergency, to the safety of persons.*
Messages which are of a *public correspondence* nature shall be excluded from this service.
- 33 3.14 *Ship Movement Service: A safety service in the maritime mobile service other than a port operations service, between coast stations and ship stations, or between ship stations, in which messages are restricted to those relating to the movement of ships.*
Messages which are of a *public correspondence* nature shall be excluded from this service.
- 34 3.15 *Aeronautical Mobile Service: A mobile service between aeronautical stations and aircraft stations, or between aircraft stations, in which survival craft stations may participate; emergency position-indicating radiobeacon stations may also participate in this service on designated distress and emergency frequencies.*

- 35 3.16 *Aeronautical Mobile-Satellite Service*: A mobile-satellite service in which *mobile earth stations* are located on board aircraft; *survival craft stations* and *emergency position-indicating radiobeacon stations* may also participate in this service.
- 36 3.17 *Broadcasting Service*: A radiocommunication service in which the transmissions are intended for direct reception by the general public. This service may include sound transmissions, *television* transmissions or other types of transmission (CONV.).
- 37 3.18 *Broadcasting-Satellite Service*: A radiocommunication service in which signals transmitted or retransmitted by *space stations* are intended for direct reception by the general public.

In the broadcasting-satellite service, the term "direct reception" shall encompass both *individual reception* and *community reception*.

- 38 3.19 *Radiodetermination Service*: A radiocommunication service for the purpose of *radiodetermination*.
- 39 3.20 *Radiodetermination-Satellite Service*: A radiocommunication service for the purpose of *radiodetermination* involving the use of one or more *space stations*.
- 40 3.21 *Radionavigation Service*: A *radiodetermination* service for the purpose of *radionavigation*.
- 41 3.22 *Radionavigation-Satellite Service*: A *radiodetermination-satellite* service used for the purpose of *radionavigation*.
This service may also include *feeder links* necessary for its operation.
- 42 3.23 *Maritime Radionavigation Service*: A *radionavigation* service intended for the benefit and for the safe operation of ships.
- 43 3.24 *Maritime Radionavigation-Satellite Service*: A *radionavigation-satellite* service in which *earth stations* are located on board ships.
- 44 3.25 *Aeronautical Radionavigation Service*: A *radionavigation* service intended for the benefit and for the safe operation of aircraft.
- 45 3.26 *Aeronautical Radionavigation-Satellite Service*: A *radionavigation-satellite* service in which *earth stations* are located on board aircraft.
- 46 3.27 *Radiolocation Service*: A *radiodetermination* service for the purpose of *radiolocation*.
- 47 3.28 *Meteorological Aids Service*: A radiocommunication service used for meteorological, including hydrological, observations and exploration.
- 48 3.29 *Earth Exploration-Satellite Service*: A radiocommunication service between *earth stations* and one or more *space stations*, which may include links between *space stations*, in which:

- information relating to the characteristics of the Earth and its natural phenomena is obtained from *active sensors* or *passive sensors* on *earth satellites*;
- similar information is collected from airborne or Earth-based platforms;
- such information may be distributed to *earth stations* within the system concerned;
- platform interrogation may be included.

This service may also include *feeder links* necessary for its operation.

- 49 3.30 *Meteorological-Satellite Service: An earth exploration-satellite service for meteorological purposes.*
- 50 3.31 *Standard Frequency and Time Signal Service: A radiocommunication service for scientific, technical and other purposes, providing the transmission of specified frequencies, time signals, or both, of stated high precision, intended for general reception.*
- 51 3.32 *Standard Frequency and Time Signal-Satellite Service: A radiocommunication service using space stations on earth satellites for the same purposes as those of the standard frequency and time signal service.*
- This service may also include *feeder links* necessary for its operation.
- 52 3.33 *Space Research Service: A radiocommunication service in which spacecraft or other objects in space are used for scientific or technological research purposes.*
- 53 3.34 *Amateur Service: A radiocommunication service for the purpose of self-training, intercommunication and technical investigations carried out by amateurs, that is, by duly authorized persons interested in radio technique solely with a personal aim and without pecuniary interest.*
- 54 3.35 *Amateur-Satellite Service: A radiocommunication service using space stations on earth satellites for the same purposes as those of the amateur service.*
- 55 3.36 *Radio Astronomy Service: A service involving the use of radio astronomy.*
- 56 3.37 *Safety Service: Any radiocommunication service used permanently or temporarily for the safeguarding of human life and property (CONV.).*
- 57 3.38 *Special Service: A radiocommunication service, not otherwise defined in this Section, carried on exclusively for specific needs of general utility, and not open to public correspondence.*

Section IV. Radio Stations and Systems

- 58 4.1 *Station: One or more transmitters or receivers or a combination of transmitters and receivers, including the accessory equipment, necessary at one location for carrying on a radiocommunication service, or the radio astronomy service.*
- Each station shall be classified by the service in which it operates permanently or temporarily.
- 59 4.2 *Terrestrial Station: A station effecting terrestrial radiocommunication.*
- In these Regulations, unless otherwise stated, any *station* is a terrestrial station.
- 60 4.3 *Earth Station: A station located either on the Earth's surface or within the major portion of the Earth's atmosphere and intended for communication:*
- with one or more *space stations*; or
 - with one or more *stations* of the same kind by means of one or more reflecting *satellites* or other objects in space.

- 61 4.4 *Space Station*: A station located on an object which is beyond, is intended to go beyond, or has been beyond, the major portion of the Earth's atmosphere.
- 62 4.5 *Survival Craft Stations*: A mobile station in the maritime mobile service or the aeronautical mobile service intended solely for survival purposes and located on any lifeboat, life-raft or other survival equipment.
- 63 4.6 *Fixed Station*: A station in the fixed service.
- 64 4.7 *Aeronautical Fixed Station*: A station in the aeronautical fixed service.
- 65 4.8 *Mobile Station*: A station in the mobile service intended to be used while in motion or during halts at unspecified points.
- 66 4.9 *Mobile Earth Station*: An earth station in the mobile-satellite service intended to be used while in motion or during halts at unspecified points.
- 67 4.10 *Land Station*: A station in the mobile service not intended to be used while in motion.
- 68 4.11 *Base Station*: A land station in the land mobile service.
- 69 4.12 *Land Mobile Station*: A mobile station in the land mobile service capable of surface movement within the geographical limits of a country or continent.
- 70 4.13 *Coast Station*: A land station in the maritime mobile service.
- 71 4.14 *Coast Earth Station*: An earth station in the fixed-satellite service or, in some cases, in the maritime mobile-satellite service, located at a specified fixed point on land to provide a feeder link for the maritime mobile-satellite service.
- 72 4.15 *Ship Station*: A mobile station in the maritime mobile service located on board a vessel which is not permanently moored, other than a survival craft station.
- 73 4.16 *Ship Earth Station*: A mobile earth station in the maritime mobile-satellite service located on board ship.
- 74 4.17 *On-Board Communication Station*: A low-powered mobile station in the maritime mobile service intended for use for internal communications on board a ship, or between a ship and its lifeboats and life-rafts during lifeboat drills or operations, or for communication within a group of vessels being towed or pushed, as well as for line handling and mooring instructions.
- 75 4.18 *Port Station*: A coast station in the port operations service.
- 76 4.19 *Aeronautical Station*: A land station in the aeronautical mobile service.
- In certain instances, an aeronautical station may be located, for example, on board ship or on a platform at sea.
- 77 4.20 *Aeronautical Earth Station*: An earth station in the fixed-satellite service, or, in some cases, in the aeronautical mobile-satellite service, located at a specified fixed point on land to provide a feeder link for the aeronautical mobile-satellite service.
- 78 4.21 *Aircraft Station*: A mobile station in the aeronautical mobile service, other than a survival craft station, located on board an aircraft.

- 79 4.22 *Aircraft Earth Station: A mobile earth station in the aeronautical mobile-satellite service located on board an aircraft.*
- 80 4.23 *Broadcasting Station: A station in the broadcasting service.*
- 81 4.24 *Radiodetermination Station: A station in the radiodetermination service.*
- 82 4.25 *Radionavigation Mobile Station: A station in the radionavigation service intended to be used while in motion or during halts at unspecified points.*
- 83 4.26 *Radionavigation Land Station: A station in the radionavigation service not intended to be used while in motion.*
- 84 4.27 *Radiolocation Mobile Station: A station in the radiolocation service intended to be used while in motion or during halts at unspecified points.*
- 85 4.28 *Radiolocation Land Station: A station in the radiolocation service not intended to be used while in motion.*
- 86 4.29 *Radio Direction-Finding Station: A radiodetermination station using radio direction-finding.*
- 87 4.30 *Radiobeacon Station: A station in the radionavigation service the emissions of which are intended to enable a mobile station to determine its bearing or direction in relation to the radiobeacon station.*
- 88 4.31 *Emergency Position-Indicating Radiobeacon Station: A station in the mobile service the emissions of which are intended to facilitate search and rescue operations.*
- 89 4.32 *Standard Frequency and Time Signal Station: A station in the standard frequency and time signal service.*
- 90 4.33 *Amateur Station: A station in the amateur service.*
- 91 4.34 *Radio Astronomy Station: A station in the radio astronomy service.*
- 92 4.35 *Experimental Station: A station utilizing radio waves in experiments with a view to the development of science or technique.*
- This definition does not include *amateur stations*.
- 93 4.36 *Ship's Emergency Transmitter: A ship's transmitter to be used exclusively on a distress frequency for distress, urgency or safety purposes.*
- 94 4.37 *Radar: A radiodetermination system based on the comparison of reference signals with radio signals reflected, or retransmitted, from the position to be determined.*
- 95 4.38 *Primary Radar: A radiodetermination system based on the comparison of reference signals with radio signals reflected from the position to be determined.*
- 96 4.39 *Secondary Radar: A radiodetermination system based on the comparison of reference signals with radio signals retransmitted from the position to be determined.*
- 97 4.40 *Radar Beacon (racon): A transmitter-receiver associated with a fixed navigational mark which, when triggered by a radar, automatically returns a distinctive signal which can appear on the display of the triggering radar, providing range, bearing and identification information.*

- 98 4.41 *Instrument Landing System (ILS)*: A radionavigation system which provides aircraft with horizontal and vertical guidance just before and during landing and, at certain fixed points, indicates the distance to the reference point of landing.
- 99 4.42 *Instrument Landing System Localizer*: A system of horizontal guidance embodied in the *instrument landing system* which indicates the horizontal deviation of the aircraft from its optimum path of descent along the axis of the runway.
- 100 4.43 *Instrument Landing System Glide Path*: A system of vertical guidance embodied in the *instrument landing system* which indicates the vertical deviation of the aircraft from its optimum path of descent.
- 101 4.44 *Marker Beacon*: A transmitter in the *aeronautical radionavigation service* which radiates vertically a distinctive pattern for providing position information to aircraft.
- 102 4.45 *Radio Altimeter*: Radionavigation equipment, on board an aircraft or *spacecraft*, used to determine the height of the aircraft or the *spacecraft* above the Earth's surface or another surface.
- 103 4.46 *Radiosonde*: An automatic radio transmitter in the *meteorological aids service* usually carried on an aircraft, free balloon, kite or parachute, and which transmits meteorological data.
- 104 4.47 *Space System*: Any group of cooperating *earth stations* and/or *space stations* employing *space radiocommunication* for specific purposes.
- 105 4.48 *Satellite System*: A *space system* using one or more artificial earth *satellites*.
- 106 4.49 *Satellite Network*: A *satellite system* or a part of a *satellite system*, consisting of only one *satellite* and the cooperating *earth stations*.
- 107 4.50 *Satellite Link*: A radio link between a transmitting *earth station* and a receiving *earth station* through one *satellite*.
A satellite link comprises one up-link and one down-link.
- 108 4.51 *Multi-Satellite Link*: A radio link between a transmitting *earth station* and a receiving *earth station* through two or more *satellites*, without any intermediate *earth station*.
A multi-satellite link comprises one up-link, one or more satellite-to-satellite links and one down-link.
- 109 4.52 *Feeder Link*: A radio link from an *earth station* at a specified fixed point to a *space station*, or vice versa, conveying information for a *space radiocommunication service* other than for the *fixed-satellite service*.

Section V. Operational Terms

- 110 5.1 *Public Correspondence*: Any *telecommunication* which the offices and *stations* must, by reason of their being at the disposal of the public, accept for transmission (CONV.).
- 111 5.2 *Telegraphy**: A form of *telecommunication* which is concerned in any process providing transmission and reproduction at a distance of documentary matter, such as written or printed matter or

* *Note by the General Secretariat*: This definition is not in alignment with Annex 2 to the Convention. The corresponding definition in that Annex shall prevail to the extent that there are differences between them (see also Resolution 68).

fixed images, or the reproduction at a distance of any kind of information in such a form. For the purposes of the Radio Regulations, unless otherwise specified therein, telegraphy shall mean a form of *telecommunication* for the transmission of written matter by the use of a signal code.

- 112 5.3 *Telegram*: Written matter intended to be transmitted by *telegraphy* for delivery to the addressee. This term also includes *radiotelegrams* unless otherwise specified (CONV.).

In this definition the term *telegraphy* has the same general meaning as defined in the Convention.

- 113 5.4 *Radiotelegram*: A *telegram*, originating in or intended for a *mobile station* or a *mobile earth station* transmitted on all or part of its route over the *radiocommunication* channels of the *mobile service* or of the *mobile-satellite service*.

- 114 5.5 *Radiotelex Call*: A telex call, originating in or intended for a *mobile station* or a *mobile earth station*, transmitted on all or part of its route over the *radiocommunication* channels of the *mobile service* or the *mobile-satellite service*.

- 115 5.6 *Frequency-Shift Telegraphy*: *Telegraphy* by frequency modulation in which the telegraph signal shifts the frequency of the carrier between predetermined values.

- 116 5.7 *Facsimile*: A form of *telegraphy* for the transmission of fixed images, with or without half-tones, with a view to their reproduction in a permanent form.

In this definition the term *telegraphy* has the same general meaning as defined in the Convention.

- 117 5.8 *Telephony**: A form of *telecommunication* set up for the transmission of speech or, in some cases, other sounds.

- 118 5.9 *Radiotelephone Call*: A telephone call, originating in or intended for a *mobile station* or a *mobile earth station*, transmitted on all or part of its route over the *radiocommunication* channels of the *mobile service* or of the *mobile-satellite service*.

- 119 5.10 *Simplex Operation*: Operating method in which transmission is made possible alternately in each direction of a *telecommunication* channel, for example, by means of manual control¹.

- 120 5.11 *Duplex Operation*: Operating method in which transmission is possible simultaneously in both directions of a *telecommunication* channel¹.

- 121 5.12 *Semi-Duplex Operation*: A method which is *simplex operation* at one end of the circuit and *duplex operation* at the other¹.

- 122 5.13 *Television*: A form of *telecommunication* for the transmission of transient images of fixed or moving objects.

- 123 5.14 *Individual Reception* (in the broadcasting-satellite service): The reception of *emissions* from a *space station* in the *broadcasting-satellite service* by simple domestic installations and in particular those possessing small antennae.

¹ In general, *duplex operation* and *semi-duplex operation* require two frequencies in *radiocommunication*; *simplex operation* may use either one or two.

* *Note by the General Secretariat*: This definition is not in alignment with Annex 2 to the Convention. The corresponding definition in that Annex shall prevail to the extent that there are differences between them (see also Resolution 68).

- 124 5.15 *Community Reception* (in the broadcasting-satellite service): The reception of *emissions* from a *space station* in the *broadcasting-satellite service* by receiving equipment, which in some cases may be complex and have antennae larger than those used for *individual reception*, and intended for use:
- by a group of the general public at one location; or
 - through a distribution system covering a limited area.
- 125 5.16 *Telemetry*: The use of *telecommunication* for automatically indicating or recording measurements at a distance from the measuring instrument.
- 126 5.17 *Radiotelemetry*: *Telemetry* by means of *radio waves*.
- 127 5.18 *Space Telemetry*: The use of *telemetry* for the transmission from a *space station* of results of measurements made in a *spacecraft*, including those relating to the functioning of the *spacecraft*.
- 128 5.19 *Telecommand*: The use of *telecommunication* for the transmission of signals to initiate, modify or terminate functions of equipment at a distance.
- 129 5.20 *Space Telecommand*: The use of *radiocommunication* for the transmission of signals to a *space station* to initiate, modify or terminate functions of equipment on an associated space object, including the *space station*.
- 130 5.21 *Space Tracking*: Determination of the *orbit*, velocity or instantaneous position of an object in space by means of *radiodetermination*, excluding *primary radar*, for the purpose of following the movement of the object.

Section VI. Characteristics of Emissions and Radio Equipment

- 131 6.1 *Radiation*: The outward flow of energy from any source in the form of *radio waves*.
- 132 6.2 *Emission*: *Radiation* produced, or the production of *radiation*, by a radio transmitting *station*.
- For example, the energy radiated by the local oscillator of a radio receiver would not be an emission but a *radiation*.
- 133 6.3 *Class of Emission*: The set of characteristics of an *emission*, designated by standard symbols, e.g. type of modulation of the main carrier, modulating signal, type of information to be transmitted, and also, if appropriate, any additional signal characteristics.
- 134 6.4 *Single-Sideband Emission*: An amplitude modulated *emission* with one sideband only.
- 135 6.5 *Full Carrier Single-Sideband Emission*: A *single-sideband emission* without reduction of the carrier.
- 136 6.6 *Reduced Carrier Single-Sideband Emission*: A *single-sideband emission* in which the degree of carrier suppression enables the carrier to be reconstituted and to be used for demodulation.
- 137 6.7 *Suppressed Carrier Single-Sideband Emission*: A *single-sideband emission* in which the carrier is virtually suppressed and not intended to be used for demodulation.

- 138 6.8 *Out-of-band Emission* *: Emission on a frequency or frequencies immediately outside the *necessary bandwidth* which results from the modulation process, but excluding *spurious emissions*.
- 139 6.9 *Spurious Emission* *: Emission on a frequency or frequencies which are outside the *necessary bandwidth* and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic *emissions*, parasitic *emissions*, intermodulation products and frequency conversion products, but exclude *out-of-band emissions*.
- 140 6.10 *Unwanted Emissions* *: Consist of *spurious emissions* and *out-of-band emissions*.
- 141 6.11 *Assigned Frequency Band*: The frequency band within which the *emission* of a *station* is authorized; the width of the band equals the *necessary bandwidth* plus twice the absolute value of the *frequency tolerance*. Where *space stations* are concerned, the assigned frequency band includes twice the maximum Doppler shift that may occur in relation to any point of the Earth's surface.
- 142 6.12 *Assigned Frequency*: The centre of the frequency band assigned to a *station*.
- 143 6.13 *Characteristic Frequency*: A frequency which can be easily identified and measured in a given *emission*.
- A carrier frequency may, for example, be designated as the characteristic frequency.
- 144 6.14 *Reference Frequency*: A frequency having a fixed and specified position with respect to the *assigned frequency*. The displacement of this frequency with respect to the *assigned frequency* has the same absolute value and sign that the displacement of the *characteristic frequency* has with respect to the centre of the frequency band occupied by the *emission*.
- 145 6.15 *Frequency Tolerance*: The maximum permissible departure by the centre frequency of the frequency band occupied by an *emission* from the *assigned frequency* or, by the *characteristic frequency* of an *emission* from the *reference frequency*.
- The frequency tolerance is expressed in parts in 10^6 or in hertz.
- 146 6.16 *Necessary Bandwidth*: For a given *class of emission*, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions.

* The terms associated with the definitions given by Nos. 138, 139 and 140 shall be expressed in the working languages as follows:

Numbers	In French	In English	In Spanish
138 (6.8)	Emission hors bande	Out-of-band emission	Emisión fuera de banda
139 (6.9)	Rayonnement non essentiel	Spurious emission	Emisión no esencial
140 (6.10)	Rayonnements non désirés	Unwanted emissions	Emisiones no deseadas

- 147 6.17 *Occupied Bandwidth*: The width of a frequency band such that, below the lower and above the upper frequency limits, the *mean powers* emitted are each equal to a specified percentage $\beta/2$ of the total *mean power* of a given *emission*.
- Unless otherwise specified by the CCIR for the appropriate *class of emission*, the value of $\beta/2$ should be taken as 0.5%.
- 148 6.18 *Right-Hand* (clockwise) *Polarized Wave*: An elliptically- or circularly-polarized wave, in which the electric field vector, observed in any fixed plane, normal to the direction of propagation, whilst looking in the direction of propagation, rotates with time in a right-hand or clockwise direction.
- 149 6.19 *Left-Hand* (anticlockwise) *Polarized Wave*: An elliptically- or circularly-polarized wave, in which the electric field vector, observed in any fixed plane, normal to the direction of propagation, whilst looking in the direction of propagation, rotates with time in a left-hand or anticlockwise direction.
- 150 6.20 *Power*: Whenever the power of a radio transmitter etc. is referred to it shall be expressed in one of the following forms, according to the *class of emission*, using the arbitrary symbols indicated:
- *peak envelope power* (PX or pX);
 - *mean power* (PY or pY);
 - *carrier power* (PZ or pZ).
- For different *classes of emission*, the relationships between *peak envelope power*, *mean power* and *carrier power*, under the conditions of normal operation and of no modulation, are contained in CCIR Recommendations which may be used as a guide.
- For use in formulae, the symbol *p* denotes power expressed in watts and the symbol *P* denotes power expressed in decibels relative to a reference level.
- 151 6.21 *Peak Envelope Power* (of a radio transmitter): The average power supplied to the antenna transmission line by a transmitter during one radio frequency cycle at the crest of the modulation envelope taken under normal operating conditions.
- 152 6.22 *Mean Power* (of a radio transmitter): The average power supplied to the antenna transmission line by a transmitter during an interval of time sufficiently long compared with the lowest frequency encountered in the modulation taken under normal operating conditions.
- 153 6.23 *Carrier Power* (of a radio transmitter): The average power supplied to the antenna transmission line by a transmitter during one radio frequency cycle taken under the condition of no modulation.
- 154 6.24 *Gain of an Antenna*: The ratio, usually expressed in decibels, of the power required at the input of a loss-free reference antenna to the power supplied to the input of the given antenna to produce, in a given direction, the same field strength or the same power flux-density at the same distance. When not specified otherwise, the gain refers to the direction of maximum *radiation*. The gain may be considered for a specified polarization.

Depending on the choice of the reference antenna a distinction is made between:

- a) *absolute or isotropic gain* (G_i), when the reference antenna is an isotropic antenna isolated in space;

- b) *gain relative to a half-wave dipole (G_d)*, when the reference antenna is a half-wave dipole isolated in space whose equatorial plane contains the given direction;
 - c) *gain relative to a short vertical antenna (G_v)*, when the reference antenna is a linear conductor, much shorter than one quarter of the wavelength, normal to the surface of a perfectly conducting plane which contains the given direction.
- 155 6.25 *Equivalent Isotropically Radiated Power (e.i.r.p.)*: The product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna (*absolute or isotropic gain*).
- 156 6.26 *Effective Radiated Power (e.r.p.)* (in a given direction): The product of the power supplied to the antenna and its *gain relative to a half-wave dipole* in a given direction.
- 157 6.27 *Effective Monopole Radiated Power (e.m.r.p.)* (in a given direction): The product of the power supplied to the antenna and its *gain relative to a short vertical antenna* in a given direction.
- 158 6.28 *Tropospheric Scatter*: The propagation of *radio waves* by scattering as a result of irregularities or discontinuities in the physical properties of the troposphere.
- 159 6.29 *Ionospheric Scatter*: The propagation of *radio waves* by scattering as a result of irregularities or discontinuities in the ionization of the ionosphere.

Section VII. Frequency Sharing

- 160 7.1 *Interference*: The effect of unwanted energy due to one or a combination of *emissions*, *radiations*, or inductions upon reception in a *radiocommunication* system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy.
- 161 7.2 *Permissible Interference*¹: Observed or predicted *interference* which complies with quantitative *interference* and sharing criteria contained in these Regulations or in CCIR Recommendations or in special agreements as provided for in these Regulations.
- 162 7.3 *Accepted Interference*¹: *Interference* at a higher level than that defined as *permissible interference* and which has been agreed upon between two or more administrations without prejudice to other administrations.
- 163 7.4 *Harmful Interference**: *Interference* which endangers the functioning of a *radionavigation service* or of other *safety services* or seriously degrades, obstructs, or repeatedly interrupts a *radiocommunication service* operating in accordance with these Regulations.
- 164 7.5 *Protection Ratio (R.F.)*: The minimum value of the wanted-to-unwanted signal ratio, usually expressed in decibels, at the receiver input, determined under specified conditions such that a specified reception quality of the wanted signal is achieved at the receiver output.
- 165 7.6 *Coordination Area*: The area associated with an *earth station* outside of which a *terrestrial station* sharing the same frequency band neither causes nor is subject to interfering *emissions* greater than a permissible level.
- 166 7.7 *Coordination Contour*: The line enclosing the *coordination area*.

¹ The terms "permissible interference" and "accepted interference" are used in the coordination of frequency assignments between administrations.

* *Note by the General Secretariat*: This definition is not in alignment with Annex 2 to the Convention. The corresponding definition in that Annex shall prevail to the extent that there are differences between them (see also Resolution 68).

- 167 7.8 *Coordination Distance*: Distance on a given azimuth from an *earth station* beyond which a *terrestrial station* sharing the same frequency band neither causes nor is subject to interfering *emissions* greater than a permissible level.
- 168 7.9 *Equivalent Satellite Link Noise Temperature*: The noise temperature referred to the output of the receiving antenna of the *earth station* corresponding to the radio frequency noise power which produces the total observed noise at the output of the *satellite link* excluding noise due to *interference* coming from *satellite links* using other *satellites* and from terrestrial systems.

Section VIII. Technical Terms Relating to Space

- 169 8.1 *Deep Space*: Space at distances from the Earth approximately equal to, or greater than, the distance between the Earth and the Moon.
- 170 8.2 *Spacecraft*: A man-made vehicle which is intended to go beyond the major portion of the Earth's atmosphere.
- 171 8.3 *Satellite*: A body which revolves around another body of preponderant mass and which has a motion primarily and permanently determined by the force of attraction of that other body.
- 172 8.4 *Active Satellite*: A *satellite* carrying a *station* intended to transmit or retransmit radiocommunication signals.
- 173 8.5 *Reflecting Satellite*: A *satellite* intended to reflect radiocommunication signals.
- 174 8.6 *Active Sensor*: A measuring instrument in the *earth exploration-satellite service* or in the *space research service* by means of which information is obtained by transmission and reception of *radio waves*.
- 175 8.7 *Passive Sensor*: A measuring instrument in the *earth exploration-satellite service* or in the *space research service* by means of which information is obtained by reception of *radio waves* of natural origin.
- 176 8.8 *Orbit*: The path, relative to a specified frame of reference, described by the centre of mass of a *satellite* or other object in space subjected primarily to natural forces, mainly the force of gravity.
- 177 8.9 *Inclination of an Orbit* (of an earth satellite): The angle determined by the plane containing the *orbit* and the plane of the Earth's equator.
- 178 8.10 *Period* (of a satellite): The time elapsing between two consecutive passages of a *satellite* through a characteristic point on its *orbit*.
- 179 8.11 *Altitude of the Apogee or of the Perigee*: The altitude of the apogee or perigee above a specified reference surface serving to represent the surface of the Earth.
- 180 8.12 *Geosynchronous Satellite*: An earth *satellite* whose period of revolution is equal to the period of rotation of the Earth about its axis.
- 181 8.13 *Geostationary Satellite*: A *geosynchronous satellite* whose circular and direct *orbit* lies in the plane of the Earth's equator and which thus remains fixed relative to the Earth; by extension, a *satellite* which remains approximately fixed relative to the Earth.
- 182 8.14 *Geostationary-satellite orbit*: The *orbit* in which a *satellite* must be placed to be a *geostationary satellite*.
- 183 to 207 NOT allocated.

Frequency Allocations

ARTICLE 8

Introduction

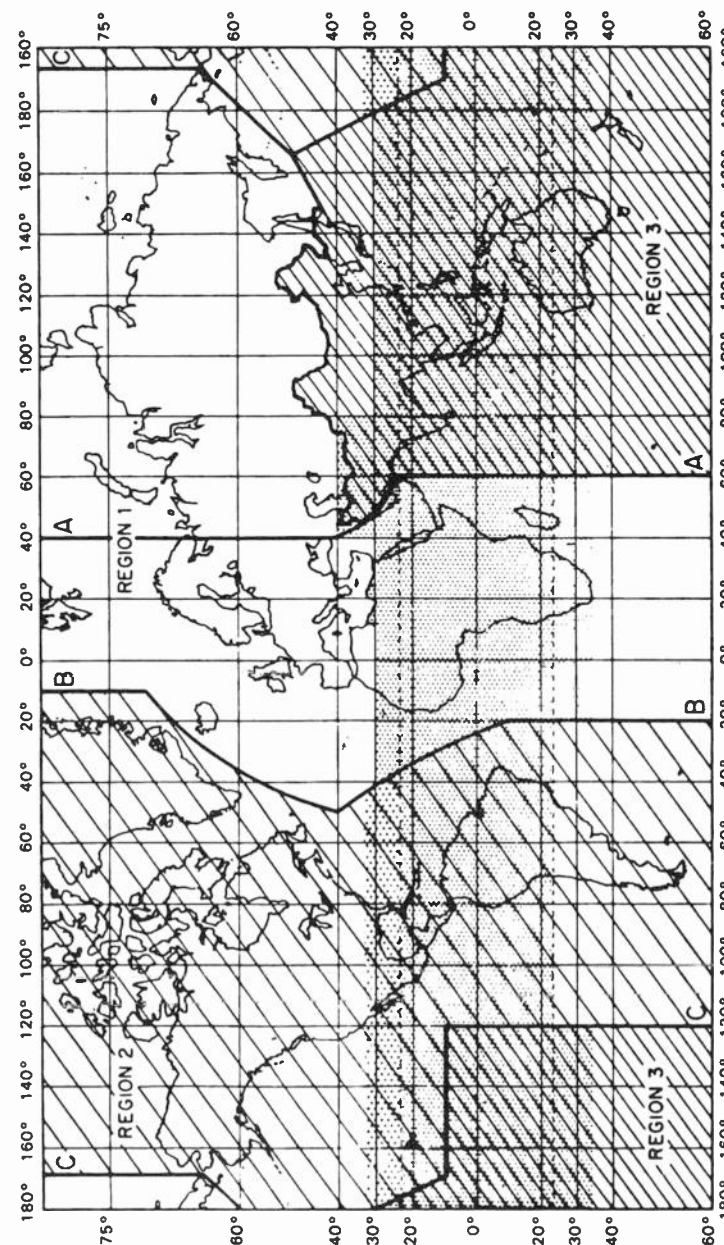
- 391 § 1. In all documents of the Union where the terms *allocation*, *allotment* and *assignment* are to be used, they shall have the meaning given them in Nos. 17 to 19, the terms used in the three working languages being as follows:

Frequency distribution to:	French	English	Spanish
Services	Attribution (attribuer)	Allocation (to allocate)	Atribución (atribuir)
Areas or countries	Allotissement (allotir)	Allotment (to allot)	Adjudicación (adjudicar)
Stations	Assignment (assigner)	Assignment (to assign)	Asignación (asignar)

Section I. Regions and Areas

- 392 § 2. For the allocation of frequencies the world has been divided into three Regions¹ as shown on the following map and described in Nos. 393 to 399:

- 392.1 ¹ It should be noted that where the words "regions" or "regional" are without a capital "R" in these Regulations, they do not relate to the three Regions here defined for purposes of frequency allocation.



The shaded part represents the Tropical Zone as defined in Nos. 406 to 410 and 411.

393 *Region 1:*

Region 1 includes the area limited on the east by line A (lines A, B and C are defined below) and on the west by line B, excluding any of the territory of Iran which lies between these limits. It also includes that part of the territory of Turkey and the Union of Soviet Socialist Republics lying outside of these limits, the territory of the Mongolian People's Republic, and the area to the north of the U.S.S.R. which lies between lines A and C.

394 *Region 2:*

Region 2 includes the area limited on the east by line B and on the west by line C.

395 *Region 3:*

Region 3 includes the area limited on the east by line C and on the west by line A, except the territories of the Mongolian People's Republic, Turkey, the territory of the U.S.S.R. and the area to the north of the U.S.S.R. It also includes that part of the territory of Iran lying outside of those limits.

396 The lines A, B and C are defined as follows:

397 *Line A:*

Line A extends from the North Pole along meridian 40° East of Greenwich to parallel 40° North; thence by great circle arc to the intersection of meridian 60° East and the Tropic of Cancer; thence along the meridian 60° East to the South Pole.

398 *Line B:*

Line B extends from the North Pole along meridian 10° West of Greenwich to its intersection with parallel 72° North; thence by great circle arc to the intersection of meridian 50° West and parallel 40° North; thence by great circle arc to the intersection of meridian 20° West and parallel 10° South; thence along meridian 20° West to the South Pole.

399 *Line C:*

Line C extends from the North Pole by great circle arc to the intersection of parallel 65° 30' North with the international boundary in Bering Strait; thence by great circle arc to the intersection of meridian 165° East of Greenwich and parallel 50° North; thence by great circle arc to the intersection of meridian 170° West and parallel

10° North; thence along parallel 10° North to its intersection with meridian 120° West; thence along meridian 120° West to the South Pole.

400 § 3. For the purposes of these Regulations, the term "African Broadcasting Area" means:

- 401 a) African countries, parts of countries, territories and groups of territories situated between the parallels 40° South and 30° North;
- 402 b) islands in the Indian Ocean west of meridian 60° East of Greenwich, situated between the parallel 40° South and the great circle arc joining the points 45° East, 11° 30' North and 60° East, 15° North;
- 403 c) islands in the Atlantic Ocean east of line B defined in No. 398 of these Regulations, situated between the parallels 40° South and 30° North.

404 § 4. The "European Broadcasting Area" is bounded on the west by the western boundary of Region 1, on the east by the meridian 40° East of Greenwich and on the south by the parallel 30° North so as to include the western part of the U.S.S.R., the northern part of Saudi Arabia and that part of those countries bordering the Mediterranean within these limits. In addition, Iraq and Jordan are included in the European Broadcasting Area.

405 § 5. The "European Maritime Area" is bounded on the north by a line extending along parallel 72° North from its intersection with meridian 55° East of Greenwich to its intersection with meridian 5° West, then along meridian 5° West to its intersection with parallel 67° North, thence along parallel 67° North to its intersection with meridian 30° West; on the west by a line extending along meridian 30° West to its intersection with parallel 30° North; on the south by a line extending along parallel 30° North to its intersection with meridian 43° East; on the east by a line extending along meridian 43° East to its intersection with parallel 60° North, thence along parallel 60° North to its intersection with meridian 55° East and thence along meridian 55° East to its intersection with parallel 72° North.

406 § 6. (1) The "Tropical Zone" (see map in No. 392) is defined as:

- 407 a) the whole of that area in Region 2 between the Tropics of Cancer and Capricorn;

- 408 b) the whole of that area in Regions 1 and 3 contained
between the parallels 30° North and 35° South with the
addition of:
- 409 1) the area contained between the meridians 40°
East and 80° East of Greenwich and the parallels
30° North and 40° North;
- 410 2) that part of Libya north of parallel 30° North.
- 411 (2) In Region 2, the Tropical Zone may be extended to parallel
33° North, subject to special agreements between the countries con-
cerned in that Region (see Article 7).
- 412 § 7. A sub-Region is an area consisting of two or more countries
in the same Region.

Section II. Categories of Services and Allocations

413 *Primary, Permitted and Secondary Services*

- 414 § 8. (1) Where, in a box of the Table in Section IV of this Article, a
band is indicated as allocated to more than one service, either on a
worldwide or Regional basis, such services are listed in the following
order:
- 415 a) services the names of which are printed in "capitals"
(example: FIXED); these are called "primary" ser-
vices;
- 416 b) services the names of which are printed in "capitals
between oblique strokes" (example: /RADIOLOCA-
TION/); these are called "permitted" services (see
No. 419);
- 417 c) services the names of which are printed in "normal
characters" (example: Mobile); these are called
"secondary" services (see Nos. 420 to 423).
- 418 (2) Additional remarks shall be printed in normal characters
(example: MOBILE except aeronautical mobile).
- 419 (3) Permitted and primary services have equal rights, except that,
in the preparation of frequency plans, the primary service, as com-
pared with the permitted service, shall have prior choice of frequencies.

- 420 (4) Stations of a secondary service:
- 421 a) shall not cause harmful interference to stations of pri-
mary or permitted services to which frequencies are
already assigned or to which frequencies may be
assigned at a later date;
- 422 b) cannot claim protection from harmful interference
from stations of a primary or permitted service to
which frequencies are already assigned or may be
assigned at a later date;
- 423 c) can claim protection, however, from harmful interfer-
ence from stations of the same or other secondary ser-
vice(s) to which frequencies may be assigned at a later
date.

- 424 (5) Where a band is indicated in a footnote of the Table as allo-
cated to a service "on a secondary basis" in an area smaller than a
Region, or in a particular country, this is a secondary service (see
Nos. 420 to 423).

- 425 (6) Where a band is indicated in a footnote of the Table as allo-
cated to a service "on a primary basis", or "on a permitted basis" in an
area smaller than a Region, or in a particular country, this is a primary
service or a permitted service only in that area or country (see
No. 419).

426 *Additional Allocations*

- 427 § 9. (1) Where a band is indicated in a footnote of the Table as "also
allocated" to a service in an area smaller than a Region, or in a partic-
ular country, this is an "additional" allocation, i.e. an allocation which
is added in this area or in this country to the service or services which
are indicated in the Table (see No. 428).
- 428 (2) If the footnote does not include any restriction on the service
or services concerned apart from the restriction to operate only in a
particular area or country, stations of this service or these services shall
have equality of right to operate with stations of the other primary ser-
vice or services indicated in the Table.
- 429 (3) If restrictions are imposed on an additional allocation in
addition to the restriction to operate only in a particular area or
country, this is indicated in the footnote of the Table.

430 *Alternative Allocations*

431 § 10. (1) Where a band is indicated in a footnote of the Table as "allocated" to one or more services in an area smaller than a Region, or in a particular country, this is an "alternative" allocation, i.e. an allocation which replaces, in this area or in this country, the allocation indicated in the Table (see No. 432).

432 (2) If the footnote does not include any restriction on stations of the service or services concerned, apart from the restriction to operate only in a particular area or country, these stations of such a service or services shall have an equality of right to operate with stations of the primary service or services, indicated in the Table, to which the band is allocated in other areas or countries.

433 (3) If restrictions are imposed on stations of a service to which an alternative allocation is made, in addition to the restriction to operate only in a particular country or area, this is indicated in the footnote.

434 *Miscellaneous Provisions*

435 § 11. (1) Where it is indicated in these Regulations that a service may operate in a specific frequency band subject to not causing harmful interference, this means also that this service cannot claim protection from harmful interference caused by other services to which the band is allocated under Chapter III of these Regulations.

436 (2) Except if otherwise specified in a footnote, the term "fixed service", where appearing in Section IV of this Article, does not include systems using ionospheric scatter propagation.

Section III. Description of the Table of Frequency Allocations

437 § 12. (1) The heading of the Table in Section IV of this Article includes three columns, each of which corresponds to one of the Regions (see No. 392). Where an allocation occupies the whole of the width of the Table or only one or two of the three columns, this is a worldwide allocation or a Regional allocation, respectively.

438 (2) The frequency band referred to in each allocation is indicated in the left-hand top corner of the part of the Table concerned.

439 (3) Within each of the categories specified in Nos. 415 to 417, services are listed in alphabetical order according to the French language. The order of listing does not indicate relative priority within each category.

440 (4) In the case where there is a parenthetical addition to an allocation in the Table, that service allocation is restricted to the type of operation so indicated.

441 (5) The footnote references which appear in the Table below the allocated service or services apply to the whole of the allocation concerned.

442 (6) The footnote references which appear to the right of the name of a service are applicable only to that particular service.

443 (7) In certain cases, the names of countries appearing in the footnotes have been simplified in order to shorten the text.

MHz
470 — 890

Allocation to Services									
Region 1			Region 2			Region 3			
470 — 790 BROADCASTING			470 — 512 BROADCASTING Fixed Mobile 674 675			470 — 585 FIXED MOBILE BROADCASTING			
			512 — 608 BROADCASTING 678			673 677 679			
			608 — 614 RADIO ASTRONOMY Mobile-Satellite except aeronautical mobile- satellite (Earth-to-space)			585 — 610 FIXED MOBILE BROADCASTING RADIONAVIGATION 688 689 690			
			614 — 806 BROADCASTING Fixed Mobile 675 692 693			610 — 890 FIXED MOBILE BROADCASTING			
790 — 862 FIXED BROADCASTING									
694 695 696 697 698 699 702			806 — 890 FIXED MOBILE BROADCASTING			-			
862 — 890 FIXED MOBILE except aeronautical mobile BROADCASTING 703			700			677 688 689 690 691 693 701			
699 704									

673 *Additional allocation:* in China, the band 470 — 485 MHz is also allocated to the space research (space-to-Earth) and the space operation (space-to-Earth) services on a primary basis subject to agreement obtained under the procedure set forth in Article 14, subject to not causing harmful interference to existing and planned broadcasting stations.

674 *Different category of service:* in Mexico and Venezuela, the allocation of the band 470 — 512 MHz to the fixed and mobile services is on a primary basis (see No. 425), subject to agreement obtained under the procedure set forth in Article 14.

675 *Different category of service:* in Chile, Colombia, Ecuador, the United States, Guyana and Jamaica, the allocation of the bands 470 — 512 MHz and 614 — 806 MHz to the fixed and mobile services is on a primary basis (see No. 425), subject to agreement obtained under the procedure set forth in Article 14.

676 *Additional allocation:* in Burundi, Cameroon, the Congo, Ethiopia, Israel, Kenya, Libya, Senegal, Sudan, Syria, and Yemen (P.D.R. of), the band 470 — 582 MHz is also allocated to the fixed service on a secondary basis.

677 *Alternative allocation:* in Pakistan, the bands 470 — 582 MHz and 610 — 890 MHz are allocated to the broadcasting service on a primary basis.

678 *Additional allocation:* in Costa Rica, El Salvador, Ecuador, the United States, Guatemala, Guyana, Honduras, Jamaica and Venezuela, the band 512 — 608 MHz is also allocated to the fixed and mobile services on a primary basis, subject to agreement obtained under the procedure set forth in Article 14.

679 *Additional allocation:* in India, the band 549.75 — 550.25 MHz is also allocated to the space operation service (space-to-Earth) on a secondary basis.

680 *Additional allocation:* in the United Kingdom, the following bands are also allocated to the aeronautical radionavigation service on a primary basis: 582 — 590 MHz until 31 December 1987; 598 — 606 MHz until 31 December 1994. All new assignments to stations in the aeronautical radionavigation service in these bands are subject to the agreement of the Administrations of the following countries: the Federal Republic of Germany, Belgium, Denmark, Spain, France, Ireland, Luxembourg, Morocco, Norway and the Netherlands.

681 *Additional allocation:* in Belgium, the band 582 — 606 MHz is also allocated to the radionavigation service on a primary basis until 31 December 1984.

682 *Additional allocation:* in France and Italy, the band 582 — 606 MHz is also allocated to the radionavigation service on a permitted basis until 1 January 1990.

683 *Additional allocation:* in Oman, the band 582 — 606 MHz is also allocated to the radionavigation service on a secondary basis.

684 *Additional allocation:* in Israel, Libya, Syria and Sudan, the band 582 — 790 MHz is also allocated to the fixed and mobile, except aeronautical mobile, services on a secondary basis.

- 685 *Additional allocation:* in Denmark and Kuwait, the band 590 — 598 MHz is also allocated to the aeronautical radionavigation service on a primary basis until 1 January 1995.
- 686 *Additional allocation:* in the United Kingdom, the band 590 — 598 MHz is also allocated to the aeronautical radionavigation service on a primary basis. All new assignments to stations in the aeronautical radionavigation service, including those transferred from the adjacent bands, shall be subject to coordination with the Administrations of the following countries: the Federal Republic of Germany, Belgium, Denmark, Spain, France, Ireland, Luxembourg, Morocco, Norway and the Netherlands.
- 687 *Additional allocation:* in the African Broadcasting Area (see Nos. 400 to 403), the band 606 — 614 MHz is also allocated to the radio astronomy service on a permitted basis.
- 688 *Additional allocation:* in China, the band 606 — 614 MHz is also allocated to the radio astronomy service on a primary basis.
- 689 In Region 1, except in the African Broadcasting Area (see Nos. 400 to 403), and in Region 3, the band 608 — 614 MHz is also allocated to the radio astronomy service on a secondary basis. In making assignments to stations of other services to which the band is allocated, administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference. Emissions from space or airborne stations can be particularly serious sources of interference to the radio astronomy service (see Nos. 343 and 344 and Article 36).
- 690 *Additional allocation:* in India, the band 608 — 614 MHz is also allocated to the radio astronomy service on a primary basis.
- 691 *Additional allocation:* in New Zealand, the band 610 — 620 MHz is also allocated to the amateur service on a secondary basis.
- 692 *Different category of service:* in Costa Rica, El Salvador and Honduras, the allocation of the band 614 — 806 MHz to the fixed service is on a primary basis (see No. 425), subject to agreement obtained under the procedure set forth in Article 14.
- 693 Within the frequency band 620 — 790 MHz, assignments may be made to television stations using frequency modulation in the broadcasting-satellite service subject to agreement between the administrations concerned and those having services, operating in accordance with the Table, which may be affected (see Resolutions 33 and 507). Such stations shall not produce a power flux-density in excess of the value -129 dB (W/m²) for angles of arrival less than 20° (see Recommendation 705) within the territories of other countries without the consent of the administrations of those countries.
- 694 *Additional allocation:* in Bulgaria, Hungary, Mongolia, Poland, the German Democratic Republic, Roumania, Czechoslovakia and the U.S.S.R., the band 645 — 862 MHz is also allocated to the aeronautical radionavigation service on a permitted basis.
- 695 *Alternative allocation:* in Spain and France, the band 790 — 830 MHz is allocated to the broadcasting service on a primary basis.
- 696 *Alternative allocation:* in Greece, Italy, Morocco and Tunisia, the band 790 — 838 MHz is allocated to the broadcasting service on a primary basis.
- 697 *Additional allocation:* in the Federal Republic of Germany, Denmark, Finland, Israel, Liechtenstein, Norway, the Netherlands, Sweden, Switzerland and Yugoslavia, the band 790 — 830 MHz, and in these same countries and in Spain and France, the band 830 — 862 MHz are also allocated to the mobile, except aeronautical mobile, service on a primary basis. However, stations of the mobile service in the countries mentioned in connection with each band referred to in this footnote shall not cause harmful interference to, or claim protection from, stations of services operating in accordance with the Table in countries other than those mentioned in connection with the band.
- 698 *Additional allocation:* in Austria, the band 790 — 862 MHz is also allocated to the mobile, except aeronautical mobile, service on a secondary basis.
- 699 *Additional allocation:* in Norway and Sweden, the bands 806 — 890 MHz and 942 — 960 MHz are also allocated to the mobile-satellite, except aeronautical mobile-satellite, service on a primary basis. The use of this service is limited to operation within national boundaries and subject to agreement obtained under the procedure set forth in Article 14. This service shall not cause harmful interference to services operating in accordance with the Table.
- 700 *Additional allocation:* in Region 2, the band 806 — 890 MHz is also allocated to the mobile-satellite, except aeronautical mobile-satellite, service on a primary basis. The use of this service is intended for operation within national boundaries and subject to agreement obtained under the procedure set forth in Article 14.
- 701 *Additional allocation:* in Region 3, the bands 806 — 890 MHz and 942 — 960 MHz are also allocated to the mobile-satellite, except aeronautical mobile-satellite, service on a primary basis. The use of this service is limited to operation within national boundaries and subject to agreement obtained under the procedure set forth in Article 14. This service shall not cause harmful interference to services operating in accordance with the Table.
- 702 *Alternative allocation:* in Italy, the band 838 — 854 MHz is allocated to the broadcasting service on a primary basis as from 1 January 1995.
- 703 In Region 1, in the band 862 — 960 MHz, stations of the broadcasting service shall be operated only in the African Broadcasting Area (see Nos. 400 to 403) excluding Algeria, Egypt, Libya and Morocco. Such operations shall be in accordance with the Final Acts of the African VHF/UHF Broadcasting Conference, Geneva, 1963.
- 704 *Additional allocation:* in Bulgaria, Hungary, Mongolia, Poland, the German Democratic Republic, Roumania, Czechoslovakia and the U.S.S.R., the band 862 — 960 MHz is also allocated to the aeronautical radionavigation service on a permitted basis until 1 January 1998. Up to this date, the aeronautical radionavigation service may use the band, subject to agreement obtained under the procedure set forth in Article 14. After this date, the aeronautical radionavigation service may continue to operate on a secondary basis.

Bibliography

Part I: Space Services

An enormous amount of technical, legal, and regulatory information has been produced concerning space services. Although the interest herein is in telecommunications and, in particular, spectrum management, the international treaties and regulations form the basis on how space is used. This bibliography is divided into two parts: Legal and Regulatory and Spectrum Engineering, although there is some overlap in some subjects. The ITU Radio Regulations and CCIR documents are presented at the end. The 1985 and 1988 Space Conferences may amend the Radio Regulations and various portions may be overtaken by such events. It is expected that the results of the Conference will be published in the *Telecommunication Journal*, several IEEE publications, and various other periodicals.

For basic space law, it is suggested that *The Modern International Law of Outer Space* by Christol and the *Manual on Space Law* by Jasentuliyana and Lee be considered as first readings. In the technical area, *Communications Satellites in the Geostationary Orbit* by Jansky and Jeruchim should be considered a first reading by those having interests in communications satellites and the geostationary orbit.

Additional references on space services are listed elsewhere in this book under other categories such as modeling, antennas, propagation, etc.

A. Legal and Regulatory

- [1] "Agreement relating to the International Telecommunications Satellite Organization (INTELSAT), with annexes," Feb. 12, 1973, 23 UST 3813, TIAS 7532.
- [2] P. Arnopoulos, "The international politics of the orbit-spectrum issue," *Ann. Air and Space Law*, vol. 7, 1982.
- [3] "Assignment of orbital locations to space stations in the domestic fixed-satellite service," Memorandum Opinion and Order, FCC 83-186, Federal Communications Commission, Aug. 12, 1983.
- [4] R. E. Butler, "World administrative radio conference for planning broadcasting satellite service," *J. Space Law*, vol. 5, nos. 1 and 2, Spring and Fall 1977.
- [5] B. Cheng, "The legal status of outer space and relevant issues: Delimitation of outer space and definition of peaceful use," *J. Space Law*, vol. 11, nos. 1 and 2, Spring and Fall 1983.
- [6] C. Q. Christol, *Satellite Power System (SPS) International Agreements*. Washington, DC: U.S. Dept. of Energy, Office of Energy Research, 1978.
- [7] —, "The 1974 Brussels convention relating to the distribution of program-carrying signals transmitted by satellite: An aspect of human rights," *J. Space Law*, vol. 6, no. 1, Spring 1978.
- [8] —, *The Modern International Law of Outer Space*. New York: Pergamon Press, 1982.
- [9] A. A. Cocca, "The geostationary orbit, focal point of space telecommunications law," *Telecommun. J.*, vol. 45, no. 4, Apr. 1978.
- [10] R. R. Colino, "The INTELSAT definitive arrangements: Ushering in a new era in satellite communications," European Broadcasting Union, Monograph No. 9, Geneva, 1973.
- [11] —, "International cooperation between communications satellite systems: An overview of current practices and future prospects," *J. Space Law*, vol. 5, nos. 1 and 2, Spring and Fall 1977.
- [12] "Convention on the International Maritime Satellite Organization (INMARSAT)," July 16, 1979, 31 UST 1, TIAS 9605.
- [13] Declaration of the First Meeting of Equatorial Countries (Bogota Declaration), (Dec. 3, 1976), reprinted in C. Q. Christol, *The Modern International Law of Outer Space*. New York: Pergamon, 1982.
- [14] S. E. Doyle, Chairman, "First report of the FCC Advisory Committee for ITU 1985 Space WARC (ORB-85)," Washington, DC, Dec. 1983.
- [15] E. D. DuCharme, R. R. Bowen, and M. J. R. Irwin, "The genesis of the 1985/87 ITU World Administrative Radio Conference on the use of the geostationary-satellite orbit and the planning of space services utilizing it," *Ann. Air and Space Law*, vol. 7, 1982.
- [16] J. E. Fawcett, *International Law and the Uses of Outer Space*. Dobbs Ferry, NY: Oceana, 1968.
- [17] E. Galloway, "Consensus decision-making by the United Nations Committee on the peaceful uses of outer space," *J. Space Law*, vol. 7, no. 1, Spring 1979.
- [18] —, "The history and development of space law: International law and United States law," *Ann. Air and Space Law*, vol. 7, 1982.
- [19] —, "Law and Security in Outer Space: The role of Congress in space law and policy," *J. Space Law*, vol. 11, no. 1 and 2, Spring and Fall 1983.
- [20] S. Gorove, "Legal aspects of the space shuttle," *Int. Lawyer*, vol. 13, no. 1, Winter 1979.
- [21] —, "The geostationary orbit: Issues of law and policy," *Amer. J. Int. Law*, vol. 73, no. 3, July 1979.
- [22] —, *United States Space Law—National and International Regulation*, Vol. 1. Dobbs Ferry, NY: Oceana, looseleaf service, 1982.
- [23] R. S. Jakhu, "The legal status of the geostationary orbit," *Ann. Air and Space Law*, vol. 7, 1982.
- [24] N. Jasentuliyana and R. S. K. Lee, Eds., *Manual to Space Law*. Dobbs Ferry, NY: Oceana, 1979.
- [25] N. Jasentuliyana, "The work of the United Nations Committee on the Peaceful Uses of Outer Space in 1982," *J. Space Law*, vol. 10, no. 1, Spring 1982.
- [26] M. Kinsley, *Outer Space and Inner Sanctum: Government, Business and Satellite Communications*. New York: Wiley, 1976.
- [27] N. M. Matte and H. De Saussure, *Legal Implications of Remote Sensing from Outer Space*. Leyden, The Netherlands: Sythoff, 1976.
- [28] E. Pepin, *History of the International Institute of Space Law, IAF*. New York: American Institute of Aeronautics and Astronautics, 1982.
- [29] A. S. Piradov, Ed., *International Space Law*, translated into English by Boris Belitsky, Selected Soviet Bibliography. Moscow: Progress Publishers, 1976.
- [30] C. E. Rankin, III, "Utilization of the geostationary orbit—A need

for orbital allocation?" *Columbia J. Transnat. Law*, vol. 13, no. 1, 1974.

- [31] C. G. M. Reijnen, *Utilization of Outer Space and International Law*. Amsterdam: Elsevier, 1981.
- [32] M. A. Rothblatt, "The impact of international satellite communication law upon access to the geostationary orbit and the electromagnetic spectrum," *Texas Int. Law J.*, vol. 16, no. 2, Spring 1981.
- [33] —, "Satellite communications and spectrum allocation," *Amer. J. Int. Law*, vol. 76, no. 1, Jan. 1982.
- [34] —, "ITU regulation of satellite communication," *Stanford J. Int. Law*, vol. 18, no. 1, Spring 1982.
- [35] "Satellite communications," Part 25, Rules and Regulations, Federal Communications Commission, 1984.
- [36] D. D. Smith, *Space Stations: International Law and Policy*. Boulder, CO: Westview Press, 1979.
- [37] D. D. Smith and M. A. Rothblatt, "Geostationary platforms: Legal estates in space," *J. Space Law*, vol. 10, no. 1, Spring 1982.
- [38] M. L. Stern, "Communications satellites and the geostationary orbit: Reconciling equitable access with efficient use," *Law and Policy in Int. Business*, Georgetown University, vol. 14, no. 3, 1983.
- [39] R. F. Stowe, "The development of international law relating to remote sensing of the earth from outer space," *J. Space Law*, vol. 5, nos. 1 and 2, Spring and Fall 1977.
- [40] —, "The legal and political considerations of the 1985 world administrative radio conference," *J. Space Law*, vol. 11, nos. 1 and 2, Spring and Fall 1983.
- [41] "Treaty on principles governing the activities of states in the exploration and use of outer space, including the moon and other celestial bodies," Oct. 10, 1967, 18 UST 2410, TIAS 6347.
- [42] A. G. Vicas, "An economic assessment of CCIR'S five methods for assuring guaranteed access to the orbit-spectrum resource," *Ann. Air and Space Law*, vol. 7, 1982.
- [43] G. D. Wallenstein, *International Telecommunication Agreements*. Dobbs Ferry, NY: Oceana, looseleaf service updated to Dec. 1982.
- [44] K. Wiewiorowska, *Bezposrednia Telewizja Satelitarna, Studium Prawnomiedzynarodowe* (Direct Broadcast Satellites, A Study of International Problems). Warszawa—Lodz: Polska Akademia Nauk, 1981.

B. Spectrum Engineering

- [1] A. S. Acampora, "The ultimate capacity of frequency-reuse communication satellites," *Bell Syst. Tech. J.*, vol. 59, no. 7, Sept. 1980.
- [2] M. Afifi and P. Foldes, "Optimum contiguous multibeam antenna coverage," *IEEE AP-S Int. Symp. Digest*, Quebec, Canada, June 1980.
- [3] H. Akima, "Sharing of the band 12.2–12.7 GHz between the broadcasting-satellite and fixed services," NTIA-Report-80-32, US Dept. of Commerce, Boulder, CO, Jan. 1980.
- [4] Analysis of the 1977 Geneva plan for satellite broadcasting at 12 GHz," *EBU Monograph 3222*, European Broadcasting Union, Brussels, Belgium, 1977.
- [5] A. M. Ballard, "Rosette Constellations of Earth Satellites," *IEEE Trans. Aerospace and Electron. Syst.*, vol. 16, no. 5, Sept. 1980.
- [6] J. P. Beyer, R. D. Briskman, D. W. Lipke, and K. Manning, "Some orbital spacing considerations for geostationary communications satellites, (using the 4 and 6 GHz frequency bands)," *COMSAT Corp. Tech. Memo*, no. DS-1-68, Oct. 25, 1968.
- [7] S. V. Borodich, L. Y. Kantor, and S. P. Kurilov, "The Intersputnik international communication satellite system," *Telecommun. J.*, vol. 45, no. 3, Mar. 1978.
- [8] F. Bove and L. Tomati, "A planning method for television broadcasting from satellites," *EBU Review—Tech. Part*, no. 158, Aug. 1976.
- [9] R. R. Bowen, "The Canadian approach to the development of communications by satellite in the 12-GHz band," *IEEE Trans.*

Commun., vol. COM-29, no. 8, Aug. 1981, or *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, no. 3, Aug. 1981.

- [10] R. R. Bowen and J. G. Chambers, "Planning of the 12 GHz broadcasting satellite service in region 2," Paper 84-0649, *AIAA 10th Communication Satellite Systems Conference*, Orlando, FL, Mar. 1984.
- [11] W. H. Braun, "2 degree spacing: Impact on domestic satellite systems," *Satellite Commun.*, vol. 5, no. 11, Nov. 1981.
- [12] H. E. Curtis, "Interference between satellite communication systems and common carrier surface systems," *Bell Syst. Tech. J.*, vol. 41, no. 3, May 1962.
- [13] J. H. Davidson and P. Sawitz, "SOUP-3 user and programmers manual," ORI, Inc., Silver Spring, MD, Sept. 1981.
- [14] S. Das and G. Sharp, "Satellite system interference modeling (11.7–12.2 GHz)," Federal Communications Commission, FCC Report No. RS-76-04, Sept. 1976.
- [15] N. F. de Groot, "Frequency management for deep-space research," *Telecommun. J.*, vol. 50, no. 1, Jan. 1983.
- [16] H. Dodel and B. A. Pontano, "Frequency reuse in collocated earth and terrestrial stations," *COMSAT Tech. Rev.*, vol. 3, no. 2, Fall 1973.
- [17] J. C. Fuenzalida, "A comparative study of the utilization of the geostationary orbit," *Proc. INTELSAT/IEE Conf. Digital Satellite Commun.*, Nov. 1969.
- [18] J. C. Fuenzalida and N. K. M. Chitre, "Frequency-sharing considerations between geostationary communications satellites and terrestrial radio relays," *COMSAT Tech. Rev.*, vol. 1, no. 1, Fall 1971.
- [19] J. C. Fuenzalida and E. Podraczky, "Reuse of the frequency spectrum at the satellite," AIAA Paper no. 70-442, *AIAA 3rd Commun. Satellite Syst. Conf.*, Los Angeles, CA, Apr. 1970.
- [20] A. Gelly, "Planning feeder links to broadcasting satellites," Paper 84-0650, *AIAA 10th Commun. Satellite Syst. Conf.*, Orlando, FL, Mar. 1984.
- [21] R. G. Gould and E. E. Reinhart, "The 1977 WARC on broadcasting satellites: Spectrum management aspects and implications," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part II, Aug. 1977.
- [22] R. A. Hedinger and M. C. Jeruchim, "On the relationship between geostationary orbit capacity and the interference allowance," *IEEE Trans. Commun.*, vol. COM-32, no. 5, May 1984.
- [23] A. L. Hiebert and W. Sollfrey, "Techniques for the analysis of spectral and orbital congestion in space systems," R-3046-AF, Rand Corp., Mar. 1984.
- [24] J. L. Hult and E. E. Reinhart, "Satellite spacing and frequency sharing for communication and broadcast services," *Proc. IEEE*, vol. 59, no. 2, Feb. 1971.
- [25] Y. Ito, T. Mizuno, and T. Muratani, "Effective utilization of geostationary orbit through optimization," *IEEE Trans. Commun.*, vol. COM-27, no. 10, Part I, Oct. 1979.
- [26] D. M. Jansky, "Effective use of the geostationary orbit through coordination," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part II, Aug. 1977.
- [27] D. Jansky, Ed., *World Atlas of Satellites*. Dedham, MA: Artech House, 1982.
- [28] D. M. Jansky and M. C. Jeruchim, *Communications Satellites in the Geostationary Orbit*. Dedham, MA: Artech House, 1983.
- [29] M. C. Jeruchim, "A statistical approach to satellite interference levels," *Conf. Rec. Int. Conf. Commun.*, IEEE, Toronto, Canada, June 1978.
- [30] M. C. Jeruchim and F. E. Lilley, "Spacing limitations of geostationary satellites using multilevel PSK signals," *IEEE Trans. Commun.*, vol. COM-20, no. 10, Oct. 1972.
- [31] M. C. Jeruchim and J. H. Moore, "The effect of station-keeping error on the distribution of carrier-to-interference ratio," *IEEE Trans. Commun.*, vol. COM-30, no. 7, July 1982.
- [32] M. C. Jeruchim, H. Ng, and D. M. Jansky, "Regulatory and technical factors in geostationary orbit utilization," *IEEE Trans. Commun.*, vol. COM-27, no. 10, Oct. 1979.
- [33] J. K. S. Jowett and A. K. Jefferis, "Ultimate communications

- capacity of the geostationary satellite," *Proc. IEEE*, vol. 116, no. 8, Aug. 1969.
- [34] L. Ya Kantor, "Evaluation of efficiency in the use of the geostationary satellite orbit by a spot-beam satellite system," *Telecommun. J.*, vol. 49, no. 1, Jan. 1982.
 - [35] W. E. Katzenstein, R. P. Moore, and H. G. Kimball, "Spectrum allocations above 40 GHz (WARC-79 results)," *IEEE Trans. Commun.*, vol. COM-29, no. 8, Aug. 1981, or *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, no. 3, Aug. 1981.
 - [36] J. W. Kiebler and H. G. Kimball, "The impact of WARC-79 on space applications," *IEEE Trans. Commun.*, vol. COM-29, no. 8, Aug. 1981, or *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, no. 3, Aug. 1981.
 - [37] L. Lee, "A new formulation of spectrum-orbit utilization efficiency for satellite communications in interference-limited situations," *IEEE Trans. Commun.*, vol. COM-32, no. 2, Feb. 1984.
 - [38] "Licensing of space stations in the domestic fixed-satellite service and related revisions of part 25 of the rules and regulations," Report and Order, CC Docket 81-704, Federal Communications Commission, Aug. 16, 1983.
 - [39] "List of radio and radar astronomy observatories," Committee on Radio Frequencies, National Academy of Sciences, Washington, DC, Mar. 1, 1983.
 - [40] P. Locke and A. Rinker, "Low-orbit satellites—An interference model," *Telecommun. J.*, vol. 45, no. 5, May 1978.
 - [41] W. G. Long, Jr., "Technical considerations affecting satellite communications spectrum management," *IEEE Trans. Commun.*, vol. COM-27, no. 10, Part I, Oct. 1979.
 - [42] L. Lundquist and M. J. Pagones, "Channel spacing: A trade-off parameter in frequency assignments," *Telecommun. J.*, vol. 48, no. 4, Apr. 1981.
 - [43] A. S. May and M. J. Pagones, "Model for computation of interference to radio-relay systems from geostationary satellites," *Bell Syst. Tech. J.*, vol. 50, no. 1, Jan. 1971.
 - [44] T. Mizuna, Y. Ito, and T. Muratoni, "Computer tools for optimizing orbit use," Paper 84-0651, *AIAA 10th Commun. Satellite Syst. Conf.*, Orlando, FL, Mar. 1984.
 - [45] H. Ng, "Satellite interference model program: User's manual," Report TN-77-3, Dept. of Commerce, Office of Telecommunications, Annapolis, MD, June 1977.
 - [46] T. O'Leary, "Satellite broadcasting networks—A fast planning method," *EBU Review—Tech. Part*, no. 164, Feb. 1977.
 - [47] H. R. Ottøy et al., "SOUP-5 version 3 user's manual," Report 2039, ORI, Inc., Silver Spring, MD, Nov. 1982.
 - [48] V. Pankonin and R. M. Price, "Radio astronomy and spectrum management: The impact of WARC-79," *IEEE Trans. Commun.*, vol. COM-29, no. 8, Aug. 1981, or *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, no. 3, Aug. 1981.
 - [49] P. J. Phillips and T. M. Sullivan, "Techniques for the management of frequency bands shared between terrestrial stations and mobile or transportable earth stations," *IEEE Trans. Commun.*, vol. COM-29, no. 8, Aug. 1981, or *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, no. 3, Aug. 1981.
 - [50] B. A. Pontano, "Methods of interference cancellation for improved orbit and spectrum utilization," *Conf. Rec., Nat. Telecommun. Conf.*, IEEE, Houston, TX, Dec. 1980.
 - [51] J. B. Potts, "Orbit resource management for the fixed satellite service (FSS)," Paper 84-0654, *AIAA 10th Commun. Satellite Conf.*, Orlando, FL, Mar. 1984.
 - [52] E. E. Reinhart, "Orbit-spectrum efficiency of the 12-GHz broadcasting satellite plans," *Conf. Rec., IEEE Global Telecommun. Conf.*, Nov. 28–Dec. 1, 1983, San Diego, CA.
 - [53] —, "Regulatory considerations (direct broadcasting satellites)," *COMSAT Tech. Rev.*, vol. 11, no. 2, Fall 1981.
 - [54] E. E. Reinhart et al., "The impact of WARC-79 on the broadcasting satellite service," *IEEE Trans. Commun.*, vol. COM-29, no. 8, Aug. 1981, or *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, no. 3, Aug. 1981.
 - [55] "Report of the conference preparatory meeting to the WARC-ORB-85," CCIR, International Telecommunication Union, Geneva, Switzerland, July 1984.
 - [56] P. H. Sawitz, "Spectrum-orbit utilization: An overview," *Conf. Rec., Nat. Telecommun. Conf.*, IEEE, New Orleans, LA, Dec. 1975.
 - [57] G. Sharp, "Reduced domestic satellite orbit spacings at 4/6 GHz," Federal Communications Commission, Report FCC/OST R83-2, May 1983.
 - [58] G. L. Sharp, "Reduced domestic satellite orbit spacing," Paper 84-0652, *AIAA 10th Commun. Satellite Conf.*, Orlando, FL, Mar. 1984.
 - [59] A. Sinha, "Optimum orbit location of a communication satellite," *COMSAT Tech. Rev.*, vol. 12, no. 2, Fall 1982.
 - [60] P. Stavroulakis and S. C. Moorthy, "A statistical approach to the interference reduction of a class of satellite transmissions," *Conf. Rec., Nat. Telecommun. Conf.*, IEEE, Washington, DC, Dec. 1979.
 - [61] N. Sultan, W. F. Payne, and D. R. Carter, "Efficient spectrum utilization for multiple beams, frequency reuse, mobile satellite system," Conference Publication No. 224, *Radio Spectrum Conservation Techniques*, IEE (London), Sept. 1983.
 - [62] D. Tong, "Time phased introduction of advanced technologies—Its impact on orbit/spectrum conservation," Paper 84-0653, *AIAA 10th Commun. Satellite Conf.*, Orlando, FL, Mar. 1984.
 - [63] D. V. Z. Wadsworth, "Longitude-reuse plan doubles communication satellite capacity of geostationary arc," *Proc. AIAA 8th Commun. Satellite Syst. Conf.*, 1980.
 - [64] J. H. C. Wang and E. D. Davis, "The Quasi-stationary satellite orbit," Report RS-75-01, Federal Communications Commission, Feb. 1975.
 - [65] P. J. Waterman, "Conducting radio astronomy in the EMC environment," *IEEE Trans. Electromagn. Compat.*, vol. EMC-26, no. 1, Feb. 1984.
 - [66] H. L. Weinberger, "Communication satellite spectrum conservation through advanced technology," *Fifth Int. Wroclaw Symp. Electromagn. Compat.*, Wroclaw, Poland, Sept. 1980.
 - [67] H. J. Weiss, "Relating to the efficiency of utilization of the geostationary orbit/spectrum in the fixed-satellite service," *Proc. IEEE*, vol. 68, no. 12, Dec. 1980.
 - [68] J. E. Whitworth, "DBS/FS frequency sharing," *COMSAT Tech. Rev.*, vol. 11, no. 2, Fall 1981.

C. ITU Space

Space Related Parts of the ITU Radio Regulations and Appendices (Edition of 1982):

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|-------------|--|
| Article 8. | Frequency allocations. |
| Article 11. | Coordination of frequency assignments to stations in a space radiocommunication service except stations in the broadcasting-satellite service and to appropriate terrestrial stations. |
| Article 13. | Notification and recording in the master international frequency register of frequency assignments to radio astronomy and space radiocommunication stations except stations in the broadcasting-satellite service. |
| Article 15. | Coordination, notification, and recording of frequency assignments to stations of the broadcasting-satellite service in the frequency bands 11.7–12.2 GHz (in regions 2 and 3) and 11.7–12.5 GHz (in region 1) and to the other services to which these bands are allocated, so far as their relationship to the broadcasting-satellite service in these bands is concerned. |
| Article 27. | Terrestrial radiocommunication services sharing frequency bands with space radiocommunication services above 1 GHz. |
| Article 28. | Space radiocommunication services sharing frequency bands with terrestrial radiocommunication services above 1 GHz. |
| Article 29. | Special rules relating to space radiocommunication services. |
| Article 30. | Broadcasting service and broadcasting satellite service. |

Article 32.	Amateur service and amateur-satellite service.
Article 35.	Radiodetermination service and radiodetermination-satellite service.
Article 36.	Radio astronomy service.
Article 59.	Conditions to be observed in the maritime mobile service and in the maritime mobile-satellite service.
Article 61.	Order of priority of communications in the maritime mobile service and in the maritime mobile-satellite service.
Article 66.	Public correspondence in the maritime mobile service and the maritime mobile-satellite service.
Appendix 3.	Notices relating to space radiocommunications and radio astronomy stations.
Appendix 4.	Advance publication information to be furnished for a satellite network.
Appendix 28.	Method for the determination of the coordination area around an earth station in frequency bands between 1 GHz and 40 GHz shared between space and terrestrial radiocommunication services.
Appendix 29.	Method of calculation for determining if coordination is required between geostationary-satellite networks sharing the same frequency bands.
Appendix 30.	Provisions for all services and associated plan for the

broadcasting-satellite service in frequency bands 11.7-12.2 GHz (in regions 2 and 3) and 11.7-12.5 GHz (in region 1).

Space Related Parts of Other ITU Publications:

- [1] Article 33, "Rational use of the radio frequency spectrum and of the geostationary satellite orbit," Int. Telecommun. Convention, Nairobi, 1982.
- [2] "Final acts of the regional administrative conference for the planning of the broadcasting-satellite service in region 2 (SAT-83)," Geneva, 1983.
- [3] "Space research and radioastronomy," CCIR Green Book, vol. II, 1982 or latest edition.
- [4] "Fixed-satellite service," CCIR Green Book, vol. IV-1, 1982 or latest edition.
- [5] "Frequency sharing and coordination between systems in the fixed-satellite service and radio relay systems," CCIR Green Book, vol. IV/IX-2, 1982 or latest edition.
- [6] "Mobile services," CCIR Green Book, vol. VIII, 1982 or latest edition.
- [7] "Broadcasting-satellite service (sound and television)," CCIR Green Book, vol. X/XI-2, 1982 or latest edition.

Bibliography

Part II: Propagation

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Many papers have been published recently that concern land mobile communications above 800 MHz and, in particular, cellular land mobile. Most of these have been published in the *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY* and the *Bell System Technical Journal*. The bibliography presented herein lists some papers that concern propagation above 800 MHz. Further information can be obtained by consulting the *IEEE PRESS* book *Land-Mobile Communications Engineering* that contains reprints of some of the significant papers on mobile propagation emphasizing cellular radio systems and propagation in the 900 MHz region of the spectrum [1].

REFERENCES

- [1] D. Botson, G. F. McClure, and S. R. McConoughey, *Land Mobile Communications Engineering*. New York: IEEE PRESS, 1984.

A. General References

- [1] M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation: Interference and Diffraction of Light*, 3rd. ed. New York: Pergamon, 1965.
- [2] H. Bremmer, *Terrestrial Radio Waves*. New York: Elsevier, 1949.
- [3] K. Bullington, "Radio propagation fundamentals," *Bell Syst. Tech. J.*, vol. 36, no. 3, May 1957.
- [4] R. K. Crane, "A review of transhorizon propagation phenomena," *Radio Sci.*, vol. 16, no. 5, Sept.—Oct., 1981.
- [5] P. David and J. Voge, *Propagation of Waves*. New York: Pergamon, 1969.
- [6] V. A. Fock, *Electromagnetic Diffraction and Propagation Problems*. New York: Pergamon, 1965.
- [7] H. T. Friis, "Introduction to radio and antennas," *IEEE Spectrum*, vol. 8, no. 4, Apr. 1971.
- [8] A. Ishimaru, *Wave Propagation and Scattering in Random Media*. New York: Academic Press, 1978.
- [9] D. E. Kerr, *Propagation of Short Radio Waves*, McGraw Hill, New York, NY, 1951; reprinted Dover, New York, NY, 1965.
- [10] R. C. Kirby, "Radio-Wave Propagation," in *Electronics Engi-*

neers' Handbook, D. G. Fink, Ed. New York: McGraw Hill, 1975. (Note: contains many references.)

- [11] M. Weisberger, R. Meidenbauer, H. Riggins, and S. Marcus, *Radio Wave Propagation: A Handbook of Practical Techniques for Computing Basic Transmission Loss and Field Strength*. Annapolis, MD: Electromagnetic Compatibility Analysis Center, 1982. (Available from National Technical Information Service, Springfield, VA; Retrieval no. AD A122 090.

B. VLF, LF, and MF Bands

- [12] H. R. Anderson, "A computer program system for predicting and plotting medium wave broadcast groundwave field strength contours," *IEEE Trans. Broadcast.*, vol. BC-26, no. 3, Sept. 1980.
- [13] W. C. Bain, "Models of the ionospheric D region at noon," IEE Conference Publication 195, IEE, London, April 1981.
- [14] C. P. Bell and P. Knight, "Daytime sky-wave propagation in the LF broadcasting band," *EBU Review—Tech. Part*, no. 167, Feb. 1978.
- [15] L. A. Berry, "User's guide to low frequency radio coverage programs," Technical Memorandum 78-247, Dept. of Commerce, Office of Telecommunications, Boulder, CO, Jan. 1978.
- [16] J. E. Bickel *et al.*, "Experimental observations of magnetic field effects on VLF propagation at night," *Radio Sci.*, vol. 5, no. 1, Jan. 1970.
- [17] L. Espenschied, C. N. Anderson, and A. Bailey, "Transatlantic radio telephone transmission," *Proc. IRE*, vol. 14, no. 1, Feb. 1926.
- [18] Federal Communications Commission, Rules and Regulations, Part 73, Broadcasting, Washington, DC, 1984 or latest edition.
- [19] D. A. Norton, "Low and medium frequency radio propagation," in *Electromagnetic Wave Propagation*, M. Desirant and J. C. Michaels, Eds. London: Academic Press, 1980.
- [20] J. W. Porter *et al.*, "Design considerations for a LORAN-C timing receiver in a hostile signal-to-noise environment," 12th Annual Precise Time and Time Interval Applications and Planning Meeting, National Aeronautics and Space Administration, Greenbelt, MD, Dec. 1980.
- [21] S. N. Samadder, "The theory of LORAN-C ground wave propagation—A review," *J. Inst. Navigat.*, vol. 26, no. 3, 1979.
- [22] J. R. Wait and K. P. Spies, "Characteristics of the earth-ionosphere waveguide for VLF radio waves," Technical Note 300, National Bureau of Standards, Dec. 1964.
- [23] J. C. H. Wang, "Medium frequency skywave propagation in region 2," *IEEE Trans. Broadcast.*, vol. BC-25, no. 2, Sept. 1979.
- [24] A. D. Watt, *VLF Radio Engineering*. New York: Pergamon, 1967.

C. High Frequency Bands

- [25] A. F. Barghausen *et al.*, "Predicting long term operational parameters of high-frequency skywave telecommunication systems," ESSA Tech. Report ERL 110-ITS-78, Environmental Sciences Services Administration, May 1969.
- [26] J. A. Betts, *High Frequency Communications*. New York, NY: American Elsevier, 1967.

areas for VHF mobile radio networks," *Proc. IEE*, London, vol. 116, no. 9, Sept. 1969.

- [95] M. Hata, "Empirical formula for propagation loss in land ionosphere," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 10, no. 5, Sept. 1980.
- [118] B. R. Bean and E. J. Dutton, *Radio Meteorology*, NBS

- [27] K. G. Budden, *Radio Waves in the Ionosphere*. Cambridge: Cambridge University Press, 1961.
- [52] E. N. Gilbert, "Line-of-sight paths over random terrain," *Bell Syst. Tech. J.*, vol. 54, no. 4, Apr. 1975.
- [53] C. A. Huff, A. C. Leden, and W. A. Kissick, "A guide to

Bibliography

Part II: Propagation

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REFERENCES

- [1] D. Botson, G. F. McClure, and S. R. McConoughey, *Land Mobile Communications Engineering*. New York: IEEE PRESS, 1984.
- A. General References**
- [1] M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation: Interference and Diffraction of Light*, 3rd. ed. New York: Pergamon, 1965.
- [2] H. Bremmer, *Terrestrial Radio Waves*. New York: Elsevier, 1949.
- [3] K. Bullington, "Radio propagation fundamentals," *Bell Syst. Tech. J.*, vol. 36, no. 3, May 1957.
- [4] R. K. Crane, "A review of transhorizon propagation phenomena," *Radio Sci.*, vol. 16, no. 5, Sept.-Oct., 1981.
- [5] P. David and J. Voge, *Propagation of Waves*. New York: Pergamon, 1969.
- [6] V. A. Fock, *Electromagnetic Diffraction and Propagation Problems*. New York: Pergamon, 1965.
- [7] H. T. Friis, "Introduction to radio and antennas," *IEEE Spectrum*, vol. 8, no. 4, Apr. 1971.
- [8] A. Ishimaru, *Wave Propagation and Scattering in Random Media*. New York: Academic Press, 1978.
- [9] D. E. Kerr, *Propagation of Short Radio Waves*, McGraw Hill, New York, NY, 1951; reprinted Dover, New York, NY, 1965.
- [10] R. C. Kirby, "Radio-Wave Propagation," in *Electronics Engi-*

neers' Handbook, D. G. Fink, Ed. New York: McGraw Hill, 1975. (Note: contains many references.)

- [11] M. Weisberger, R. Meidenbauer, H. Riggins, and S. Marcus, *Radio Wave Propagation: A Handbook of Practical Techniques for Computing Basic Transmission Loss and Field Strength*. Annapolis, MD: Electromagnetic Compatibility Analysis Center, 1982. (Available from National Technical Information Service, Springfield, VA; Retrieval no. AD A122 090.

B. VLF, LF, and MF Bands

- [12] H. R. Anderson, "A computer program system for predicting and plotting medium wave broadcast groundwave field strength contours," *IEEE Trans. Broadcast.*, vol. BC-26, no. 3, Sept. 1980.
- [13] W. C. Bain, "Models of the ionospheric D region at noon," IEE Conference Publication 195, IEE, London, April 1981.
- [14] C. P. Bell and P. Knight, "Daytime sky-wave propagation in the LF broadcasting band," *EBU Review—Tech. Part*, no. 167, Feb. 1978.
- [15] L. A. Berry, "User's guide to low frequency radio coverage programs," Technical Memorandum 78-247, Dept. of Commerce, Office of Telecommunications, Boulder, CO, Jan. 1978.
- [16] J. E. Bickel *et al.*, "Experimental observations of magnetic field effects on VLF propagation at night," *Radio Sci.*, vol. 5, no. 1, Jan. 1970.
- [17] L. Espenschied, C. N. Anderson, and A. Bailey, "Transatlantic radio telephone transmission," *Proc. IRE*, vol. 14, no. 1, Feb. 1926.
- [18] Federal Communications Commission, Rules and Regulations, Part 73, Broadcasting, Washington, DC, 1984 or latest edition.
- [19] D. A. Norton, "Low and medium frequency radio propagation," in *Electromagnetic Wave Propagation*, M. Desirant and J. C. Michaels, Eds. London: Academic Press, 1980.
- [20] J. W. Porter *et al.*, "Design considerations for a LORAN-C timing receiver in a hostile signal-to-noise environment," 12th Annual Precise Time and Time Interval Applications and Planning Meeting, National Aeronautics and Space Administration, Greenbelt, MD, Dec. 1980.
- [21] S. N. Samadder, "The theory of LORAN-C ground wave propagation—A review," *J. Inst. Navigat.*, vol. 26, no. 3, 1979.
- [22] J. R. Wait and K. P. Spies, "Characteristics of the earth-ionosphere waveguide for VLF radio waves," Technical Note 300, National Bureau of Standards, Dec. 1964.
- [23] J. C. H. Wang, "Medium frequency skywave propagation in region 2," *IEEE Trans. Broadcast.*, vol. BC-25, no. 2, Sept. 1979.
- [24] A. D. Watt, *VLF Radio Engineering*. New York: Pergamon, 1967.

C. High Frequency Bands

- [25] A. F. Barghausen *et al.*, "Predicting long term operational parameters of high-frequency skywave telecommunication systems," ESSA Tech. Report ERL 110-ITS-78, Environmental Sciences Services Administration, May 1969.
- [26] J. A. Betts, *High Frequency Communications*. New York, NY: American Elsevier, 1967.

- [27] K. G. Budden, *Radio Waves in the Ionosphere*. Cambridge: Cambridge University Press, 1961.
- [28] CCIR, "Ionospheric propagation (study group 6)," Documents of the XV Plenary Assembly, vol. VI, International Radio Consultative Committee, Geneva, Switzerland, 1982.
- [29] Central Radio Propagation Laboratory, "Ionospheric radio propagation," NBS Circular 464, Boulder, CO, 1948.
- [30] K. Davies, *Ionospheric Radio Propagation*. National Bureau of Standards Monograph 80, U.S. Government Printing Office, 1965.
- [31] —, *Ionospheric Radio Waves*. Waltham, MA: Blaisdell, 1969.
- [32] P. Hansen, "Measurements of basic transmission loss for HF ground-wave propagation over sea water," *Radio Sci.*, vol. 12, no. 3, May-June 1977.
- [33] G. Jacobs and T. J. Cohen, *The Shortwave Propagation Handbook*. Port Washington, NY: Cowan Publishing Co., 1982.
- [34] W. B. Jones et al., "Advances in ionospheric mapping by numerical methods," Technical Note 337, National Bureau of Standards, Washington, DC, Feb. 1965.
- [35] J. M. Kelso, *Radio Ray Propagation in the Ionosphere*. New York: McGraw-Hill, 1964.
- [36] D. L. Lucas and G. W. Haydon, "MUF-FOT predictions by electronic computers," National Bureau of Standards Report 6789, U.S. Dept. of Commerce, Boulder, CO, 1961.
- [37] J. A. Ratcliffe, *An Introduction to the Ionosphere and Magnetosphere*. Cambridge: Cambridge University Press, 1959.
- [38] G. Rishbeth and O. K. Garriott, *Introduction to Ionospheric Physics*. New York: Academic Press, 1969.
- [39] C. M. Rush, "HF propagation: What we know and what we need to know," IEE Conference Publication 195, IEE, London, April 1981.
- [52] E. N. Gilbert, "Line-of-sight paths over random terrain," *Bell Syst. Tech. J.*, vol. 54, no. 4, Apr. 1975.
- [53] G. A. Hufford, A. G. Longley, and W. A. Kissick, "A guide to the use of the ITS irregular terrain model in the area prediction mode," NTIA Report 82-100 ITS, U.S. Dept. of Commerce, Institute for Telecommunication Sciences, Boulder, CO, 1982.
- [54] IEE, *Tropospheric Wave Propagation*, IEE Conference Publication 48, London, 1968.
- [55] W. C. Jakes, "An Approximate Method to Estimate an Upper Bound on the Effect of Multipath Delay Distortion on Digital Transmission," *IEEE Trans. Commun.*, vol. COM-27, no. 1, Jan. 1979.
- [56] T. Kaliszewski, "Modifications and extensions of the CCIR groundwave prediction program for rough sea paths," Program and Abstracts, 1976 National Radio Science Meeting, Amherst, MA, Oct. 1976.
- [57] H. L. Kirke, "Calculation of ground-wave field strength over a composite land and sea path," *Proc. IRE*, vol. 37, no. 5, May 1949.
- [58] U. Kuhn, "Propagation measurements beyond line-of-sight during thunderstorms," *Proc. IEE*, London, vol. 115, no. 6, June 1968.
- [59] A. H. La Grone, "Forecasting television service fields," *Proc. IRE*, vol. 48, no. 6, June 1960.
- [60] A. G. Longley and G. A. Hufford, "Sensor path loss measurements—Analysis and comparison with propagation models," Report OTR-75-74, U.S. Dept. of Commerce, Institute of Telecommunication Sciences, Boulder, CO, Oct. 1975.
- [61] —, "The long-term variability of radio signals—A new empirical study," NTIA-TM-79-28, U.S. Dept. of Commerce, Institute of Telecommunication Science, Boulder, CO, Dec. 1979.
- [62] A. G. Longley and R. K. Reasoner, "Comparison of propagation measurements with predicted values in the 20 to 10,000 MHz range," ESSA Tech. Report ERL 148-ITS-97, U.S. Dept. of Commerce, Institute of Telecommunication Sciences, Boulder, CO, Jan. 1970.
- [63] A. G. Longley and P. L. Rice, "Prediction of tropospheric radio transmission loss over irregular terrain—A computer method," ESSA Tech. Report 148-ITS-97, U.S. Dept. of Commerce, Institute for Telecommunication Sciences, Boulder, CO, 1968.
- [64] M. N. Lustgarten and J. A. Madison, "An empirical propagation model (EPM-73)," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, Part II, Aug. 1977.
- [65] G. Millington, "Ground-wave propagation over an inhomogeneous smooth earth," *Proc. IEE*, London, Part III, vol. 96, no. 39, Jan. 1949.
- [66] —, "Ground-wave propagation across a land/sea boundary," *Nature*, vol. 163, no. 4131, Jan. 1949.
- [67] G. Millington and G. Isted, "Ground-wave propagation over an inhomogeneous smooth earth," *Proc. IEE*, London, vol. 97, Part III (Radio Communication and Engineering), no. 48, July 1950.
- [68] K. A. Norton, P. L. Rice, and L. E. Volger, "The use of angular distance in estimating transmission loss and fading range for propagation through a turbulent atmosphere over irregular terrain," *Proc. IRE*, vol. 43, no. 10, Oct. 1955.
- [69] R. H. Ott, "An alternative integral equation for propagation over irregular terrain," *Radio Sci.*, vol. 6, no. 4, Apr. 1971.
- [70] R. H. Ott, L. E. Vogler, and G. A. Hufford, "Ground wave propagation over irregular inhomogeneous terrain: Comparisons of calculations and measurements," *IEEE Trans. Antennas Propagat.*, vol. AP-27, no. 2, Mar. 1979.
- [71] F. H. Palmer, "Report on the great lakes propagation measurements program: Comparisons of the Canadian data with predictions of FCC R-6602," CRC-Report 1332, Communications Research Centre, Ottawa, Canada, Feb. 1980.
- [72] —, "Measurements of VHF/UHF propagation characteristics over arctic paths," *IEEE Trans. Antennas Propagat.*, vol. AP-28, no. 6, Nov. 1980.
- [73] R. A. Pappert and C. L. Goodhart, "A numerical study of

D. VHF, UHF, and Microwave Bands

VHF, UHF, microwave, including ground wave, ducting, tropospheric scatter, and line-of-sight propagation:

- [40] G. H. Brown, J. Epstein, and D. W. Peterson, "Comparative propagation measurements; television transmitters at 67.25, 288.510 and 910 megacycles," *RCA Review*, June 1948.
- [41] CCIR, "Propagation in non-ionized media (study group 5)," Documents of the XV Plenary Assembly, vol. V, International Radio Consultative Committee, Geneva, Switzerland, 1982.
- [42] S. Chang, "A new combined antenna and propagation model," *IEEE Antennas Propagat. Symp. Record*, Quebec, June 1980.
- [43] H. T. Dougherty, "A survey of microwave fading mechanisms, and applications," ESSA Tech. Report ERL-69-WPL-4, U.S. Dept. of Commerce, Boulder, CO, Mar. 1968.
- [44] H. T. Dougherty and E. J. Dutton, "The role of elevated ducting for radio service and interference fields," Report NTIA-81-69, Institute of Telecommunication Sciences, National Telecommunications and Information Administration, Boulder, CO, Mar. 1981.
- [45] H. T. Dougherty and B. A. Hart, "Recent progress in duct propagation predictions," *IEEE Trans. Antennas Propagat.*, vol. AP-27, no. 4, July 1979.
- [46] H. T. Dougherty and R. E. Wilkerson, "Determination of antenna height for protection against microwave diffraction fading," *Radio Sci.*, vol. 2, no. 2, Feb. 1967.
- [47] F. DuCastel, *Tropospheric Wave Propagation Beyond the Horizon*. New York: Pergamon, 1966.
- [48] N. Elson, "Ground-wave propagation across a land/sea boundary," *Nature*, vol. 164, no. 4159, July 16, 1949.
- [49] J. Epstein and D. Peterson, "An experimental study of wave propagation at 850 mc," *Proc. IRE*, vol. 41, no. 5, May 1953.
- [50] H. Fine, "UHF propagation within line of sight," T.R.R. Report No. 2.4.12, Federal Communications Commission, Washington, DC, June 1951.
- [51] A. J. Giger and J. Shapira, "Interference caused by ground scattering in terrestrial microwave radio systems," Conference Record, IEEE International Conference on Communications, Boston, MA, June 19-21, 1983.

- tropospheric ducting at HF," *Radio Sci.*, vol. 14, no. 5, Sept. 1979.
- [74] P. L. Rice and J. W. Herbstreit, "Tropospheric propagation," in *Advances in Electronic and Electron Physics*, L. Marton, Ed. New York: Academic Press, 1964.
 - [75] P. L. Rice, A. G. Longley, K. A. Norton, and A. P. Barsis, "Transmission loss predictions for tropospheric communication circuits," Technical Note 101, National Bureau of Standards, Boulder, CO, Revised Jan. 1967.
 - [76] S. Rotherham, "Ground-wave propagation, part 1: Theory for short distances," *Proc. IEE*, London, Part F, vol. 128, no. 5, Oct. 1981.
 - [77] —, "Ground-wave propagation, part 2: Theory for medium and long distances and reference propagation curves," *Proc. IEE*, London, Part F, vol. 128, no. 5, Oct. 1981.
 - [78] C. L. Ruthroff, "Multiple-path fading on line-of-sight microwave radio systems as a function of path length and frequency," *Bell Syst. Tech. J.*, vol. 50, no. 7, Sept. 1971.
 - [79] O. Sasaki and T. Akiyama, "Multipath delay characteristics on line-of-sight microwave radio system," *IEEE Trans. Commun.*, vol. COM-27, no. 12, Dec. 1979.
 - [80] J. A. Saxton and B. N. Harden, "Ground-wave field strength surveys at 100 and 600 MHz," *Proc. IEE*, London, Part III, vol. 101, no. 71, May 1954.
 - [81] M. S. Sodha *et al.*, "Focusing of waves in ducts," *Radio Sci.*, vol. 7, no. 11, Nov. 1972.
 - [82] M. C. Stevens, "Multipath and interference effects in secondary surveillance radar systems," *Proc. IEE*, London, Part F, vol. 128, no. 1, Feb. 1981.
 - [83] V. N. Troitsky, "A method for determining statistical characteristics of SHF, UHF, and VHF interfering signals over long distances in land and coastal areas," presented at the 4th Symposium and Technical Exhibition on Electromagnetic Compatibility, Zurich, Switzerland, Mar. 1981.
 - [84] A. Vigants, "Space diversity engineering," *Bell Syst. Tech. J.*, vol. 54, no. 1, Jan. 1975.
 - [85] —, "Microwave radio obstruction fading," *Bell Syst. Tech. J.*, vol. 60, no. 6, July-Aug. 1981.
 - [86] M. A. Weissberger, R. L. Hinkle, and W. T. Shelton, "Estimating outage time in terrestrial microwave systems caused by mobile or stationary in-band interference sources," 1975 IEEE Electromagnetic Compatibility Symposium Record, San Antonio, Texas, Oct. 1975.
 - [87] M. S. Wheeler, "Microwave relay fading statistics as a function of terrain clearance factor," *IEEE Trans. Antennas Propagat.*, vol. AP-25, no. 2, Mar. 1977.
 - mobile radio services," *IEEE Trans. Veh. Technol.*, vol. VT-29, no. 3, Aug. 1980.
 - [96] L. G. Hause, "UHF radio propagation data for low antenna heights," Technical Report ERL-134-ITS-93-1, U.S. Dept. of Commerce, Institute for Telecommunication Sciences, Boulder, CO, Nov. 1969.
 - [97] R. W. Hubbard *et al.*, "Measuring characteristics of microwave mobile channels," Report NTIA-78-5, U.S. Dept. of Commerce, Institute for Telecommunication Sciences, Boulder, CO, Nov. 1977.
 - [98] W. C. Jakes, Ed., *Microwave Mobile Communications*. New York: John Wiley, 1974.
 - [99] M. E. Johnson and G. D. Gierhart, "(1978) Applications guide for propagation and interference analysis computer programs (0.1 to 20 GHz)," DOT-Report FAA-RD-77-60, Mar. 1978.
 - [100] R. W. King and J. H. Causebrook, "Computer programs for UHF co-channel interference prediction using a terrain data bank," BBC-RD-1974/6, British Broadcasting Corporation, Feb. 1974.
 - [101] S. Kozono and K. Watanabe, "Influence of environmental buildings on land mobile radio propagation," *IEEE Trans. Commun. Technol.*, vol. COM-25, no. 10, Oct. 1977.
 - [102] W. Kuebler and R. Leggett, "Deterministic calculation of terrain dependent propagation loss," IEEE National Telecommunications Conference Record, Washington, DC, 1979.
 - [103] W. C. Y. Lee, "Studies of base-station antenna height effects on mobile radio," *IEEE Trans. Veh. Technol.*, vol. VT-29, no. 2, May 1980.
 - [104] A. G. Longley, "Radio propagation in urban areas," Report OT-78-144, U.S. Dept. of Commerce, Institute for Telecommunications Sciences, Boulder, CO, Apr. 1978.
 - [105] R. W. Lorenz, "Field strength prediction method for a mobile telephone system using a topographical data bank," IEE Conference Publication No. 188, IEE, London, 1980.
 - [106] R. Luebbers *et al.*, "GTD Terrain Reflecting Model Applied to ILS Glide Slope," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 18, no. 1, Jan. 1982.
 - [107] A. Malaga, "An empirical path loss model for HF/VHF propagation in urban areas," *Radio Sci.*, vol. 16, no. 3, May 1981.
 - [108] Y. Okumura *et al.*, "Field strength and its variability in VHF and UHF land mobile service," Review of the Tokyo Electrical Communication Laboratory, Sept.-Oct. 1978.
 - [109] D. O. Reudink, "Properties of mobile radio propagation above 400 MHz," *IEEE Trans. Veh. Technol.*, vol. VT-23, no. 4, Nov. 1974.
 - [110] M. Sengoku, "Telephone traffic in a mobile radio communications system using dynamic frequency assignments," *IEEE Trans. Veh. Technol.*, vol. VT-29, no. 2, May 1980.
 - [111] N. H. Shepherd, "Radio wave loss deviation and shadow loss at 900 MHz," *IEEE Trans. Veh. Technol.*, vol. VT-26, no. 4, Nov. 1977.
 - [112] R. D. Smith, "A comparison of measured data and ITS model predictions: VOR and TACAN signal strengths," FAA-RD-77-106, Federal Aviation Administration, Washington, DC, Jan. 1978.
 - [113] G. L. Turin, "Introduction to spread-spectrum antimultipath techniques and their application to urban digital radio," *Proc. IEEE*, vol. 68, no. 3, Mar. 1980.
 - [114] P. I. Wells, "The attenuation of UHF radio signals by houses," *IEEE Trans. Veh. Technol.*, vol. VT-26, no. 4, Nov. 1977.

E. Land and Aeronautical Mobile

- [88] B. W. P. Adams, "An empirical routine for estimating reflection loss in military radio paths in the VHF and UHF bands," *IEE Conference Publication 169*, IEE, London, 1978.
- [89] A. P. Barsis, "Radio wave propagation over irregular terrain in the 76-9200 MHz range," *IEEE Trans. Veh. Technol.*, vol. VT-20, no. 3, Aug. 1971.
- [90] A. Barsis *et al.*, "Analysis of propagation measurements over irregular terrain," Technical Report ERL-114-ITS-82, U.S. Dept. of Commerce, Institute of Telecommunication Sciences, Boulder, CO, Mar. 1969.
- [91] K. Bullington, "Radio propagation for vehicular communications," *IEEE Trans. Veh. Technol.*, vol. VT-26, no. 4, Nov. 1977.
- [92] R. Carey, "Technical factors affecting the assignment of facilities in the domestic public land mobile radio service," FCC Report R-6406, Federal Communications Commission, June 24, 1964.
- [93] J. Damelin, 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, Federal Communications Commission, Washington, DC, Sept. 1966.
- [94] R. Edwards and J. Durkin, "Computer prediction of service areas for VHF mobile radio networks," *Proc. IEE*, London, vol. 116, no. 9, Sept. 1969.
- [95] M. Hata, "Empirical formula for propagation loss in land

F. Earth-to-Space Paths

- [115] J. Aarons, "Global morphology of ionospheric scintillation," *Proc. IEEE*, vol. 70, no. 4, Apr. 1982.
- [116] J. Aarons, H. E. Whitney, and R. S. Allen, "Global morphology of ionospheric scintillations," *Proc. IEEE*, vol. 59, no. 2, Feb. 1971.
- [117] J. Awaka *et al.*, "ETS-II experiments part V: Effect of the ionosphere," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 16, no. 5, Sept. 1980.
- [118] B. R. Bean and E. J. Dutton, *Radio Meteorology*, NBS

Monograph 92, National Bureau of Standards, Boulder, CO, 1966.

- [119] B. H. Briggs and J. A. Parkin, "On the variation of radio star scintillations with zenith angle," *J. Atmos. Terr. Phys.*, vol. 25, no. 6, June 1963.
- [120] D. C. Cox, "Depolarization of radio waves by atmospheric hydrometeors on earth space paths: A review," *Radio Sci.*, vol. 16, no. 5, Sept.-Oct. 1981.
- [121] D. C. Cox and H. W. Arnold, "Results from the 19- and 28-GHz COMSTAR satellite propagation experiments at Crawford Hill," *Proc. IEEE*, vol. 70, no. 5, May 1982.
- [122] R. K. Crane, "Propagation at centimeter and millimeter wavelengths," *Proc. IEEE*, vol. 59, no. 2, Feb. 1971.
- [123] D. J. Fang and M. S. Pontes, "4/6 GHz ionospheric scintillation measurements during the peak of sunspot cycle 21," *COMSAT Tech. Rev.*, vol. 11, no. 2, Fall 1981.
- [124] L. T. Gusler and D. C. Hogg, "Some calculations on coupling between satellite-communications and terrestrial radio-relay systems due to scattering by rain," *Bell Syst. Tech. J.*, vol. 49, no. 7, Sept. 1970.
- [125] D. A. Hill, "A survey of earth-to-satellite propagation factors between 2.5 and 275 GHz," OT Report 74-43, U.S. Department of Commerce, Office of Telecommunications, Boulder, CO, July 1974.
- [126] J. L. Hult and E. E. Reinhart, "Satellite sharing and frequency sharing for communication and broadcast services," *Proc. IEEE*, vol. 59, no. 2, Feb. 1971.
- [127] L. J. Ippolito, R. D. Kaul and R. G. Wallace, "Propagation effects handbook for satellite systems design," NASA Reference Publication 1082, Second ed., National Aeronautics and Space Administration, Greenbelt, MD, Dec. 1981.
- [128] S. O. Lane and W. L. Stutzman, "Spatial rain rate distribution modeling for earth-space link propagation calculations," Abstracts of the North American Radio Science Meeting, Quebec, June 1980.
- [129] L. S. Lee, "The feasibility of two one-parameter polarization control methods in satellite communications," *IEEE Trans. Commun.*, vol. COM-29, no. 5, May 1981.
- [130] H. J. Liebe and W. M. Welch, "Molecular attenuation and phase dispersion between 40 and 14 GHz for path models from different altitudes," Rep. OT-73-10, U.S. Dept. of Commerce, Office of Telecomm., Boulder, CO, May 1973.
- [131] S. H. Lin, H. J. Bergmann, and M. V. Pursley, "Rain attenuation on earth-satellite paths—A summary of 10-year experiments and studies," *Bell Syst. Tech. J.*, vol. 59, no. 2, Feb. 1980.
- [132] R. L. Olsen, D. V. Rogers, and D. B. Hodge, "The aR^b relation in the calculation of rain attenuation," *IEEE Trans. Antennas Propagat.*, vol. AP-26, no. 2, Mar. 1978.
- [133] D. O. Reudink, "Estimates of path loss and radiated power for UHF mobile-satellite systems," *Bell Syst. Tech. J.*, vol. 62, no. 8, Oct. 1983.
- [134] A. W. Straiton, "The absorption and reradiation of radio waves by oxygen and water in the atmosphere," *IEEE Trans. Antennas Propagat.*, vol. AP-23, no. 4, July 1975.
- [135] R. R. Taur, "Ionospheric scintillation at 4 and 6 GHz," *COMSAT Tech. Rev.*, vol. 3, no. 1, Spring 1973.
- [136] W. I. Thompson, "A survey of electromagnetic wave transmission in the earth's atmosphere over the frequency (wavelength) range 3 kHz (100 km) to 3,000 THz (0.1 μ m)," DOT-TSC-NASA-71-6, Transportation Systems Center, Cambridge, Massachusetts, Feb. 1971.
- [137] M. A. Weissberger and R. H. Meidenbauer, "Modeling rain attenuation on earth-space microwave links," in *IEEE International Antennas and Propagation Symposium Digest*, Quebec, Canada, June 1980.
- [138] K. C. Yeh and C. H. Liu, "Radio wave scintillations in the ionosphere," *Proc. IEEE*, vol. 70, no. 4, Apr. 1982.

G. Foliage

- [139] K. A. Chamberlin, "Investigation and development of VHF ground-air propagation computer modeling including the attenuating effects of forested areas for within line-of-sight

propagation paths," Report EER 51-1, Ohio University, Athens, OH, Mar. 1981.

- [140] N. C. Currie, E. E. Martin, and F. B. Dyer, "Radar foliage penetration measurements at millimeter wavelengths," ESS/GIT-A-1485-TR-4, Georgia Institute of Technology, Atlanta, GA, Dec. 31, 1975.
- [141] D. Dence and T. Tamir, "Radio loss of lateral waves in forest environments," *Radio Sci.*, vol. 4, no. 4, Apr. 1969.
- [142] H. R. Head, "The influence of trees on television field strengths at ultra-high frequencies," *Proc. IRE*, vol. 48, no. 6, June 1960.
- [143] A. Kinase, "Influences of terrain irregularities and environmental clutter surroundings on the propagation of broadcasting waves in the UHF and VHF bands," Japan Broadcasting Corporation (NHK) Technical Monograph 14, Mar. 1969.
- [144] S. Krevsky, "HF and VHF radio wave attenuation through jungle and woods," *IEEE Trans. Antennas Propagat.*, vol. AP-11, no. 4, July 1963.
- [145] A. H. La Grone, "Propagation of VHF and UHF electromagnetic waves over a grove of trees in full leaf," *IEEE Trans. Antennas Propagat.*, vol. AP-25, no. 6, Nov. 1977.
- [146] D. L. Sachs and P. J. Wyatt, "A conducting slab model electromagnetic propagation within a jungle medium," *Radio Sci.*, vol. 3, no. 2, Feb. 1968.
- [147] J. A. Saxton and J. A. Lane, "VHF and UHF reception, effects of trees and other obstacles," *Wireless World*, May 1955.
- [148] T. Tamir, "Radio wave propagation along mixed paths in forest environments," *IEEE Trans. Antennas Propagat.*, vol. AP-25, no. 4, July 1977.
- [149] M. A. Weissberger and J. Hauber, "Modeling the increase in loss caused by propagation through a grove of trees," Abstracts of the North American Radio Science Meeting, Quebec, June 1980.

H. Rain

- [150] R. K. Crane, "Prediction of attenuation by rain," *IEEE Trans. Commun.*, vol. COM-28, no. 9, Sept. 1980.
- [151] —, "A two-component rain model for the prediction of attenuation and diversity improvement," Thayer School of Engineering, Dartmouth College, NH, Feb. 1982.
- [152] E. Damosi *et al.*, "A systematic comparison of rain attenuation and prediction methods for terrestrial paths," URSI Commission F Open Symposium, Preprints of Papers, Lennoxville, Canada, May 1980.
- [153] D. C. Hogg, "Millimeter-wave communication through the atmosphere," *Science* 1968, vol. 159, no. 3810, 1968.
- [154] S. H. Lin, "Nationwide long term rain rate statistics and empirical calculations of 11 GHz microwave rain attenuation," *Bell Syst. Tech. J.*, vol. 56, no. 9, Nov. 1977.
- [155] T. Maseng and P. M. Bakken, "A stochastic dynamic model of rain attenuation," *IEEE Trans. Commun.*, vol. COM-29, no. 5, May 1981.
- [156] R. G. Medhurst, "Rainfall attenuation of centimeter waves: Comparison of theory and experiment," *IEEE Trans. Antennas Propagat.*, vol. AP-13, no. 4, July 1965.
- [157] T. Oguchi, "Attenuation of electromagnetic waves due to rain with distorted raindrops," *Journal Radio Research Lab. (Tokyo)*, vol. 11, Jan. 1964.
- [158] —, "Scattering from hydrometers: A survey," *Radio Sci.*, vol. 16, no. 5, Sept.-Oct. 1981. (Note: Contains many references.)
- [159] T. L. Osborne, "Application of rain attenuation data to 11-GHz radio-path engineering," *Bell Syst. Tech. J.*, vol. 56, no. 9, Nov. 1977.
- [160] R. R. Persinger, W. L. Stutzman, R. E. Castle, Jr., and C. W. Bostian, "Millimeter wave attenuation and prediction using piecewise uniform rain rate model," *IEEE Trans. Antennas Propagat.*, vol. AP-28, no. 2, Mar. 1980.

I. Computer Techniques and Topographic Data Bases

- [161] H. R. Anderson, "A computer program system for predicting and plotting medium wave broadcast groundwave field

- strength contours," *IEEE Trans. Broadcast.*, vol. BC-26, no. 3, Sept. 1980.
- [162] F. Bonfatti *et al.*, "Structure and use of a geographic data base for mobile radio propagation prediction," Conference Record, IEEE International Conference on Communications, Boston, MA, June 19-22, 1983.
- [163] K. A. Chamberlin, "Investigation and development of VHF ground-air propagation computer modeling including the attenuating effects of forested areas for within line-of-sight propagation paths," Report EER 51-1, Ohio University, Athens, OH, Mar. 1981.
- [164] E. Damosso and B. Lingua, "A computer prediction technique for land mobile propagation in VHF and UHF bands," Conference Record, IEEE International Conference on Communications, Boston, MA, June 19-22, 1983.
- [165] J. Durkin, "Computer prediction of service areas for VHF and UHF land mobile radio services," *IEEE Trans. Veh. Technol.*, vol. VT-26, no. 4, Nov. 1977.
- [166] R. Edwards and J. Durkin, "Computer prediction of service areas for VHF mobile radio networks," *Proc. IEE*, London, vol. 116, no. 9, Sept. 1969.
- [167] W. E. Frazier and D. S. Anderson, "A propagation model for electromagnetic compatibility analysis," 9th Tri-Service Conference on Electromagnetic Compatibility, IIT Research Institute, Chicago, IL, Oct. 1963.
- [168] M. F. A. Ibrahim, "Signal Strength prediction in urban areas using a topographical and environmental data base," Conference Record, IEEE International Conference on Communications, Boston, MA, June 19-22, 1983.
- [169] F. Ikegami and S. Yoshida, "Feasibility of predicting mean field strength for urban mobile radio by aid of building data bases," Conference Record, IEEE International Conference on Communications, Boston, MA, June 19-22, 1983.
- [170] R. W. King and J. H. Causebrook, "Computer programs for UHF co-channel interference prediction using a terrain data bank," BBC-RD-1974/6, British Broadcasting Corporation, Feb. 1974.
- [171] K. Loew and R. W. Lorenz, "Determination of service areas for mobile communication with a topographical data base," Conference Record, IEEE International Conference on Communications, Boston, MA, June 19-22, 1983.
- [172] A. G. Longley and P. L. Rice, "Prediction of tropospheric radio transmission loss over irregular terrain—A computer method 1968," ESSA Tech. Report 148-ITS-97, U. S. Dept. of Commerce, Institute for Telecommunications Sciences, Boulder, CO, 1968.
- [173] R. W. Lorenz, "Field strength prediction method for a mobile telephone system using a topographic data bank," IEE Conference Publication No. 118, IEE, London, 1980.
- [174] S. Meyer, "Coverage prediction for rural telephony systems," Conference Record, IEEE International Conference on Communications, Boston, MA, June 19-22, 1983.
- [175] H. Niimi, T. Hirabayashi, and M. Kajiyama, "Computer aided analysis of propagation characteristics using topographical mesh-data bases," Conference Record, IEEE International Conference on Communications, Boston, MA, June 19-22, 1983.
- [176] J. H. Whitteker, "Propagation prediction from a topographic data base," Conference Record, IEEE International Conference on Communications, Boston, MA, June 19-22, 1983.

Author Index

- A**
Arnaud, J. -F., 240
- B**
Bellchambers, W. H., 11
Berry, L. A., 171
Borman, W. M., 111
Bromery, R., 286
Buesing, R. T., 355
Bullington, K., 400
Buss, L. A., 124
- C**
CCIR, 334, 375
Chan, G., 263
Cohen, D., 257
Cram, C., 236
Cutts, R. L., 124
- D**
da Silva, J., 263
Dayharsh, T. I., 177
de Mercado, J., 263
Dorian, C., 111
Durkin, J., 424, 433
- E**
Edwards, R., 433
Egli, J. J., 415
- F**
Francis, J., 11
- G**
Gamble, W. D., 139
Garber, G. W., 248
Gianessi, M., 144
Green, D. H., 433
- H**
Hagn, G. H., 177, 186
Hale, W. K., 204
Harada, W. I., 303
Hensler, T., 236
Hinkle, R. L., 348
Hummel, E., 11
- J**
Jansky, D. M., 177
Johnson, R., 111
- K**
Katz, L., 342
Khabiri, M. K., 39
Kirby, R. C., 31, 85
- L**
Levy, J. S., 348
Luther, W. A., 271
- M**
Matheson, R. J., 198
Mayher, R., 257
McMahon, J. H., 383
Miller, J. E., 111
- N**
Negro, F. M., 22
Neham, E. A., 429
Nickelson, R. L., 11
Northrop, G. M., 389
Novillo-Fertrell y Paredes, J. -M., 22
- O**
Olms, K., 70
O'Neill, J. J., Jr., 27
Overtveld, G., 263
- P**
Parlow, R. D., 90
Porter, R. D., 139
Pratt, R. M., 348
Probst, S. E., 147
- R**
Railton, G. H., 81
Reinhart, E. E., 94
Robinson, G. O., 43
Roy, D. A., 165
Rutkowski, J., 121
- S**
Smith, E. K., 31
Spaulding, A. D., 186
Stružak, R. G., 228
Sviridenko, S. S., 159
- T**
Tanaka, S., 74
Tou, C. P., 165
- V**
Vincent, W. R., 441
- W**
Wall, A., 286
Webbink, D. W., 277
Withers, D., 105
Wojnar, A., 327
- Z**
Zoellner, J. A., 222

Subject Index

A

Adjacent bands, 295
 interference calculation, 375
 Adjacent channels, 295
 interference models, 383
 Aeronautical mobile services, 111
 AFAM
 see Automated Frequency Assignment Model
 Air Traffic Control (ATC)
 frequency assignment, 236
 Airways
 international, 43
 Amateur services
 Papua New Guinea, 81
 ANSI, 153
 Antennas, 105, 198, 295, 303
 bibliography, 295
 design, 389
 models, 383
 receiving, 415
 transmitting, 415
 Apertures
 bibliographies, 295
 APSK, 165
 Articulation index, 334
 Articulation score, 334
 Asia
 WARC allocations, 74
 Assignment algorithms, 153
 Atmospheric refraction
 effect on propagation, 400
 Automated Frequency Assignment Model, 429
 Automated Radar Terminal System (ARTS)-IIIA processor, 348

B

Bibliography
 computer techniques, 481
 earth-to-space paths, 481
 foliage, 481
 ITU radio regulations, 477
 land and aeronautical mobile, 481
 legal and regulatory, 477
 propagation, 481
 rain, 481
 space services, 477
 spectrum engineering, 477
 topographic databases, 481
 Binary integrators, 348
 Broadcasting
 feeder links, 105
 FM, 124
 in Europe, 240
 radio services, 124, 240
 satellites, 1
 Business radio
 licenses, 144

C

Calculators, programmable
 for spectrum management, 257
 Canada
 Department of Communications, 263

CCIR

see International Radio Consultative Committee

CCITT, 11, 22

Central Europe

 post-WARC, 70

Channel lattices, 240

Channel maps, 222

Channels

 allocation, 433

 assignment, 204, 240, 355

 capacity, 389

 multiple, 433

 occupancy, 186

 ordering, 228

 separation, 355

 sequences, 433

CISPR (International Special Committee on Radio Interference), 124

Cochannel models, 383

Common carrier services, 124

Communication satellites systems, 389

Communication theory

 application to spectrum efficiency, 159

 efficient spectrum utilization, 165

Computational aids

 for satellite communication systems, 389

Computers, 198

 databases, 248, 481

 interference, 286

 use by Canadian Department of Communications, 263

 use in spectrum management, 257

 use to forecast propagation, 303

 use to predict service areas, 424

Conferences

 future, 43, 74, 85

 ITU, 27

 preparation, 147

Crandall, Robert, 277

D

Databases

 frequency assignment, 236

 spectrum management, 248, 303

 topographic, 481

 utilization, 248

Data files

see Databases

Data processing, 198

Defense Satellite Communications System, 139

Definitions, 186, 457

 frequency allocation, 1

 of spectrum management, 1, 177

 spectrum efficiency, 165, 171

 spectrum metrics, 171

Developed and developing countries, 27

Diffraction

 around curvature of earth, 400

Digital modulation, 153, 165

Direct voice communication, 236

E

Earth satellites

 use as relays for communication system, 389

- Earth-to-space paths
 - bibliography, 481
- Economics
 - of spectrum, 153
- Electromagnetic compatibility, 1, 177, 303
 - analysis, 228, 303, 334
 - environmental studies, 198
 - radio systems, 327, 342
 - tests, 263
- Emissions
 - characteristics, 457
 - classification and designation, 271
 - spectra, 348
- Europe
 - broadcast services, 240
- F
- FAA (Federal Aviation Administration)
 - frequency assignment model, 236
 - radio navigation, 348
- FCC, 144, 277
 - role in U.S. national spectrum management, 124
 - spectrum management task force, 383, 429
- Federal Government (U.S.), 139, 198, 236, 248
- Feedback integrators, 348
- Feeder links, 43
 - broadcasting satellite, 105
- Files of data
 - spectra, 248
- Fixed-satellite service, 43
 - impact of 1979 WARC, 94
- Foliage
 - bibliography, 481
- Free-space field, 400
- Frequency allocation, 471
 - definition, 1, 455
 - mobile radio, 433
 - NABER, 144
 - Papua New Guinea, 81
 - spectrum value, 277
 - tables, 455, 471
 - WARC (1979), 74, 94, 147
- Frequency assignment, 204, 228, 375
 - FAA, 236
 - games and strategies, 222
 - use of minicomputers, 257
- Frequency bands, 43, 70, 74, 348, 455, 471, 481
- Frequency coordination, 144
- Frequency dependent rejection, 375
- Frequency distance, 375
- Frequency-distance constrained channels, 204
- Frequency management, 39
 - Central Europe, 70
 - radio spectrum measurement, 198
- Frequency planning
 - broadcasting services in Europe, 240
 - optimum, 228
- Frequency separation
 - versus interference protection, 355
- Frequency spectrum
 - engineering system, 303
 - productivity, 277
 - RF, 441
- G
- Games
 - frequency assignment, 222
 - simulation, 222
- Geostationary satellite orbit
 - effect of WARC-79, 105
- Government master files, 248
- Graph coloring, 204
- Ground stations
 - for satellite communication system, 389
- H
- Harmful interference, 39, 139
- HF broadcasting, 74
- History
 - of ITU, 11
 - of spectrum management, 1
- I
- IEC (International Electrotechnical Commission), 124
- IEEE standards, 153
- INTELSAT, 43
- Interference
 - prediction model, 342
 - protection, 355
- Intermodulation, 295, 355
 - interference models, 383
 - products, 433
- Intermodulation-free frequencies
 - for multiple-channel mobile radio, 433
- International Frequency Registration Board, 11, 22, 43
 - assistance to member countries, 39
 - frequency registration, 271
- International harmonization, 286
- International Radio Consultative Committee, 11, 43, 124, 153, 257
 - bibliography, 477
 - evolution, 31
 - future aspects, 31
 - impact of WARC-79, 85
- International Telecommunication Convention
 - Madrid (1932), 22
 - Nairobi (1982), 22
- International Telecommunication Union, 11, 31, 43
 - bibliography, 477
 - Plenipotentiary Conference (1982), 27
- International Telegraph Union (1862–1932), 31
- Inter-satellite service
 - impact of 1979-WARC, 94
- INTERSPUTNIK, 43
- Ionospheric waves, 303
- Irregular terrain
 - radio propagation, 415
- ITU
 - see International Telecommunication Union
- J
- Japan
 - WARC allocations, 74
- L
- Land and aeronautical mobile service
 - bibliography, 481
- Land mobile services, 111, 153, 277
 - channel separation, 355
 - coverage estimation, 429
 - frequency assignment model, 383
 - in U.K., 424
 - modulation, 355
 - VHF and UHF, 424
- Lattices, regular, 240

ws
international, 5
on spectrum, 5
U.S., 5

Legal and regulatory bibliography, 477

Level-spacing criteria
receiver-oriented, 327

Levin, Harvey
study on TV stations, 277

Licenses
business radio, 144

M

Madrid Convention (1932), 22

Manufacturers' responsibilities
technical standards, 286

Maritime mobile services, 111

Master International Frequency Register, 39

Message occupancy, 186

Microwave communications
bibliography, 295

Minicomputers
for radar frequency assignment, 257
use for spectrum management, 263

Minimum interference thresholds, 334

Mobile radio systems
multiple-channel, 433

Mobile-satellite services
impact of 1979 WARC, 94, 111

Models
for frequency assignment, 236, 429
for spectrum efficiency, 159
for spectrum management, 257
interference prediction, 342
propagation forecasting, 303
spectrum engineering, 295

Modulation, 165
land mobile service, 355

N

NABER

see National Association of Business and Educational Radio

Nairobi Convention (1982), 22

National Association of Business and Educational Radio, 144

National Telecommunications and Information Administration, 348

Noise

indigenous, 415
man-made, 441
models, 383
RF, 303, 441

Nomographs

for design of satellite communication systems, 389

O

Oceania

WARC allocations, 74

Orbit utilization efficiency, 105

Output performance criteria
user-oriented, 327

P

Papua New Guinea

WARC-79, 81

Parabolic antennas, 389

Pave Paws radar system, 139

Performance degradation
of voice-modulated radio systems, 334

Personal computers, 286

Phillips, Almarin
study of TV stations, 277

Plan position indicator (PPI)
interference prediction, 342

Plenary Assembly (1980)
CISPR, 124

Plenipotentiary Conference
ITU (1982), 27

Point-to-point radio transmission, 400

Propagation
Automated Frequency Assignment Model (AFAM), 429
bibliography, 481
forecasting using computers, 303
formulas and tables, 383
path loss, 295
radio, 400

Psophometer method, 334

Pulse amplitude distributions, 342

R

Radar

frequency assignment, 240
PPI displays, 342
spectrum signature, 441

Radiated power
relation to received power, 400

Radiators, 286

Radio communication systems, 303

EMC criteria, 327
voice-modulated, 334

Radio equipment, 457

Radio interference
man-made sources, 286

Radio propagation
above 30 MHz, 400
above 40 MHz, 415
over plane earth, 400
over irregular terrain, 415

Radio relay systems, 159

Radio services, 457, 471

business, 144
broadcasting, 124
private, 124

Radio spectrum, 303
Central Europe, 70
management, 1, 177
measurement, 198
utilization, 39, 85, 159, 228

Radio stations and systems, 457

Radio waves
propagation medium, 303

Rain
bibliography, 481

Received power
relation to radiated power, 400

Receivers, 198
intermodulation, 383
models, 159, 383

Regions and areas, 471

Regular networks, 240

Regulations, 177
FCC, 286
international radio, 43
ITU, 455, 477
on spectrum, 5, 39
radio, 90, 94, 105, 147, 477

Remote terminal system
FAA, 236

Resolutions
 Nairobi Convention, 22
RF spectrum
 signals and noise, 441

S

Sampling, 186
Satellite communications, 43
 bibliography, 295
 gross design, 389
Scope interference conditions, 342
Service areas
 land mobile radio, 424
Sharing criteria, 295
Sharp ridges
 transmission, 400
Signal graphs, 228
Signal processing, 348
Signals in RF spectrum, 441
Signal-to-interference ratio, 334
Space
 technical terms, 457
Space services
 bibliography, 477
 planning, 43, 74
Spectrum distribution
 planning, 43
Spectrum efficiency, 165
 definition, 171
Spectrum engineering, 295, 303
 bibliography, 295, 477
 models, 295
Spectrum management
 computer techniques, 153, 257
 databases, 248
 economics, 153
 FCC Task Force, 383, 429
 history, 1, 11
 international market, 43
 legal aspects, 5
 optimization, 228
 professionals, 1
 role of U.S. government, 1, 236, 248
 spectrum utilization, 153, 159, 165, 222, 334
 statistical models, 257
 U.S., 124, 383
 use of microcomputers, 263
Spectrum metrics, 153, 171, 177
Spectrum occupancy, 186
Spectrum signature
 radar, 441
Spectrum-space use, 171
Spectrum standards, 153
Spectrum utilization, 153, 159, 222, 441
 communication theory, 165
 radio, 228
Speech quality, 334
SSB, 355
Standards of spectrum, 153
Station-spacing criteria
 system-oriented, 327
Strategies
 frequency assignment, 222
Surface waves, 303

System review process
 Federal (U.S.), 139

T

Technical radio regulation, 94
 CCIR studies, 85
 WARC-79 changes, 90
Technological absorption, 263
Telecommunications
 growth, 1
 HF, 43, 74
 worldwide, 11
Terrestrial relay systems
 sharing problems, 159
Topography
 databases, 481
Training and trainees, 39
Transmission occupancy, 186
Transmission path attenuation
 calculation, 424
Transmissions
 see Emissions
Transmitter networks
 broadcasting, 240
 optimum frequency, 228
 power assignment, 228
Tropospheric waves, 303
TV receivers
 color, 441
TV stations
 sales prices, 277

U

UHF mobile radio, 424
United States
 Federal systems review process, 139
 ITU radio regulations, 455
 laws and regulations on spectrum, 5
 national spectrum management, 124
 preparation for WARC-1979, 147
 Radio Spectrum Measurement System (RSMS), 198

V

Vehicular-to-vehicular transmissions, 415
VHF mobile radio, 424
Video integrators, 348
Voice transmission
 performance measurement, 334

W

WARC (World Administrative Radio Conference) — 1979, 43, 94, 348
 Central Europe, 70
 changes, 90
 effect on geostationary satellite orbit, 105
 effect on mobile services, 111
 emission designation, 271
 future aspects, 74
 impact on Asia, 74
 impact on CCIR, 85
 impact on Japan, 74
 impact on Oceania, 74
 international and U.S. preparations, 147
 Papua New Guinea, 81

Editor's Biography



Fredrick Matos (S'66–M'66) received the B.S.E.E. degree from the Illinois Institute of Technology, Chicago, IL, and the M.S.E.E. from the George Washington University, Washington, DC.

He is presently in spectrum management with the National Telecommunications and Information Administration (NTIA), Washington, DC. His responsibilities include the preparations for and participation in international conferences concerning the radio spectrum. He has leading roles in the U.S. preparations for the 1986 Regional Broadcasting Conference and the 1987 Mobile Services Conference. He is active in the CCIR where he has contributed material on various subjects. He participated in U.S. preparations for 1979 World Administrative Radio Conference.

Prior to joining NTIA in 1978, he spent 10 years as a Staff Engineer and Project Manager with the IIT Research Institute for the Department of Defense Electromagnetic Compatibility Analysis Center in Annapolis, MD, where he was involved with a great variety of spectrum engineering projects. He has been a consultant to a number of radio broadcasting stations and served as the Director of Engineering for the Mediamerica Corporation, an organization of radio broadcasting companies. During the early 1960's he was employed by the RCA Service Co. on Bahama Island tracking stations of the Atlantic Missile Range where he participated in missile tests and manned space flights. He is an active radio amateur holding the extra class license with the call sign W3ICM. He teaches a course in spectrum management that he developed at the George Washington University. His professional and personal interests in telecommunications are wide ranging and include such diverse topics as amateur radio, and national and international telecommunications policy.

His parents emigrated to the United States from Slovenia, Yugoslavia, in the 1930's and settled in Blaine, OH, a small town in eastern Ohio, where his father became a coal miner. Mr. Matos credits his childhood interests in electronics and amateur radio as providing the stimulus for his career. He is married to the former Joanna Pierce of Towson, MD, and has three daughters: Jean, Marcy, and Alice.

