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ULTRA-HIGH-FREQUENCY PROPAGATION

M. Katzin*

INTRODUCTION

With the development of improved means for generating and controlling power at ultra-high frequencies, have come many applications and proposals for putting these frequencies to work, particularly in the field of communication. To mention but a few, television, local broadcasting, police and other mobile communication, and applications in aviation radio indicate the growing importance of communication by means of ultra-high-frequency waves, and, therefore, the importance of knowing the characteristics of their propagation. Many investigations, both theoretical and experimental, have been made in an endeavor to determine these characteristics, with the result that most of the more important features of the problem appear to be known. Now that television has finally rounded the corner in this country, it seems appropriate to present a short summary of the subject of ultra-high-frequency propagation.

During the past decade, this subject has been actively prosecuted on many fronts through numerous experimental and theoretical researches. This activity has built up a considerable body of knowledge and an extensive literature. Obviously, in any survey of the subject such as presented in this paper it will be possible to aim only at the high spots, reference being made to the bibliography for many of the interesting and important details.

Ultra-high-frequency propagation is governed by the same general laws that apply to ground-wave transmission on lower frequencies, the chief distinction being in order of magnitude. This difference in order of magnitude, however, is a very important one, for many of the phenomena, which at much lower frequencies are usually of negligible effect, become of controlling importance at the ultra-high frequencies. Thus, buildings, trees, and even irregularities of the terrain produce distortions of the field in their neighborhood. At the ultra-high frequencies the dimensions of such objects and irregularities may become comparable with or greater than the wavelength so that they produce well-defined reflections. A further point is that with wavelengths of the order of feet, very small path differences between separate components or rays are sufficient to result in appreciable phase differences. At lower frequencies, say in the broadcast frequency range, the wavelength is relatively so large that such effects are usually largely negligible. We see from these few examples that the shortness of the wave can be responsible for many phenomena which are not encountered at lower frequencies.

The early propagation experiments, most of them of a qualitative nature, soon established the quasi-optical behavior of these waves. Hence it is possible to borrow some of the concepts from optical theory and apply them to ultra-high-frequency propagation. The analogues of optical reflection, refraction, and diffraction are encountered in propagation at the ultra-high frequencies, so that by referring to the results of optics, many of the phenomena encountered in u-h-f work can be explained.

In this paper, we shall start from the free-space field radiated by an antenna, and proceed to show that the effect of locating the antenna above ground is similar in many respects to the optical concept of reflection. This leads to an examination of the reflecting properties of the ground, and the application of these properties in explaining propagation over plane earth will be shown. The presence of multiple reflections in urban areas will be pointed out and its effect on wide-band transmission discussed. From the case of plane earth there follows a consideration of the effect of the earth's curvature. This leads to a discussion of the phenomena of diffraction and refraction, the variable nature of the latter giving rise to fading experienced beyond the horizon. Finally, a discussion of coverage data of the Empire State television transmitter will be used to illustrate the practical application of many of the points discussed previously. Throughout, the plan will be to present theory and experiment side by side, to show the general agreement between them.

Propagation Over Plane Earth—(Level Terrain)

The radiation field in the equatorial plane of a linear antenna in free space is given by the familiar equation

$$\xi_0 = \frac{60\pi HI}{\lambda d}, \qquad (1)$$

where H—effective height of antenna,

I—antenna current $= \sqrt{W/R}$, $\begin{cases} \text{W—radiated power,} \\ \text{R—antenna radiation resistance,} \end{cases}$

λ = wavelength,

d = distance from antenna.

For a half-wave doublet, $H = \lambda/\pi$, $R = 73.3$ ohms, so that (1) becomes

$$\xi_0 = \frac{7\sqrt{W}}{d}. \qquad (2)$$

If such an antenna is placed in the vicinity of the ground, or some other plane reflecting surface, then, in first approximation, the effect of the ground on the field at any receiving point in space is equivalent to a ray regularly reflected from the ground, and the resulting field at the receiver may be con-

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sidered as due to the combination of the direct and reflected rays. The total distance traversed by the reflected ray is greater than that by the direct ray, so that a phase difference between them results. In addition, a phase shift, as well as a reduction in amplitude, takes place when a ray is reflected at the ground. This can be expressed by means of a complex reflection coefficient.,

$$\text{Reflection Coefficient} = Ke^{j\alpha}.$$

K being the reduction in amplitude, and α the phase shift on reflection. The total phase difference between the direct and reflected rays is thus the sum of the phase difference due to the difference in path length and the phase shift on reflection.

Denoting the path difference between the reflected and direct rays by Δ, and the corresponding phase lag by $\delta = 2\pi\Delta/\lambda$, the total phase lag is $\Phi = \delta - \alpha$, and the total field at the receiver is given by

$$\xi = \xi_0 \cdot \sqrt{(1-K)^2 + 4K\cos^2(\Phi/2)}. \quad (3)$$

Since the reflection coefficient of the ground enters into the expression for the total field, it is of interest to examine its properties.

The magnitude, K, of the reflection coefficient depends on the dielectric constant and conductivity of the reflecting medium, and the angle of incidence of the rays, and, in addition, different relations hold for horizontal and vertical polarization. The simplest case to consider is that of a pure dielectric, for which the phase shift on reflection is either 0 or 180°, so that the reflection coefficient is real. For horizontal polarization, the wave is always reversed on reflection from a pure dielectric (i.e., $\alpha = 180°$) while the magnitude of the reflected wave decreases from a value of K=1 at grazing incidence to a value at perpendicular incidence which depends on the dielectric constant. For small angles of the ray to the reflecting surface, the reflected wave suffers practically no attenuation on reflection, so that K differs inappreciably from unity.

For vertical polarization, however, the behavior is quite a bit different. Here, again, for grazing angles the reflected wave is reversed in phase without reduction of amplitude ($\alpha = 180°$, K=1) for grazing angles, but for increasing angles its amplitude decreases rapidly and becomes zero at a certain angle whose cotangent is equal to the square-root of the dielectric constant. Above this angle there is no change in phase on reflection ($\alpha = 0$), while the amplitude of the reflected wave increases steadily to a value at perpendicular incidence which is the same as that for horizontal polarization. Fig. 1 shows the reflection coefficient for both vertical and horizontal polarizations for a ground of zero conductivity and a dielectric constant of 9, representing Long Island ground, for ultra-high frequencies. In this case, the angle at which no reflection takes place for vertical polarization is about 18°.5.

When the conductivity of the reflecting medium is not negligible, the relations are more involved. The phase shift on reflection is other than zero or 180°, in general (complex reflection coefficient). For horizontal polarization, the phase angle of the reflection coefficient is always in the second quadrant, but, for most practical cases, the effect of conductivity is quite negligible. For vertical polarization, on the other hand, the phase angle of the reflection coefficient is in the third or fourth quadrants. Corresponding to the perfect dielectric case, the reflected wave is reversed in phase without reduction of amplitude for zero angle, and the reflected wave decreases in amplitude rapidly for increasing angles. Instead of passing through zero, however, it reaches a finite minimum value, and thereafter increases once more. At the same time, the phase shift on reflection, considered as a lag, decreases from 180° at zero angle to zero at vertical incidence, passing through 90° at the angle for which the amplitude of the reflected wave is practically a minimum. For a given dielectric constant, the effect of increasing conductivity is to lower the angle at which the amplitude of the reflected wave is a minimum. The reflection coefficients for sea water for a frequency of 50 megacycles are shown in Fig. 2.

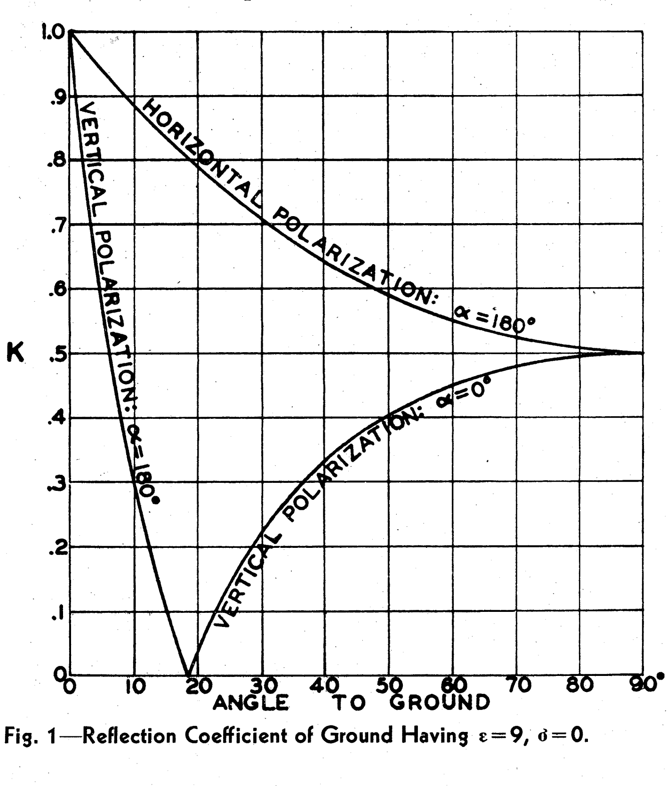


Fig. 1—Reflection Coefficient of Ground Having $\varepsilon=9$, $\sigma=0$.

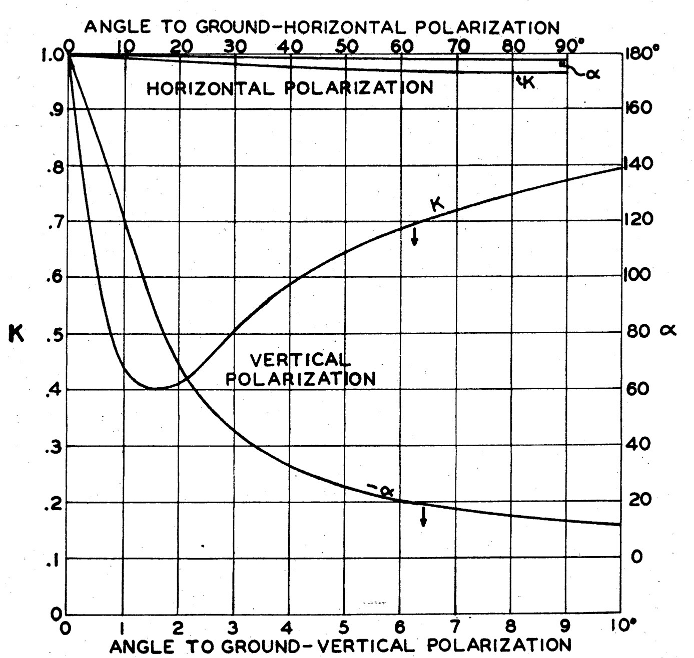


Fig. 2—Reflection Coefficient of Sea Water at 50 Mc/s. $\varepsilon=80$, $\sigma=4.10^{-11}$ e.m.u.

It is well to bear in mind the above difference in behavior of the reflection coefficient between horizontal and vertical polarization, for it is largely responsible for the difference in behavior of propagation for these two polarizations over

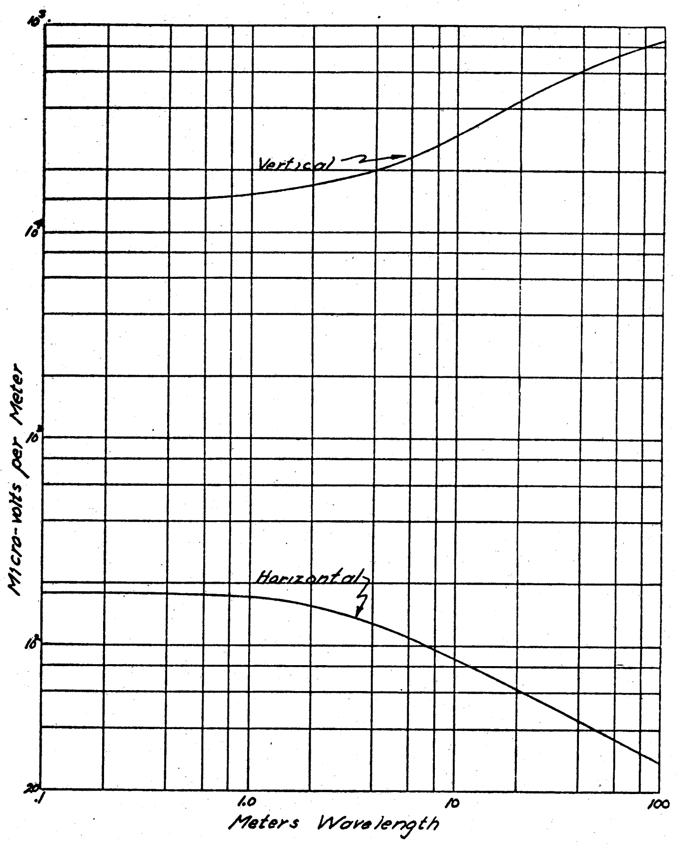


Fig. 3—Theoretical field strength vs. wavelength over salt water at a distance of 1 kilometer from a dipole 8 meters high radiating 1 watt for vertical and horizontal polarization. Receiving antenna height = 0.

mediums of good conductivity, such as sea water. To illustrate this, Fig. 3, taken from Trevor and Carter[5]*, shows the theoretical variation with frequency of received field strength for low antennas, for both vertical and horizontal polarization. At the higher frequencies, where the curves become horizontal, the dielectric current predominates over the conductivity current, and the sea water "ground" behaves like a pure dielectric, the limiting ratio of vertical to horizontal polarization field strength then being equal to the dielectric constant, in this case 80. The phase shift on reflection for vertical polarization departs from 180° as the frequency is lowered, giving increased field strengths with vertical polarization. With horizontal polarization, on the other hand, there is no appreciable change in phase of the reflected ray with frequency, but the magnitude of the reflection coefficient approaches unity more closely as the frequency is lowered, resulting in lower field strengths.

Instead of writing the reflection coefficient as $Ke^{j\alpha}$, it is convenient for some purposes to write it as $-Ke^{j\Theta}$, where $\Theta = \alpha \pm \pi$, so that Φ becomes $\delta - \Theta$. (3) then becomes

$$\xi = \xi_0 . \sqrt{(1-K)^2 + 4K \sin^2(\Phi/2)}. \qquad (3a)$$

The path difference, Δ, depends on the geometry of the circuit, as shown in Fig. 4, being a function of the antenna heights and their separation. For distances not large compared to the antenna heights, the path difference may amount to a number of wave-lengths. In such cases, as the height of the receiving antenna, or the distance, is changed, the path difference will change through a number of wavelengths, and

*Numbers refer to bibliography at end.

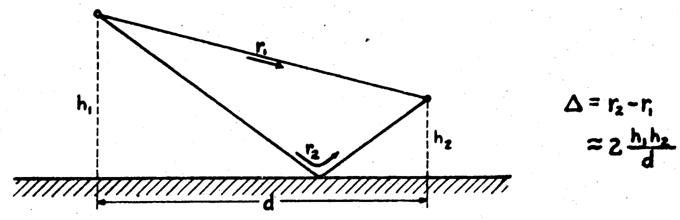


Fig. 4

the total field will fluctuate through maximums and minimums, corresponding respectively to conditions where the direct and reflected rays are in-phase and opposed. This is illustrated by Figs. 5 and 6, taken from Trevor and Carter[5].

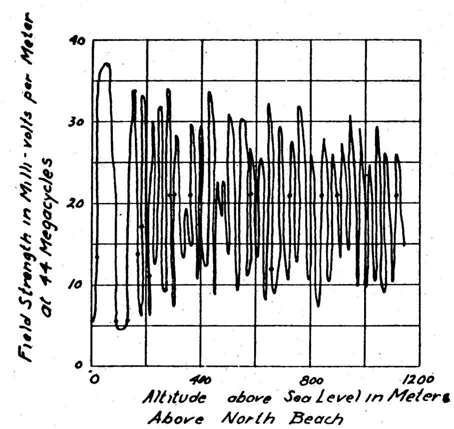


Fig. 5—Field strength vs. altitude at North Beach, 9.6 kilometers from Empire State 44-megacycle transmitter. Radiation 2 kilowatts.

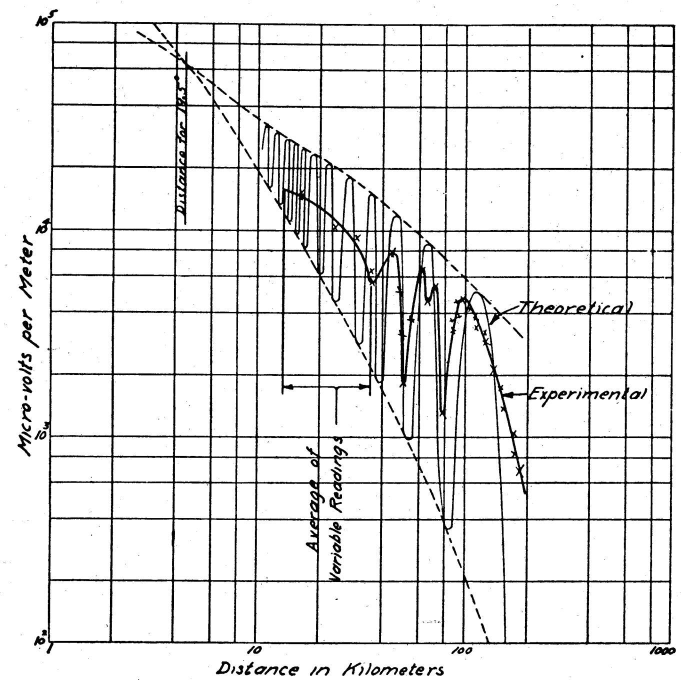


Fig. 6—Field strength vs. distance at 1200 meters altitude—Empire State 44-megacycle transmitter. Radiation 2 kilowatts.

These figures represent measurements made in an airplane on the radiation from a 44-megacycle transmitter on the Empire State Building, radiating vertically polarized waves, with a power of 2 kilowatts. Fig. 5 shows the field received at North Beach, a distance of about 6 miles, as a function of altitude. The variations of field strength with height were so rapid that it was impossible to record them manually, hence a free-hand sketch was resorted to, to portray the effects observed. Fig. 6 shows the variation of field strength with distance at a constant receiving antenna height, in this case about 4000 feet.

The previous illustrations indicate the nature of the phenomena observed when the path difference between the direct and reflected rays is of the order of wavelengths. For antenna heights small compared to their separation, which is the more usual case, the angle of the reflected ray is very small, and it is permissible to put $K=1$, while Φ will be small, except for cases like sea water. If the path difference is large enough to neglect Θ in comparison with Δ, the total received field becomes

$$\xi=\xi_o\cdot 2\sin\frac{\delta}{2}=E_o\cdot 2\sin\frac{2\pi h_1 h_2}{\lambda d}. \qquad (4)$$

If the antennas are low enough, the sine factor may be replaced by its argument, giving the familiar expression

$$\xi=\xi_o\cdot\frac{4\pi h_1 h_2}{\lambda d}$$

$$=240\pi^2\, HI\frac{h_1 h_2}{\lambda^2 d^2}. \qquad (5)$$

For a half-wave doublet, this is

$$\xi=88\sqrt{W}\,\frac{h_1 h_2}{\lambda d^2},\ \text{(watts, meters, volts/meter)}$$

$$=0.01052\sqrt{W}\frac{h_1 h_2 f}{d^2}, \qquad (6)$$

where, in the latter form, h_1 and h_2 are in feet, d in miles, f in megacycles, and W in watts. This is the familiar inverse-square law for propagation over a plane earth. Under the conditions for which it is valid, the received field varies inversely as the square of the distance, directly as the antenna heights, and directly as the frequency. It may be well to point out the conditions to which use of the above relations are restricted. (4) holds only for antenna heights that are great enough to insure that the path increment yields a phase angle much greater than Θ, and for angles small enough so that K is practically unity. (5) suffers the additional restriction that the path increment must be small enough to permit the sine term to be replaced by its argument, which means, practically, that the path increment

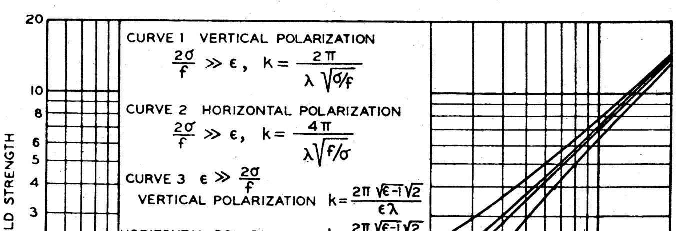


Fig. 7—Variation of received field strength with antenna height.

should be less than about $^1/_6$ wavelength. An idea of the nature and magnitude of the deviations from the simple form of (5) can be obtained from Fig. 7, taken from a paper by Burrows[22]. This figure shows the deviations at low antenna heights from the linear increase of field strength with height predicted by (5), for the two extreme cases of a good conductor (conduction current much larger than dielectric current), and a pure dielectric (dielectric current much larger than conduction current). The pure dielectric case applies sufficiently well to ultra-high-frequency propagation over land, while the pure conductor case applies to propagation over sea water. For the dielectric case (land), the linear relation of field to height holds for heights above about one-quarter wavelength for horizontal polarization, and for vertical polarization above about two wavelengths.

The "relative field strength" given by the ordinate of Fig. 7 is the ratio of the field strength at any height to that at zero height. The abscissa gives the antenna height to a scale (the factor k) which depends on the ground constants and the polarization. Curves 1 and 2, for vertical and horizontal polarization, respectively, apply to transmission over a good conductor, while curve 3 applies to the case of a pure dielectric. Curve 1, for vertical polarization, shows an initial decrease of field strength with increase of height to a minimum at a height corresponding to an abscissa value of 1.0, whereas curve 2, for horizontal polarization, indicates a steady increase of field strength with height. The height (abscissa) scales, however, are different for the two cases (different values of k). If curve 2 were plotted to the same abscissa scale as curve 1, curve 4 would result. It is seen that the great advantage of vertical over horizontal polarization in propagation over a good conductor such as sea water holds only for small heights, and that above the height corresponding to 1.0 on the abscissa of Fig. 7, horizontal polarization actually gives the greater fields. For a frequency of 50 megacycles, this height is 84 feet.

An experimental check of the linear height-field strength relation is shown in Fig. 8, taken from a paper by Burrows,

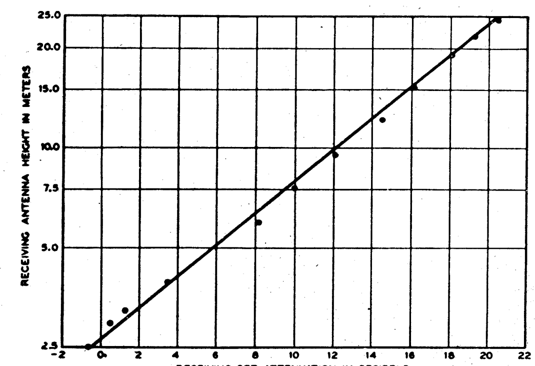


Fig. 8—Variation of received field with antenna height for 26.3 kilometer path on 34.6 megacycles with a horizontal half-wave transmitting antenna 24 meters above the ground.

Decino, and Hunt[17]. The best straight line through the log-log plot of the experimental points shows a slope very close to unity. Numerous other measurements have substantiated the linear relation predicted from (5).

Experiments conducted by Trevor and Carter[5] over the flat ground at Suffolk Airport near Riverhead yielded results showing confirmation of the theoretical inverse-square variation of field strength with distance. The results for a frequency of 41.4 megacycles are shown in Figs. 9 and 10, for

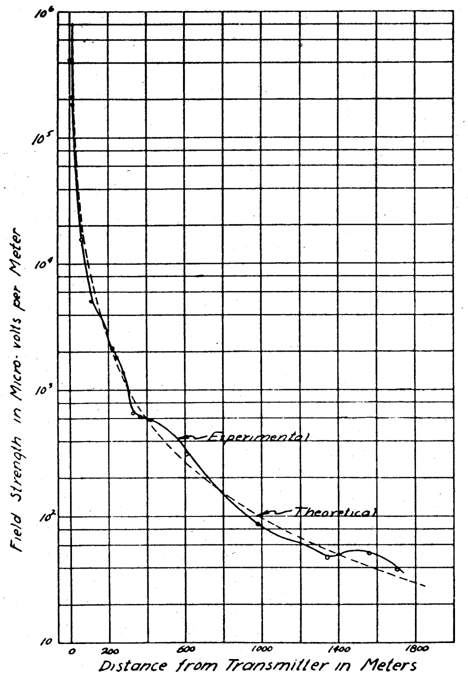


Fig. 9—Field strength vs. distance, vertical polarization, 41.4 megacycles. Transmitting and receiving antennas 2.9 and 3.1 meters above Long Island ground.

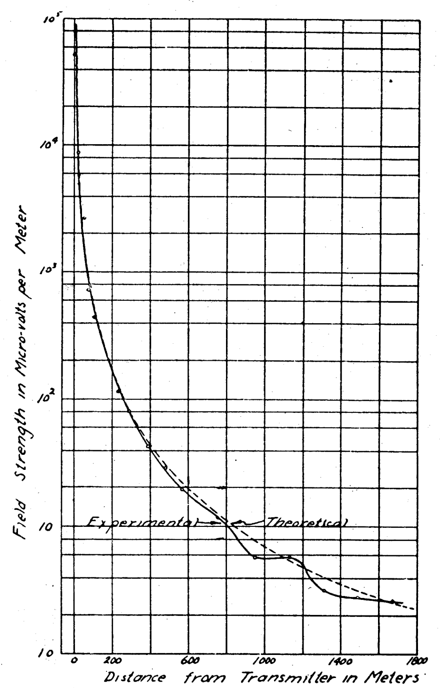


Fig. 10—Field strength vs. distance, horizontal polarization, 41.4 megacycles. Transmitting and receiving antennas 2.9 and 1.6 meters above Long Island ground.

vertical and horizontal polarization, respectively. The dotted curves in these figures represent an inverse-square-of-distance variation. Similar results were obtained at 61 megacycles. It is seen that there is not much difference between the results on horizontal and vertical polarization.

During these experiments, it was observed that any airplane flying over the field would cause large variations in received signal as the plane moved along, due to interference between the signal reflected from the plane and that received over the normal path. This is an illustration of interference at a fixed receiving location from a moving reflecting object. Similar interference effects are produced from fixed reflecting objects when the receiving (or transmitting) location is moved, as in mobile work. The interference effects then produce a standing-wave pattern in space. Such standing-wave patterns were reported by Jones[4], and studied rather extensively by Englund, Crawford, and Mumford[7]. The latter showed that individual trees, guy wires, etc., clearly produced reflections which contributed to the complex standing-wave pattern. In general, such standing waves are mostly prevalent near ground level in suburban locations or open country, so that they can be expected to subside for the most part when the antennas are placed well above the level of irregular objects and surfaces.

Urban Characteristics

The theoretical relations which have been considered above were based on an earth assumed to be a level plane. Actually, of course, the character of the ground usually differs considerably from such an ideal assumption. This is particularly true in urban locations, especially in the larger metropolitan areas with many high buildings. Buildings present surfaces which are many wavelengths in extent for ultra-high frequencies, so that well-defined reflections can be expected from them. As a result, transmission between two points in an urban area may take place over a great many paths. Since the path increments between these components may be a number of wavelengths, a slight change in location of the receiving antenna may change the phase relations between the various received components sufficiently to result in a large alteration of the resultant field. In fact, the superposition of the waves which are reflected back and forth between buildings sets up a very complicated standing-wave pattern in space. Obviously, then, the field intensity may fluctuate up and down widely as the receiving antenna is moved around. This was pointed out very forcefully by the experiments reported by Jones[4].

The standing-wave patterns which result from the superposition of the many components bouncing around building areas are dependent on the phase and amplitude relations between these components. Since for a given set of paths the phase relations depend on the frequency, entirely different standing-wave patterns usually result for frequencies differing even only moderately. Such behavior is of importance in wide-band services such as television, for the effect is equivalent to a distortion of the frequency characteristic of the system.

The simple case of two components can be used to illustrate the principles involved in this form of frequency distortion. For a given difference in path between these two components the phase difference between them will be directly proportional to the frequency. At a certain frequency, say f_1, the two components will be in phase and a maximum resultant field will be produced. If the frequency is increased by an amount which makes the phase angle due to the path difference between the two components increase by 180°, say to f_2, the two components will oppose, producing a minimum resultant field. The frequency interval $f_2 - f_1$, from maximum to minimum, or vice versa, is inversely proportional to the path increment. If this path increment is large enough, therefore, the received field will vary considerably over a band such as used for television transmission. The relations become much more complicated when a multiplicity of components is present.

Such effects have been investigated by Carter and Wickizer[19], and by R. W. George[35]. Carter and Wickizer investigated the frequency characteristic of a circuit transmitting from the RCA Building to a receiver on the 85th floor of the Empire State Building in New York City. Fig. 11 shows the frequency characteristic obtained with the transmitter on the 14th floor of the RCA Building, horizontal half-wave doublets being used for both transmitting and receiving. To explain the apparently irregular spacing of the peaks and dips in this characteristic, an artificial characteristic was constructed by assuming four components to be present, having various path lengths and amplitudes. Such a derived characteristic is shown in Fig. 12. It will be noted that this curve bears certain similarities to Fig. 11, indicating that the experimental characteristic, Fig. 11, is the resultant of a direct ray and several indirect rays having considerably longer paths.

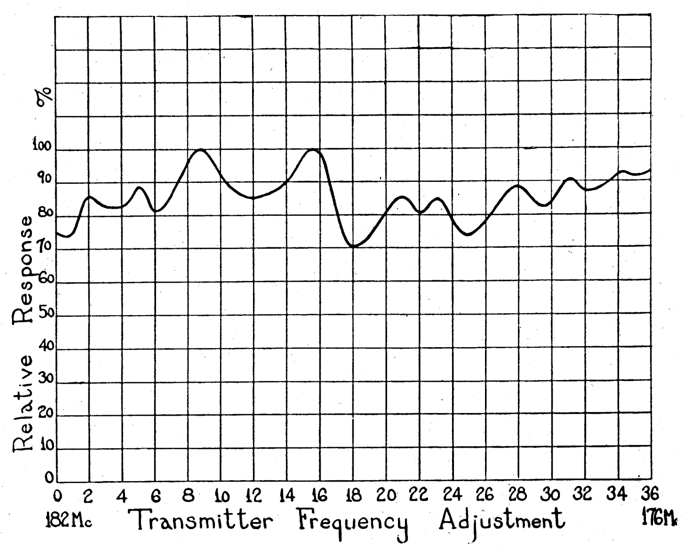


Fig. 11—Response curve with half-wave dipoles at transmitter and receiver. Horizontal polarization, transmitter at fourteenth floor.

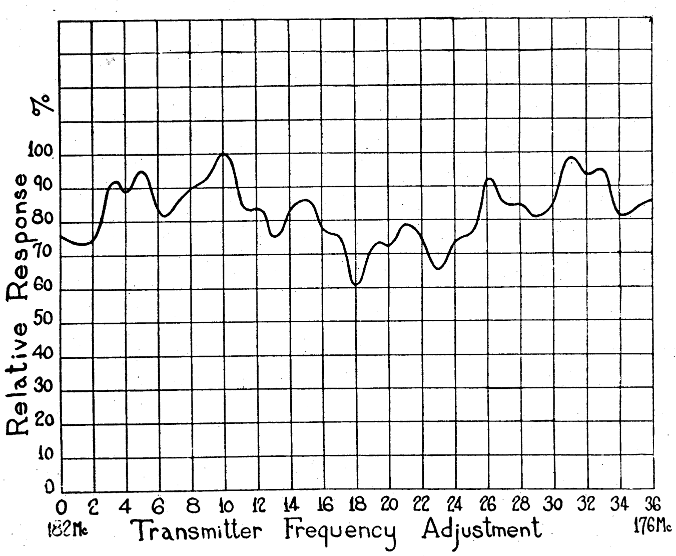


Fig. 12—Curve constructed from vector diagrams.

For this particular circuit, such large path differences would be expected only from rays arriving at relatively wide angles, so that the use of directive antennas should reduce the variations in response over the frequency band. As a check on this, Fig. 13 shows the experimental characteristic obtained with directive receiving and transmitting antennas; the maximum variations were reduced to less than ± 1 decibel.

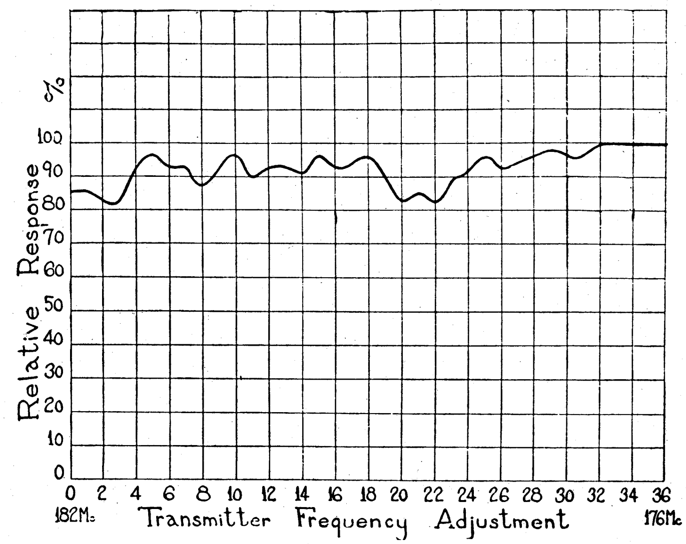


Fig. 13—Response curve with directive transmitting and receiving antennas. Horizontal polarization, transmitter at fourteenth floor.

The above characteristics were obtained using horizontal polarization. A comparison of the performance obtained with vertical polarization is afforded by Fig. 14, which was obtained with the same antennas used for Fig. 11, but arranged vertically. It will be observed that the amplitudes of the variations are much greater than for the same setup using horizontal polarization, Fig. 11. This indicates that the amplitudes of the indirect rays are greater with vertical than with horizontal polarization. A reasonable explanation for this may be deduced from the magnitude of the reflection coefficients for horizontal and vertical polarization given in Fig. 1. It will

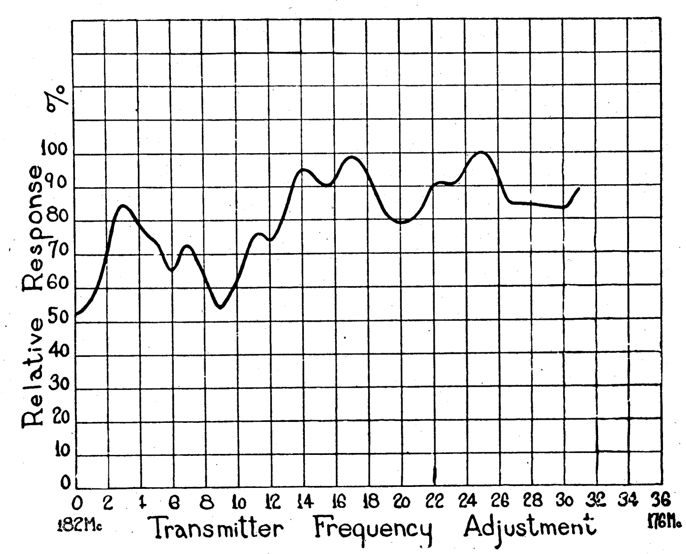


Fig. 14.—Response curve with half-wave dipoles at transmitter and receiver. Vertical polarization, transmitter at fourteenth floor.

be seen that the magnitude of the reflection coefficient for horizontal polarization (electric field parallel to the reflecting surface) is always greater than that for vertical polarization (electric field perpendicular to the reflecting surface), except for the limiting cases of grazing and perpendicular incidence. Since we are concerned with reflecting surfaces which are predominantly vertical, instead of horizontal ground to which Fig. 1 applies, the roles of horizontal and vertical polarization are interchanged, so that transmission from a vertical antenna corresponds to horizontal polarization with respect to the vertical buildings, and vice versa. Therefore, it is to be expected that vertical antennas would result in reflected ray components of higher amplitude, on the average, than would horizontal antennas.

Similar conclusions were reached by George[35], who made measurements of the received frequency characteristic over the bands from 81-86 megacycles, and 140-145 megacycles at a number of locations in the New York area. Both horizontal and vertical polarizations were used. Fig. 15 shows a mass

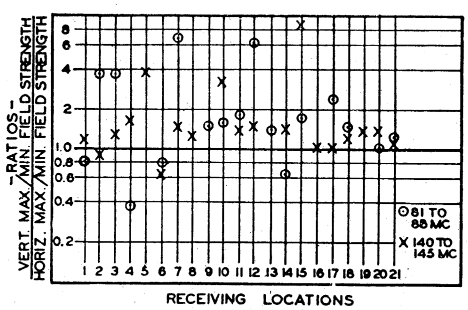


Fig. 15—Comparisons between vertical and horizontal polarization of maximum to minimum field-strength ratios obtained at each receiving location and signal-frequency range.

plot which compares the maximum-to-minimum ratios measured over the five-megacycle band for vertical and horizontal polarization. It is seen that for most of the test locations, vertical polarization resulted in larger variations over the band. In addition, for any one polarization, the mean maximum-to-minimum ratio was greater over the 140-145 megacycle band than over the band 80-85 megacycles.

Another interesting point that emerged from George's study is that, on the average, horizontal polarization produced an average field about 2 decibels stronger than vertical polarization, for both frequency bands. This is shown by Fig. 16.

The above experiments represent measurements at a number of fixed points. A more complete picture of the standing-wave variations can be obtained by mobile recording. This

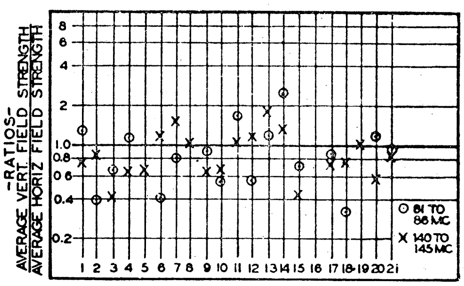
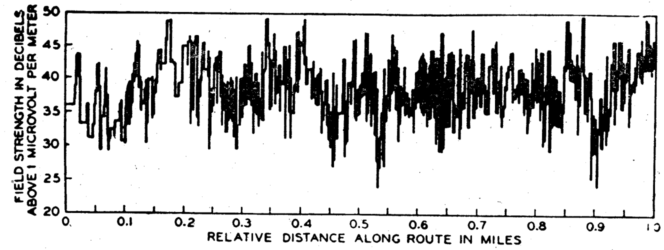


Fig. 16—Comparisons between vertical and horizontal polarization of average field strengths obtained at each receiving location and signal-frequency range.

was done in a mobile survey of the Boston area by Burrows, Hunt, and Decino[11], and of the New York area by Wickizer[38]. Sample portions of the records taken in Boston are shown in Fig. 17, which shows the much larger variations in field strength



Portion of record showing the large field strength variations as recorded while driving through the business district of Boston at a distance of about 1.5 miles from the transmitter.

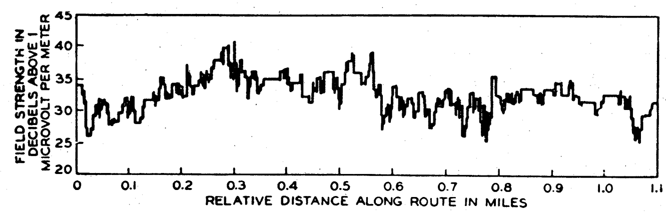


Fig. 17—Portion of record showing the small variations of field strength while driving through residential section of Boston at a distance of about 5 miles from the transmitter.

in the business district than in the residential district. A mass plot of the measurements is shown in Fig. 18, for which values averaged over short intervals of distance have been used. It is seen that most of the points lie within ± 10 decibels of the mean curve having an inverse-square-of-distance slope. The dashed line is the theoretical inverse-square-of-distance curve for level terrain plotted from (5). It thus appears that the effect of irregular terrain is to lower the mean average field by about 10 decibels and to superimpose variations of about ± 10 decibels.

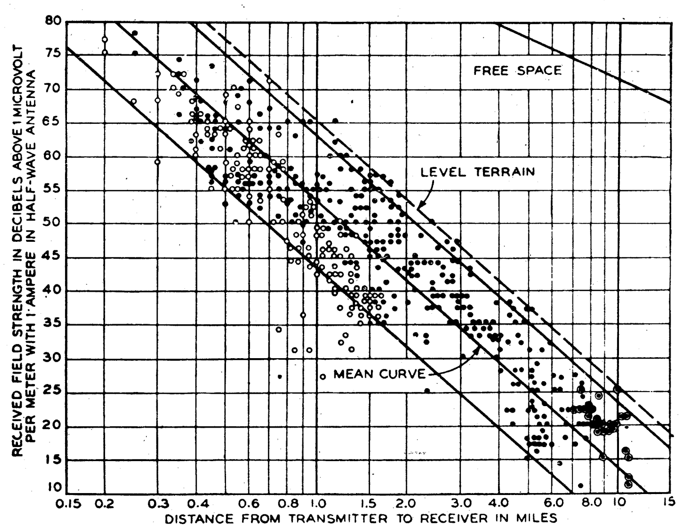


Fig. 18—Mass plot of field intensities measured at various distances from the transmitter at Berkeley and Stuart Streets in Boston. The values corresponding to distances less than two miles represent field strengths averaged over one-tenth mile intervals, while those for greater distances represent averages over one-half mile intervals. The open circles indicate fields in the high building area. Residential points outside the city limits have been enclosed in circles.

Curved Earth

Equation (4) has been derived for a plane earth, hence should not be expected to apply at distances such that the effect of the earth's curvature becomes appreciable. It breaks down completely at and beyond the horizon. In order to explain propagation beyond the horizon, it is necessary to invoke the mechanisms of diffraction and refraction, both familiar from optical theory.

As is well known, it is not correct to assume that waves travel strictly in straight lines. Rectilinear propagation is a result of wave interference between components propagated over paths at either side of the rectilinear path. If an obstacle is interposed in the path of some of these components, part of the destructive interference taking place among them will be destroyed, so that radiation into the "dark" region behind the obstacle can take place. This mechanism supplies a diffracted field which, for a given frequency, depends on the geometry of the circuit, and hence a steady field.

Refraction in the atmosphere is due to its varying index of refraction with height. The index of refraction decreases with height, so that, for wave fronts propagated nearly horizontally, the phase velocity of the upper portions of the wave front is higher than that of the lower portions, resulting in bending of the wave front downward. This downward bending of the wave front compensates in part for the curvature of the earth, resulting in increased field strengths at distances beyond the horizon. The index of refraction of the atmosphere varies with its temperature, relative humidity, and movement of air masses, so that the rise in field strength due to refraction is subject to corresponding variations. The slow fading up and down of ultra-high-frequency signals over longer paths is attributable to these variations in index of refraction. In addition, it has been demonstrated recently that reflections from atmospheric irregularities[34], for example air-mass boundaries, contributes to the field beyond the horizon, and is probably re ponsible for the more rapid types of fading experienced. This may be considered as a limiting case of refraction, much as refraction in the ionosphere is spoken of as "reflection."

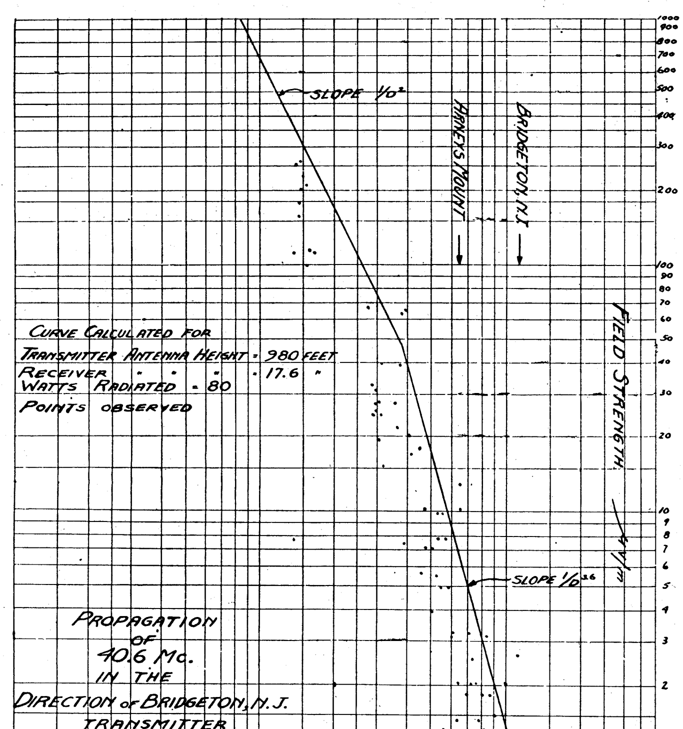


Fig. 19

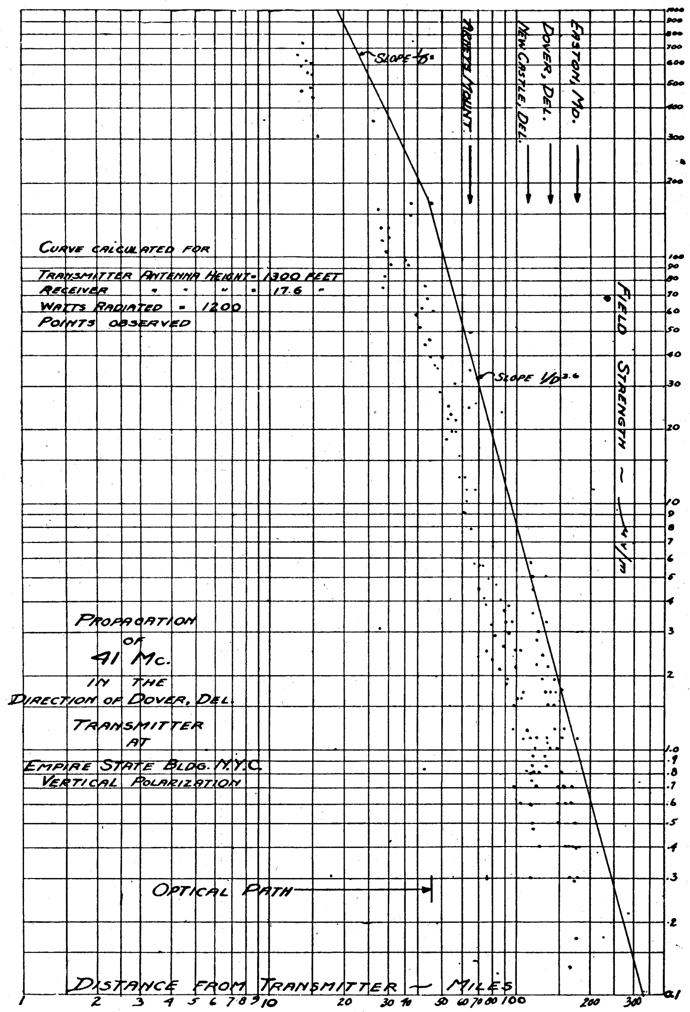


Fig. 20

Diffraction

A rigorous solution of the diffraction of radio waves around the earth is exceedingly complicated. A general solution, in the form of an infinite harmonic series, was given in 1910 by Poincare for vertical polarization, but this result was of little use for practical purposes in the radio case, since at frequencies of about 40 megacycles it has been estimated[33] that the principal contribution to the numerical result would be given by about a thousand terms either side of the six-millionth term.

first to attain a solution that was adaptable
putation, but his anaylsis was limited to
ed like a perfect conductor. The extension
including the effect of the dielectric proper-
was indicated by T. L. Eckersley[3] in 1932.
atment of the problem, taking account of
ghts, was recently worked out by van der
7,32,33, Wwedensky[16], and by Eckersley and
nese theories proceed from a solution of
ons with appropriate boundary conditions.
only the case of vertical polarization.

e other hand, attempted to assess the effect
the field beyond the horizon by applying
le, treating the earth as a perfectly absorbing
d that the screening effect could be approxi-
g the earth by a straight edge at the inter-
es tangent to the earth from transmitter and
s, Decino, and Hunt[17] showed that it was
rlook the reflected ray components by treat-
perfect absorber, and then proceeded to cor-
hod by including the effect of ground reflec-
g low antennas, at equal heights, they ar-
sion that the field beyond the horizon could
applying to (4) a correction factor due to
tion. This correction factor is the amplitude
l evolved in optical diffraction theory. For
varies inversely as the three-halves power of
according to their result, the total field
sely as the seven-halves power of distance
irrespective of frequency.

experimental data on propagation extending
n, Beverage[21] was led to an empirical rela-
tion of field strength with distance. Some
llustrate his method are shown in Figs. 19,
in the horizon of the transmitter, a straight
the log-log plot with an inverse-square of
esponding to values obtained from (5). At

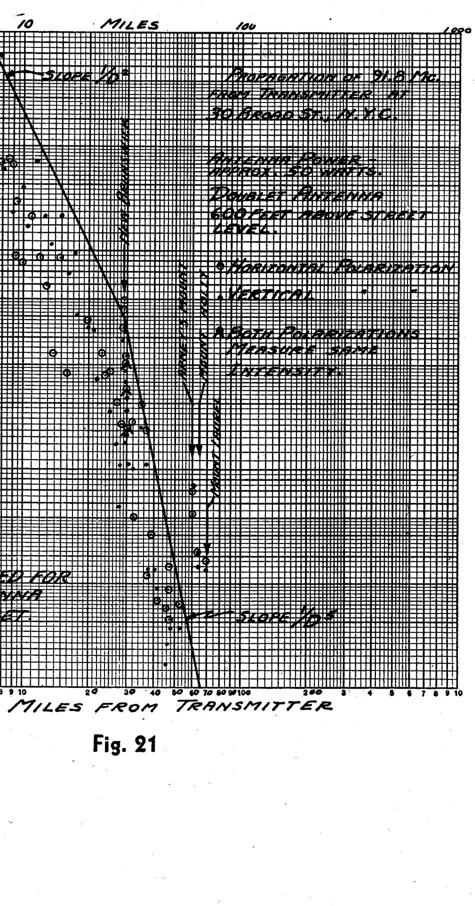


Fig. 21

the horizon distance, a second line is drawn for distances beyond the horizon with a slope to fit the data. From data taken at a number of frequencies, Beverage found that the slope of the line drawn to fit the data beyond the horizon increased with frequency. By plotting this slope against frequency, Beverage obtained Fig. 22.

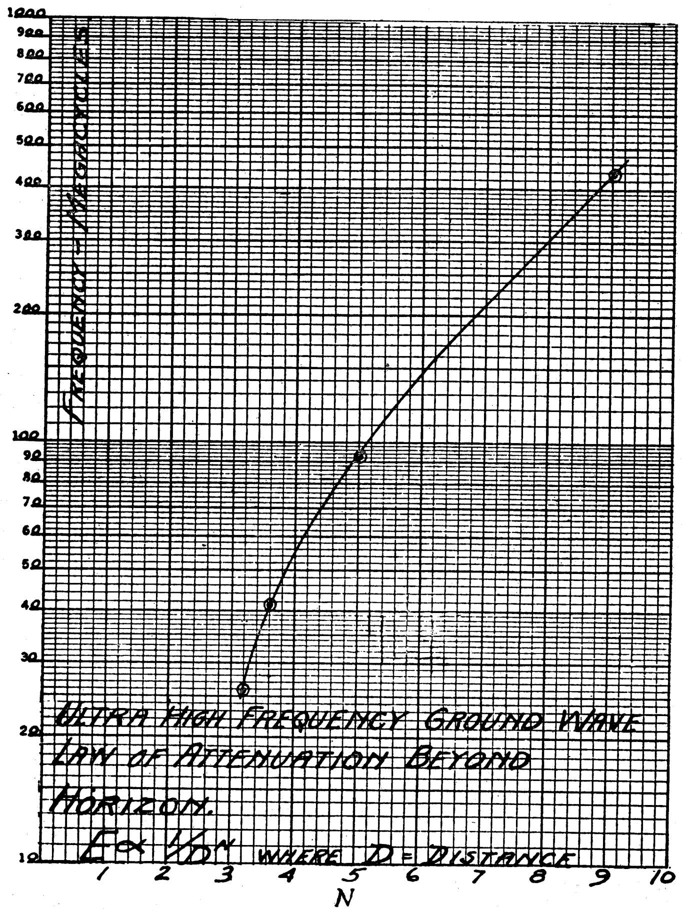


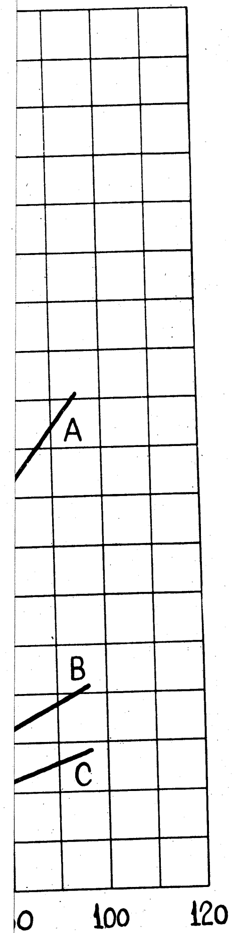
Fig. 22

This relation, of course, is purely empirical, and hence may not be justified on theoretical grounds. For one thing, the method indicates that at distances beyond the horizon the field strength varies as a negative power of distance, so that a straight line is obtained when plotted on log-log paper. On the other hand, the theoretical works of Wwedensky[16], van der Pol and Bremmer[33], and Eckersley and Millington[31] all indicate that at such distances the relation of field strength to distance is of exponential form, so that a straight line is obtained by plotting field strength to a logarithmic scale, and distance to a linear scale. This is also the type of relation obtained by von Handel and Pfister[18], although their slopes (exponents of e) are based on Watson's[1] analysis of perfect conductivity.

The theoretical works mentioned above are all in substantial agreement, hence it will be sufficient to consider only one of them. For this we select the treatment of Eckersley and Millington[33], since they have pushed their analysis to the most complete numerical results[26].

As mentioned previously, the theoretical solution is obtained in the form of an infinite series. Eckersley's curves for 6-

y-waves." The
s to fading phe-
ice area of broad-
ves" originate in



nces.
ne day.
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d that the received
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ishes a steady field
ion superimposes the
Some writers have
als are received over
he case if diffraction
ct of diffraction is of
be true, however, as
as been shown that
fective earth's radius,
izon of a transmitter
mechanism of impor-
ons there should be a
ddenly sinks to zero,
ue to refraction. This
view we must adopt

hat refraction and diffraction are mutually-assisting mechan-s. Refraction may be considered to set up a new horizon the transmitter, while diffraction carries the signal beyond new horizon into the "shadow" region.

)ue to the variable nature of refraction, however, it is icult to obtain an experimental check on the magnitude of

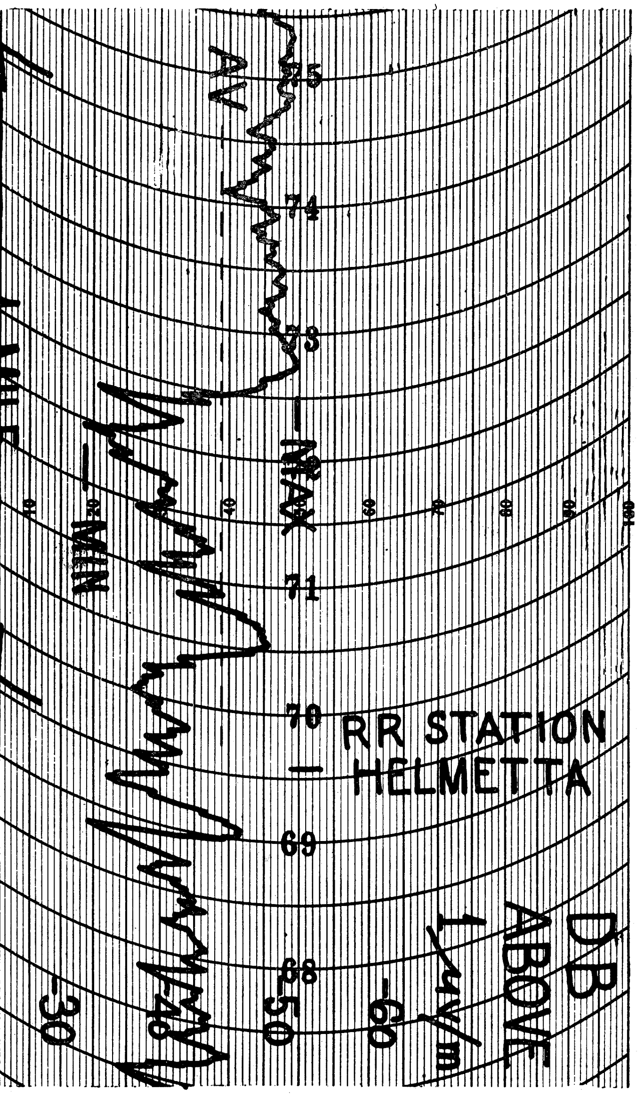

Fig. 29

raction attenuation as predicted by theory. A further nplication is that the irregular nature of practical types of rain differs widely from the smooth spherical surface on ich the theoretical works are based.

To conclude this summary of the subject of ultra-high-quency propagation, it may be of interest to show how some the phenomena discussed above affect the service area of an ra-high-frequency broadcast station. For this purpose the ults of the extensive survey made by Wickizer[38] of the 75-megacycle audio channel of the NBC television trans-tter on top of the Empire State Building will be used. In s survey, continuous recordings of the signal along a number radials from the transmitter were made in an automobile. e records showed the usual large variation in amplitude of the received field within short distances caused by buildings and other local objects. A short sample of one of the records, taken in a suburban location, is shown in Fig. 29. The records were divided into short sections and the maximum, minimum, and average values for each section determined, as shown on Fig. 29. In this way, the data were transferred to the form shown in Fig. 30, which shows the summary of the record

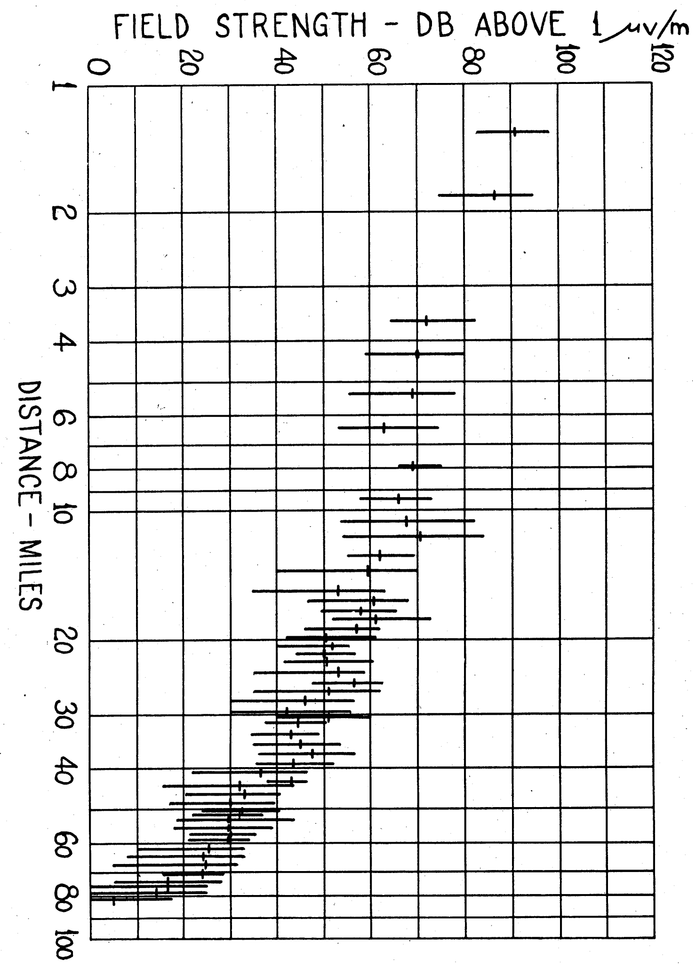

Fig. 30

taken between New York City and Camden, New Jersey. The extremities of the vertical lines represent maximum and minimum values for each section of the record, while the short horizontal bars through the vertical lines indicate the average values. From the average values, curves such as shown in Fig. 31, which corresponds to the values in Fig. 30, were then drawn. A set of such curves, showing the variation of aver-age field strengths with distance in various directions from the transmitter, provided data from which equi-signal contours could be drawn. The field-strength maps obtained in this manner are shown in Figs. 32 and 33, in which the numbers affixed to the contours represent average field strengths in decibels above one microvolt per meter, for a receiving antenna 30 feet high.

These contours represent average field-strength values as measured by the survey car along highways. They do not necessarily represent the field strength that would be obtained at a particular receiving installation. An idea of the order of magnitude of the deviations to be expected from the average

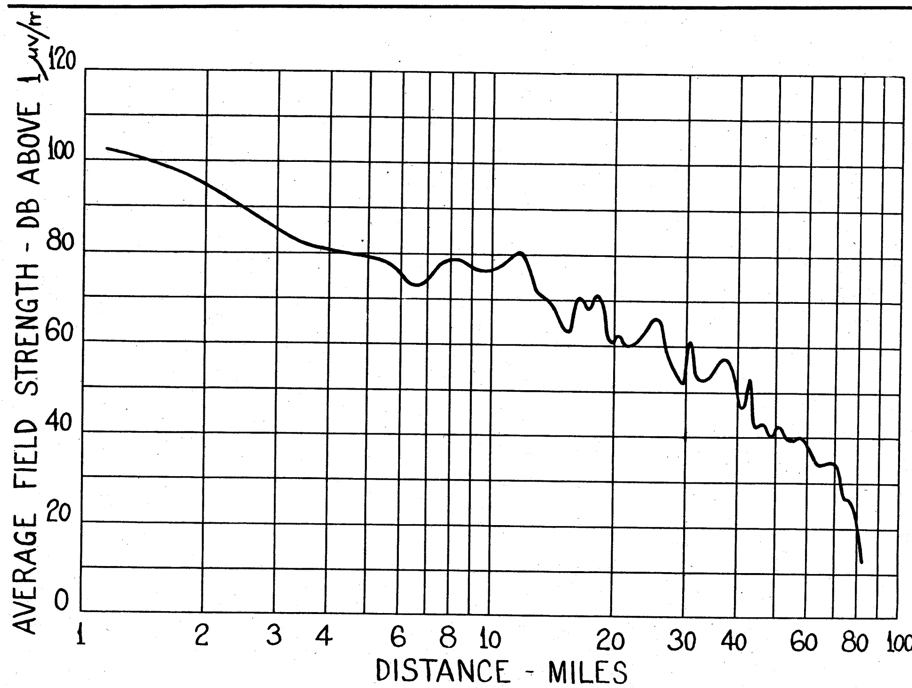

Fig. 31

values represented by the contours can be obtained from data giving the mean deviations from the average field strengths that occurred. Wickizer found that the mean deviations covered a range of about 20 decibels, roughly 10 decibels above and below the average values. It will be recalled that Burrows, Hunt, and Decinoff found a similar range in their Boston survey. As a result of these variations, then, an antenna located on one of the contours might receive a field as little as the next lower contour, or as great as the next higher contour.

Near the horizon, and beyond, refraction in the atmosphere causes a variation in field strength, or fading, which increases at greater distances from the transmitter. From the work of MacLean and Wickizer we obtained Fig. 28, showing the increase in fading range with distance from the Empire State transmitter. This figure may be used to estimate the additional variation of received field due to fading. For example, the maximum varia-

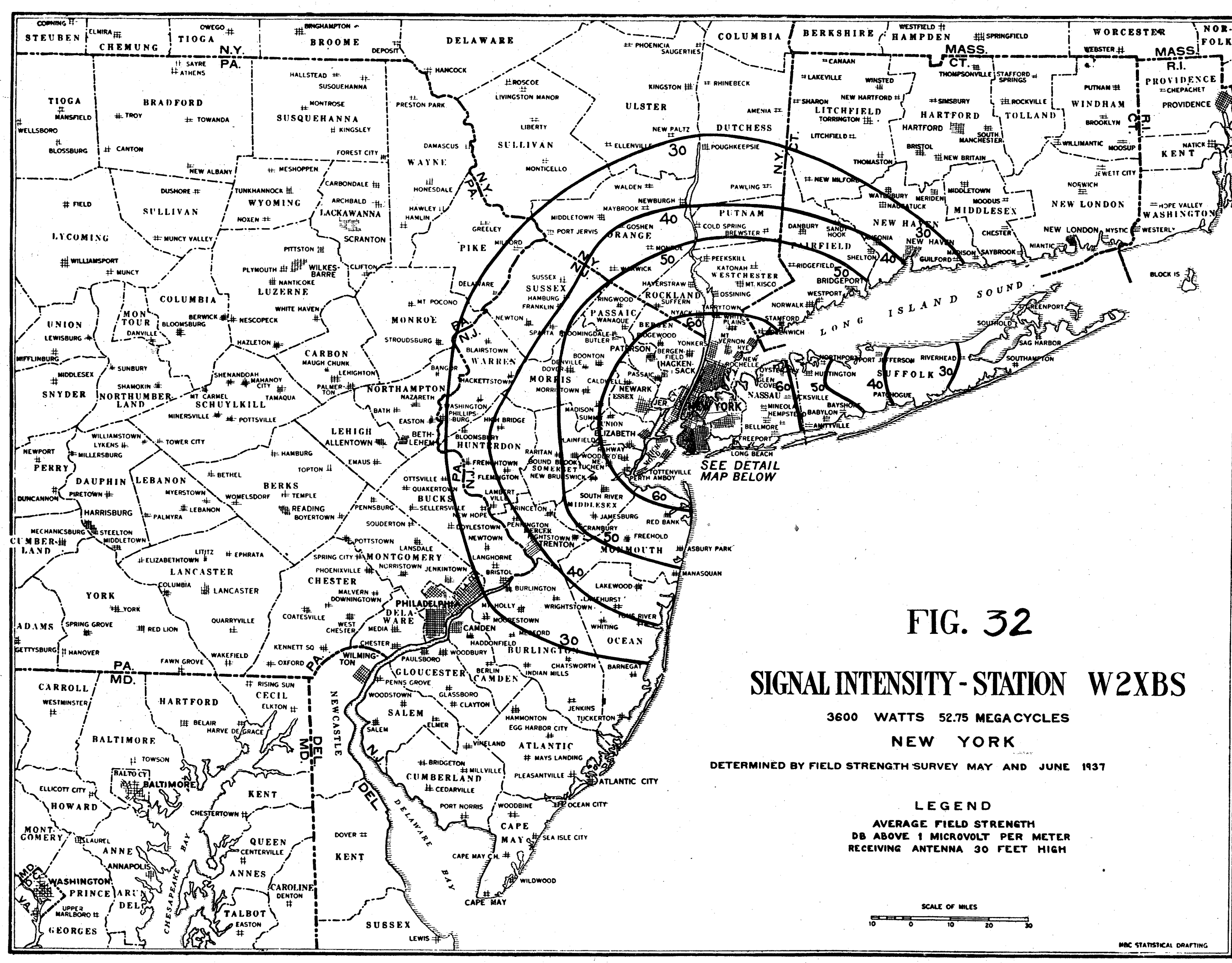

FIG. 32

SIGNAL INTENSITY - STATION W2XBS

3600 WATTS 52.75 MEGACYCLES

NEW YORK

DETERMINED BY FIELD STRENGTH SURVEY MAY AND JUNE 1937

LEGEND

AVERAGE FIELD STRENGTH
DB ABOVE 1 MICROVOLT PER METER
RECEIVING ANTENNA 30 FEET HIGH

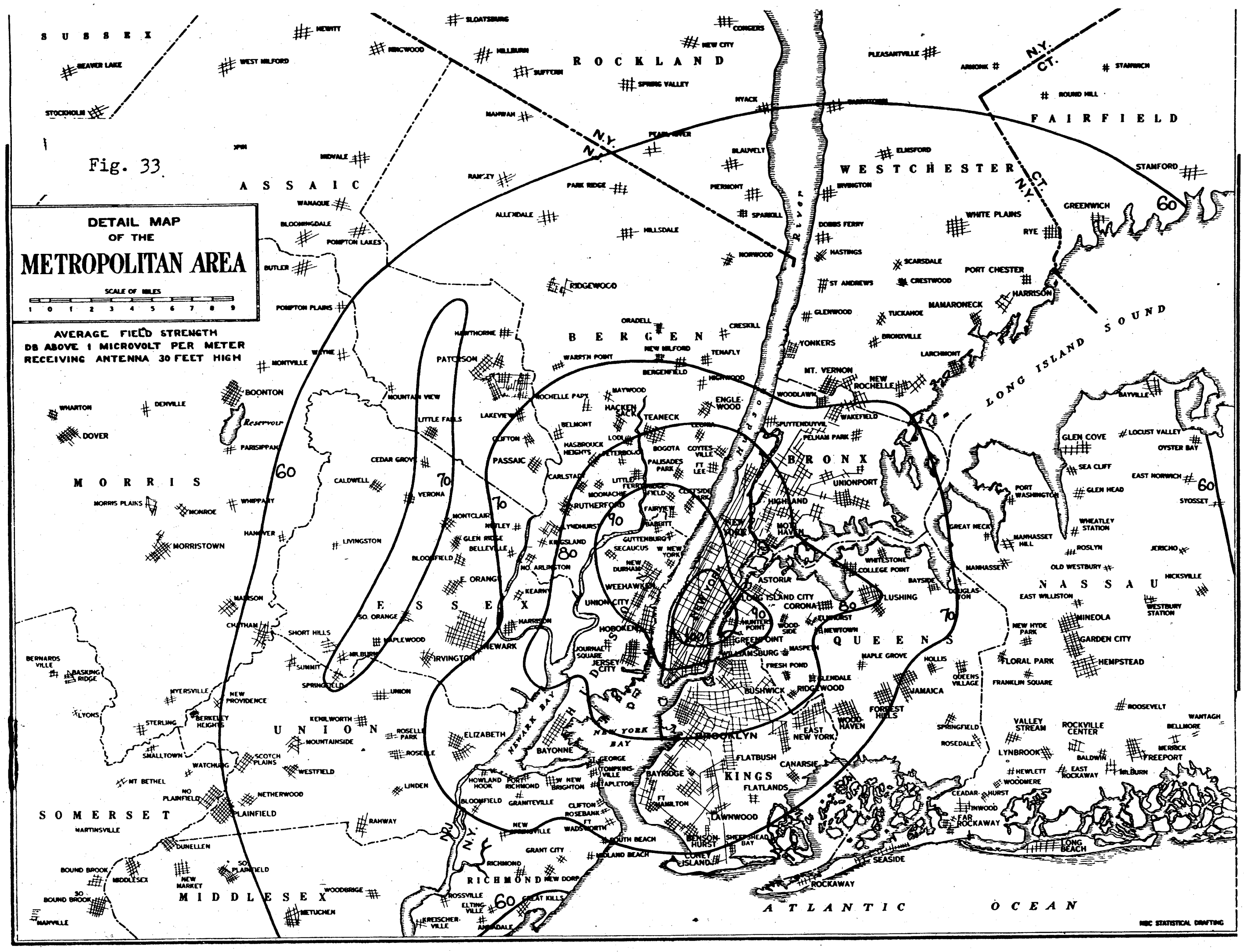

Fig. 33

tion, or fading range, at thirty-two miles, which is near the 60-decibel contour was 10 decibels, or the difference between adjacent contours. If the extreme maximum and minimum values are discarded, the variation becomes of considerably smaller range, as shown by curves B and C of Fig. 28. These represent the fading ranges which were exceeded less than five per cent and ten per cent of the time, respectively.

Wickizer combined the data showing the variations due to irregular terrain, and those due to fading, and obtained Fig. 34, showing the approximate limits of the variations from the field strengths indicated on the contour maps to be expected in practice. The results of the survey may therefore be summarized by saying that residents on any contour should receive, as their normal field strength, at least the value of the next lower contour, and some should receive as much as the next higher contour. Superimposed on this normal field will be a variation, due to refraction, increasing from zero very near the transmitter up to about 15 decibels at the 30-decibel contour. The use of Fig. 34 should, therefore, assist in interpretation of the coverage maps.

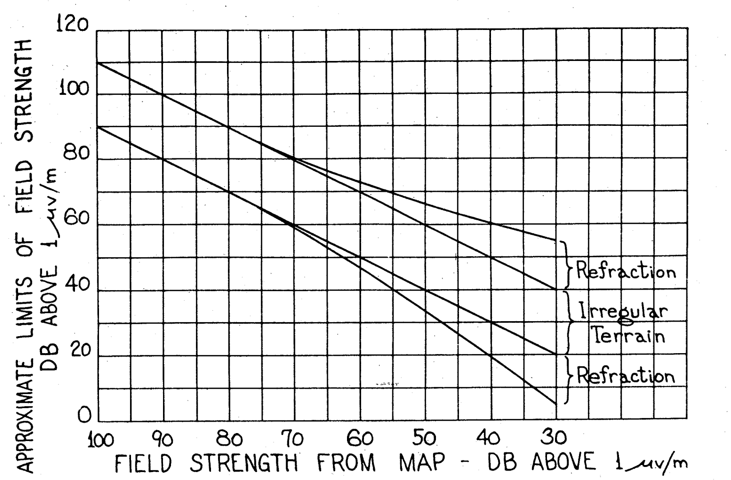

Fig. 34

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