7

Wave Propagation, Radiation, and Absorption

Edward W. Allen, Jr.
Sun City, Arizona
(Former Chief Engineer FCC)

THE NATURE OF RADIO-WAVE PROPAGATION

Radio waves are a part of a larger spectrum of electromagnetic radiation or wave motion extending from the very low frequencies which are now employed in servo-mechanisms, up through the extremely high frequencies and short wavelengths found in cosmic rays. Between these two extremes lie several ranges of frequencies which are related by reason of their being portions of a common spectrum but which exhibit such different characteristics under normal experience that their kinship may not be readily recognized. However, under certain conditions, analogies are useful for describing the characteristics of one range in terms of another. These other ranges include the frequencies used for electric-power systems; the audio frequencies used in systems for the transmission, amplification, or recording of audible sounds; the radio frequencies; radiant heat; light; and the X-rays.

The portions of the spectrum occupied by these frequency ranges are shown in Fig. 1a. The limits of each frequency range are not defined sharply, but each range overlaps slightly into the ranges above and below. The frequency ranges are marked in terms of the frequency f in Hertz (cycles per second) and are also marked in terms of the wavelength λ in space in centimeters. The wavelength λ is related to the frequency f by the formula $C = f\lambda$, where C is the velocity of light and other electromagnetic radiation in space and is approximately equal to 3×10^{10} cm/sec ($2.99795 \pm 0.00003 \times 10^{10}$).

The range comprising the presently recognized limits of the radio spectrum has been expanded in Fig. 1b with the horizontal scale in terms of megaHertz (MHz), or millions of cycles per second. The portions of the radio spectrum to which television broadcasting and television relay stations are allocated have been further expanded in Fig. 1c. The following discussion and methods apply particularly to these portions of the spectrum. (The Administrative Radio Conference [ITU, Geneva, 1959] extended their consideration of the radio spectrum to 40 GHz).

The television broadcast allocations in the United States are: channels 2 to 4, 54 to 72 MHz; channels 5 and 6, 76 to 88 MHz; channels 7 to 13, 174 to 216 MHz; channels 14 to 83, 470 to 890 MHz. Allocations for television auxiliaries—remote pickup, studio-transmitter links, and intercity relay—are provided in eight bands between 1990 MHz and 40 GHz. Allocations for common carrier relay purposes, which carry intercity television programs, and for space communications are also interspersed throughout this frequency range. The specific frequency bands and their detailed usages and sharing arrangements are too complex for inclusion here. In addition, these allocations may change from time to time as the relative needs of various services for radio frequencies change, so that the allocations included herein should be considered to be merely illustrative. Current information should be obtained, when necessary, by consulting the Rules of the FCC.

PROPAGATION IN FREE SPACE

For simplicity and ease of explanation, propagation in space and under certain conditions involving simple geometry, in which the wavefronts remain coherent, may be treated as ray propagation. It should be kept in mind that this assumption may not hold in the presence of obstructions, surface roughness, and other conditions which may be encountered in practice.

For the simplest case of propagation in space, namely that of uniform radiation in all directions from a point source, or isotropic radiator, it is

---

Reprinted in part from "Television Engineering Handbook," edited by Donald G. Fink, McGraw-Hill Book Company, Inc., 1957.

Superscript numbers refer to references at the end of this chapter.

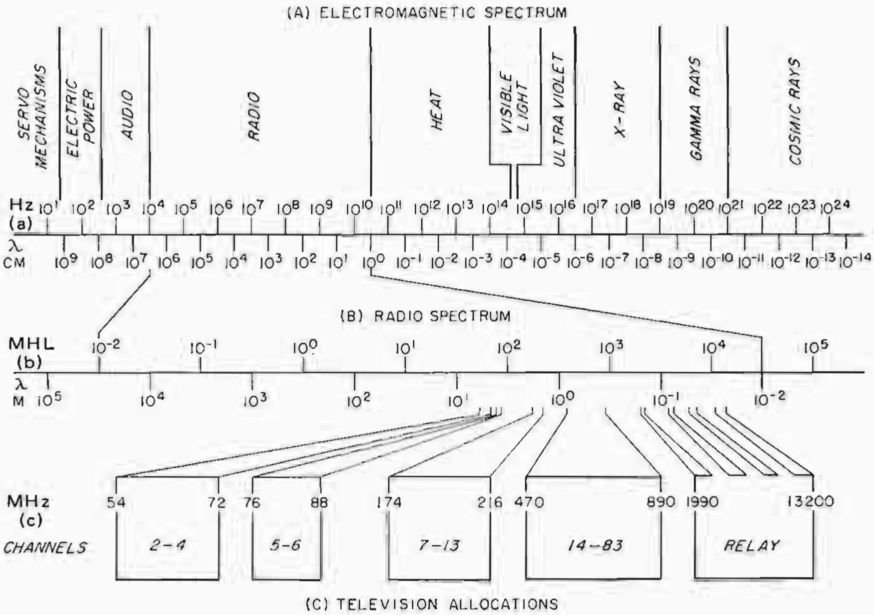


Fig. 1. (a) Electromagnetic spectrum, (b) radio spectrum, (c) television allocations.

useful to consider the analogy to a point source of light. The radiant energy passes with uniform intensity through all portions of an imaginary spherical surface located at a radius r from the source. The area of such a surface is $4\pi r^2$, and the power flow per unit area $W = P_t/4\pi r^2$, where P_t is the total power radiated by the source. In the engineering of broadcasting and of some other radio services, it is conventional to measure the intensity of radiation in terms of the strength of the electric field E_O rather than in terms of power flux density W. The power flux density is equal to the square of the field strength divided by the impedance of the medium, so for free space $W = E_O{}^2/120\pi$, and $P_t = 4\pi r^2\, E_O{}^2/120\pi$, or

$$P_t = \frac{r^2 E_O{}^2}{30} \qquad [1]$$

where P_t is in watts radiated, W is in watts per square meter, E_O is the free-space field in volts per meter, and r is the radius in meters. A more conventional and useful form of this equation, which applies also to antennas other than isotropic radiators, is

$$E_O = \frac{\sqrt{30 g_t P_t}}{r} \qquad [2]$$

where g_t is the power gain of the antenna in the pertinent direction compared with an isotropic radiator.

An isotropic antenna is useful as a reference for specifying the radiation patterns for more complex antennas but does not in fact exist. The simplest forms of practical antennas are the electric doublet and the magnetic doublet, the former a straight conductor which is short compared with the wavelength and the latter a conducting loop of short radius compared with the wavelength. For the doublet radiator the gain is 1.5 and the field strength in the equatorial plane is

$$E_O = \frac{\sqrt{45 P_t}}{r} \qquad [2a]$$

For a half-wave dipole, namely, a straight conductor one-half wave in length, the power gain is 1.64 and

$$E_O = \frac{7\sqrt{P_t}}{r} \qquad [2b]$$

From the above formulas it can be seen that for free space (1) the radiation intensity in watts per square meter is proportional to the radiated power and inversely proportional to the square of the radius or distance from the radiator, (2) the electric field strength is proportional to the square root of the radiated power and inversely proportional to the distance from the radiator.

Typical Antennas in Free Space

The formulas for the free-space patterns, power gains, and effective areas of the fundamental doublet antennas and of a few typical antennas which are used frequently in television broadcast and relay systems are shown in Fig. 2. For purposes of pattern calculation, the element spacings S are

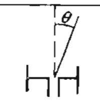
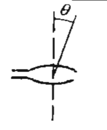
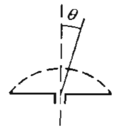
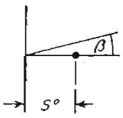
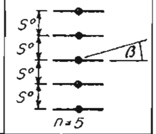
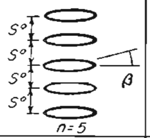
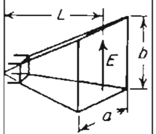
TYPE	CONFIGURATION	PATTERN	POWER GAIN OVER ISOTROPIC	EFFECTIVE AREA
ELECTRIC DOUBLET		$\cos\theta$	1.5	$1.5\,\frac{\lambda^2}{4\pi}$
MAGNETIC DOUBLET OR LOOP		$\sin\theta$	1.5	$1.5\,\frac{\lambda^2}{4\pi}$
HALF WAVE DIPOLE		$\frac{\cos(\frac{\pi}{2}\sin\theta)}{\cos\theta}$	1.64	$1.64\,\frac{\lambda^2}{4\pi}$
HALF WAVE DIPOLE AND SCREEN		$2\sin(S^\circ\cos\beta)$	6.5	$1.64\,\lambda^2/\pi$
TURNSTILE ARRAY		$\frac{\sin(n\frac{S^\circ}{2}\sin\beta)}{n\sin(\frac{S^\circ}{2}\sin\beta)}$	n OR $2L/\lambda$	$n\lambda^2/4\pi$ OR $L\lambda/2\pi$
LOOP ARRAY		$\frac{\cos\beta\sin(n\frac{S^\circ}{2}\sin\beta)}{n\sin(\frac{S^\circ}{2}\sin\beta)}$	n OR $2L/\lambda$	$n\lambda^2/4\pi$ OR $L\lambda/2\pi$
OPTIMUM HORN $L \geq a^2/\lambda$		HALF POWER WIDTH $70\,\lambda/a$ DEGREES (H PLANE) $51\,\lambda/b$ DEGREES (E PLANE)	$10\,ab/\lambda^2$	$0.81\,ab$
PARABOLA		HALF POWER WIDTH $70\,\lambda/d$ DEGREES	$2\pi d^2/\lambda^2$	$d^2/2$

Fig. 2. Patterns, gains, and areas of typical antennas.

measured in electrical angles $S^0 = 2\pi S/\lambda$. For the turnstile and loop arrays the length $L = nS$, and for $S = \lambda/2$, $n = 2L/\lambda$.

The effective area B is related to the power gain g by the formula $B = g\lambda^2/4\pi$. The physical dimensions of the antennas, their effective areas, the wavelength, etc., should be expressed in the same units. The values given for power gain and effective area are for optimum conditions, and departures will result in lesser values of power gain and effective area.[1,2]

Transmission Loss between Antennas in Free Space[9]

The maximum useful power P_r that can be delivered to a matched receiver is given by

$$P_r = \left(\frac{E\lambda}{2\pi}\right)^2 \frac{g_r}{120} \text{ watts} \qquad [3]$$

where E = received field strength in volts per meter
λ = wavelength in meters, $300/f$

f = frequency in MHz
g_r = receiving antenna power gain over an isotropic radiator

This relation between received power and the received field strength is shown by scales 2, 3, and 4 in Fig. 3 for a half-wave dipole. For example, the maximum useful power at 100 MHz that can be delivered by a half-wave dipole in a field of 50 dB above 1 μv per meter is 95 dB below 1 watt. A general relation for the ratio of the received power to the radiated power obtained from Equations 2 and 3 is

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi r}\right)^2 g_t g_r \left(\frac{E}{E_o}\right)^2 \qquad [4]$$

When both antennas are half-wave dipoles, the power-transfer ratio is

$$\frac{P_r}{P_t} = \left(\frac{1.64\lambda}{4\pi r}\right)^2 \left(\frac{E}{E_o}\right)^2 = \left(\frac{0.13\lambda}{r}\right)^2 \left(\frac{E}{E_o}\right)^2 \qquad [4a]$$

and is shown on scales 1 to 4 of Fig. 3. For free-space transmission $E/E_o = 1$.

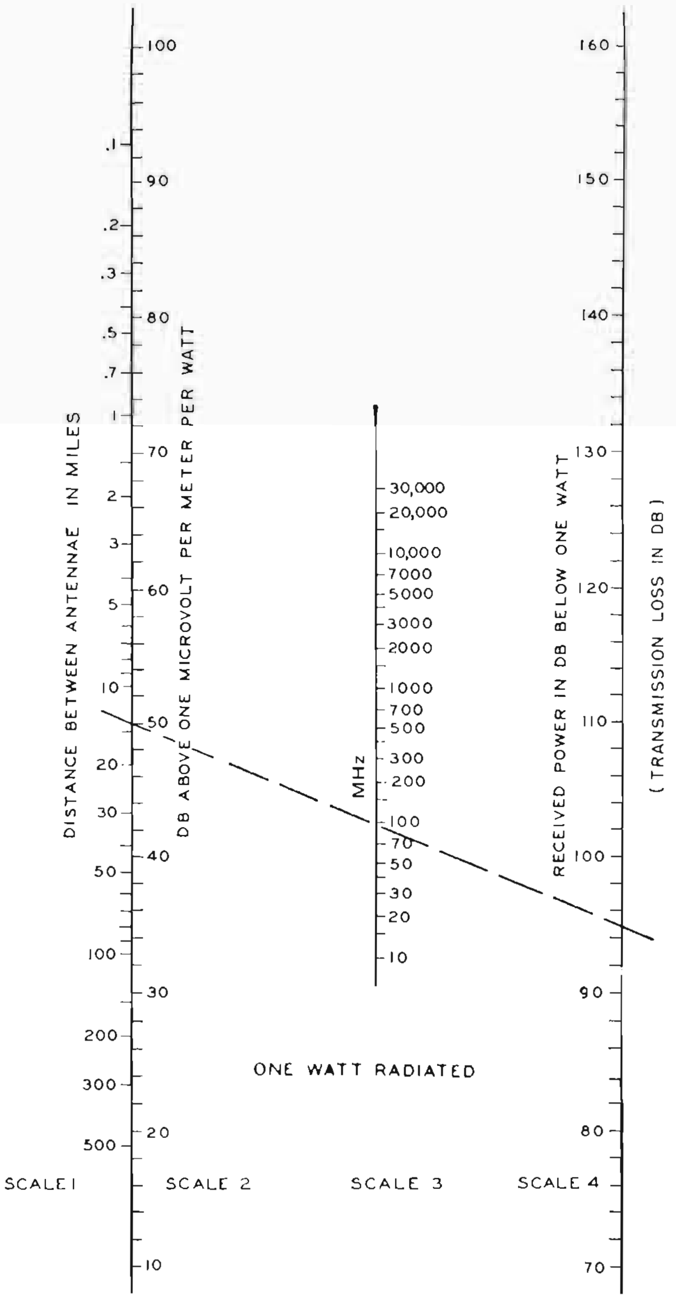


Fig. 3. Free-space field intensity and received power between half-wave dipoles.

When the antennas are horns, paraboloids, or multielement arrays, a more convenient expression for the ratio of the received power to the radiated power is given by

$$\frac{P_r}{P_t} = \frac{B_t B_r}{(\lambda r)^2} \left(\frac{E}{E_o}\right)^2 \qquad [4b]$$

where B_t and B_r are the effective areas of the transmitting and receiving antennas, respectively. This relation is obtained from Eq. 4 by substituting $g = 4\pi B/\lambda^2$, and is shown in Fig. 4 for free-space transmission when $B_t = B_r$. For example, the free-space loss at 4,000 MHz between two antennas of 10 sq. ft. effective area is about 72 dB for a distance of 30 miles.

The following formulae for the attenuation of field strengths and the loss between isotropic antennas in free space have been found useful in the engineering of space and terrestrial communication systems:

$$\begin{aligned} F_o &= 102.8 + P_t - 20 \log r \\ L_b &= 36.6 + 20 \log f + 20 \log r \\ L_b &= 139.4 + 20 \log f - F \\ L_b &= L + G_t + G_r \\ A_{iso} &= 38.55 - 20 \log f \\ A &= A_{iso} + G \end{aligned}$$

where

F_o = free space field in dB above 1 μv/m in equatorial plane of dipole antenna

r = radius in miles from antenna to point of interest

P_t = power into antenna in dB relative to one kilowatt (dBk)

L_b = basic transmission loss in dB between the terminals of two lossless isotropic antennas

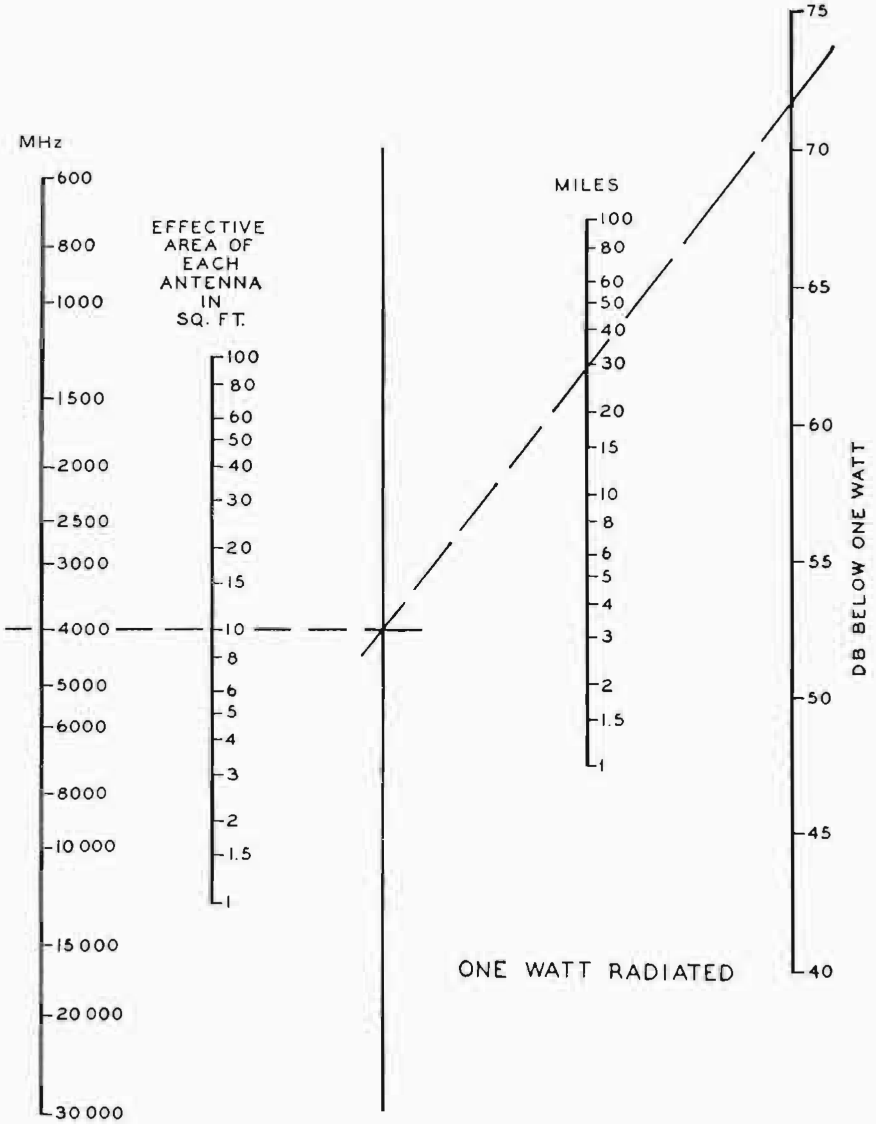


Fig. 4. Received power in free space between two antennas of equal effective areas.

G_t = gain in dB of transmitting antenna relative to isotropic
G_r = gain in dB of receiving antenna relative to isotropic
A_{iso} = area of isotropic antenna
A = effective area of antenna with gain G

PROPAGATION OVER PLANE EARTH[3,7]

The presence of the ground modifies the generation and the propagation of the radio waves so that the received field strength is ordinarily different than would be expected in free space. The ground acts as a partial reflector and as a partial absorber, and changes the phase of the refluted wave, and these properties affect the distribution of energy in the region above the earth.

Field Strengths Over Plane Earth

The geometry of the simple case of propagation between two antennas each placed several wavelengths above a plane earth is shown in Fig. 5. For isotropic antennas, for simple magnetic-doublet antennas with vertical polarization, or for simple electric-doublet antennas with horizontal polarization the resultant received field is[5,7]

$$E = \frac{E_O d}{r_1} + \frac{E_O d R e^{i\Delta}}{r_2} = E_O(\cos\theta_1 + R\cos\theta_2 e^{i\Delta}) \quad [5]$$

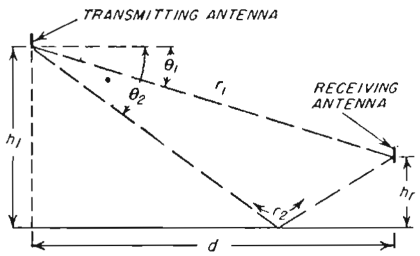


Fig. 5. Ray paths for antennas above plane earth.

For simple magnetic-doublet antennas with horizontal polarization or electric-doublet antennas with vertical polarization at both transmitter and receiver, it is necessary to correct for the cosine radiation and absorption patterns in the plane of propagation. The received field is

$$E = E_O(\cos^3\theta_1 + R\cos^3\theta_2 e^{i\Delta}) \quad [5a]$$

where E_O is the free-space field at distance d in the equatorial plane of the doublet, R is the complex reflection coefficient of the earth, $j = \sqrt{-1}$; $e^{i\Delta} = \cos\Delta + j\sin\Delta$, and Δ is the phase difference between the direct wave received over path r_1 and the ground-reflected wave received over path r_2, which is due to the difference in path lengths.

For distances such that θ is small and the differences between d and r_1 and r_2 can be neglected, Eqs. 5 and 5a become

$$E = E_O(1 + Re^{i\Delta}) \quad [6]$$

When the angle θ is very small, R is approximately equal to -1. For the case of two antennas, one or both of which may be relatively close to the earth, a surface-wave term must be added[3,4] and Eq. 6 becomes

$$E = E_O[1 + Re^{i\Delta} + (1 - R)Ae^{i\Delta}] \quad [7]$$

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:[9]

$$A \simeq \frac{-1}{1 + j(2\pi d/\lambda)(\sin\theta + z)^2} \quad [7a]$$

This approximate expression is sufficiently accurate as long as $A < 0.1$, and it gives the magnitude of A within about 2 dB for all values of A. However, as A approaches unity, the error in phase approaches 180°. More accurate values are given by Norton[7] where, in his nomenclature, $A = f(P,B)e^{i\phi}$.

The Eq. 7 for the absolute value of field strength has been developed from the successive consideration of the various components which make up the ground wave, but the following equivalent expressions may be found more convenient for rapid calculation:

$$E = E_O\left\{2\sin\frac{\Delta}{2} + j[(1 + R) + (1 - R)A]e^{i\Delta/2}\right\} \quad [8]$$

When the distance d between antennas is greater than about five times the sum of the two antenna heights h_t and h_r, the phase difference angle Δ is equal to $4\pi h_t h_r/\lambda d$ radians. Also when the angle Δ is greater than about 0.5 radian the terms inside the brackets, which include the surface wave, are usually negligible, and a sufficiently accurate expression is given by

$$E = E_O\left(2\sin\frac{2\pi h_t h_r}{\lambda d}\right) \quad [8a]$$

In this case the principal effect of the ground is to produce interference fringes or lobes, so that the field strength oscillates about the free-space field as the distance between antennas or the height of either antenna is varied.

When the angle Δ is less than about 0.5 radian, there is a region in which the surface wave may be important but not controlling. In this region $\sin \Delta/2$ is approximately equal to $\Delta/2$ and

$$E = E_O \frac{4\pi h_t' h_r'}{\lambda d} \qquad [8b]$$

In this equation $h' = h + jh_O$, where h is the actual antenna height and $h_O = \lambda/2\pi z$ has been designated as the minimum effective antenna height. The magnitude of the minimum effective height h_O is shown in Fig. 6 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.[9]

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 dB every time the antenna height is doubled, until free-space transmission is reached. Ordinarily it is sufficiently accurate to assume that h' is equal to the actual antenna height or the minimum effective antenna height, whichever is the larger.

When translated into terms of antenna heights in feet, distance in miles, effective power in kilowatts radiated from a half-wave dipole, and frequency f in MHz per second, Eq. 8b becomes the following very useful formula for the rapid calculation of approximate values of field strength for purposes of prediction or for comparison with measured values:

$$E \simeq F \frac{h_t' h_r' \sqrt{P_t}}{3d^2} \qquad [8c]$$

Transmission Loss between Antennas Over Plane Earth

The ratio of the received power to the radiated power for transmission over plane earth is obtained by substituting Eq. 8b into 4, resulting in

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi d}\right)^2 g_t g_r \left(\frac{4\pi h_t' h_r'}{\lambda d}\right)^2 = \left(\frac{h_t' h_r'}{d^2}\right)^2 g_t g_r \qquad [9]$$

This relation is independent of frequency, and is shown on Fig. 7 for half-wave dipoles ($g_t = g_r = 1.64$). 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 received power for 1 watt radiated. When the received field strength is desired, the power indicated on Fig. 7 can be transferred to scale 4 of Fig. 3, and a line through the frequency on scale 3 indicates the received field strength on scale 2. The results shown on Fig. 7 are valid as long as the value of received power indicated is lower than that shown on Fig. 3 for free-space transmission. When this condition is not met, it means that the angle Δ is too large for Eq. 8b to be accurate and that the received field strength or power oscillates around the free-space value as indicated by Eq. 8a.[9]

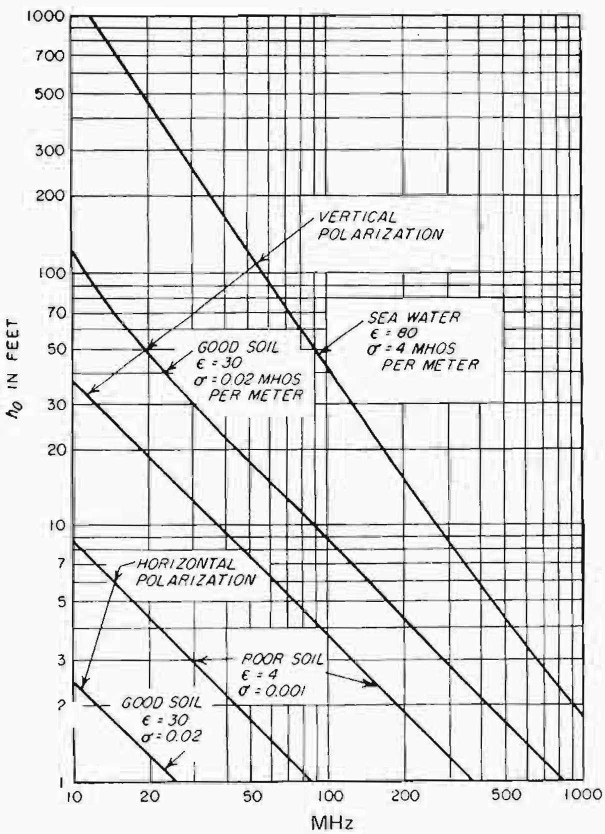


Fig. 6. Minimum effective antenna height.

PROPAGATION OVER SMOOTH SPHERICAL EARTH

Propagation within the Line of Sight

The curvature of the earth has three effects on the propagation of radio waves at points within the line of sight. First, the reflection coefficient of the ground-reflected wave differs for the curved surface

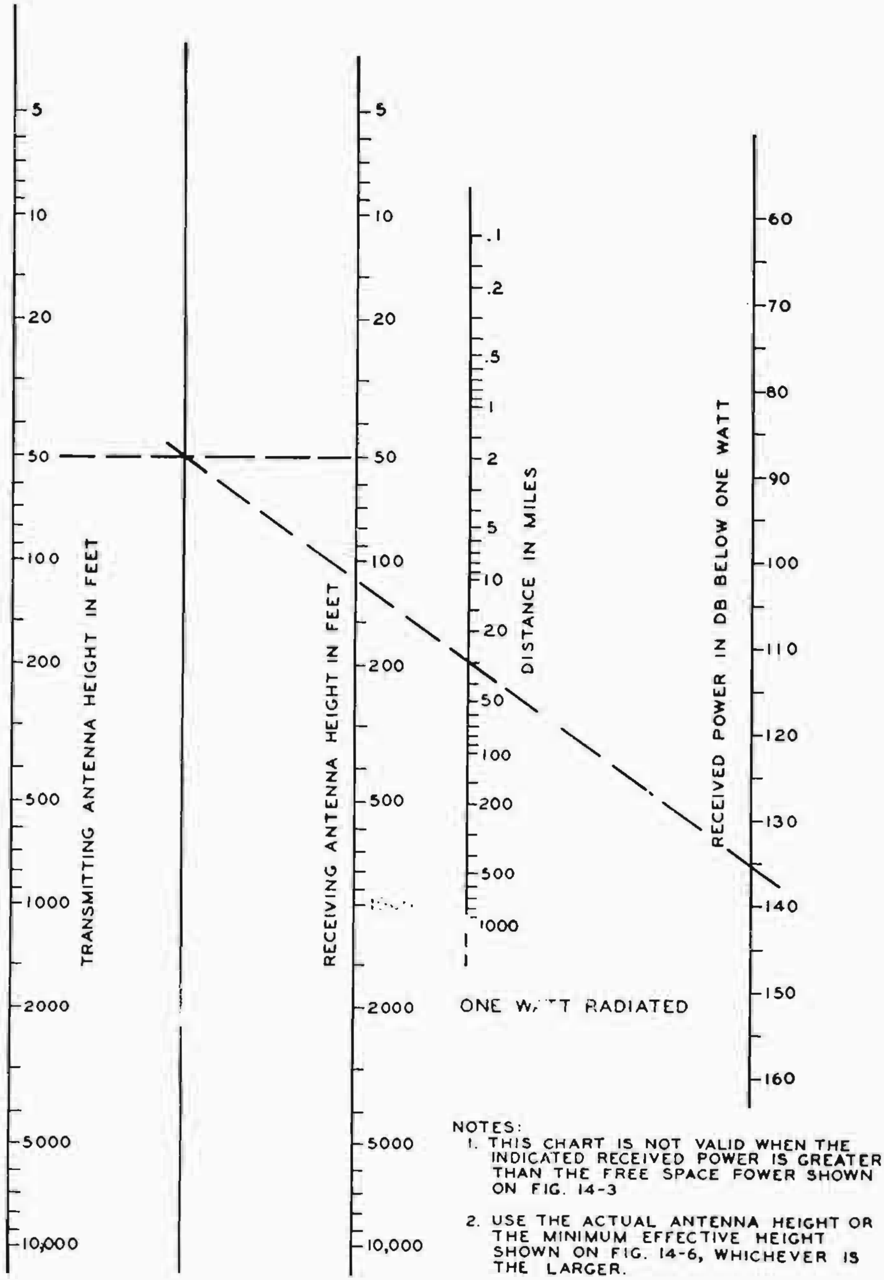


Fig. 7. Received power over plane earth between half-wave dipoles.

of the earth from that for a plane surface. This effect is of little importance, however, under the circumstances normally encountered in practice. Second, since the ground-reflected wave is reflected against the curved surface of the earth, its energy diverges more than would be indicated by the inverse distance-squared law and the ground-reflected wave must be multiplied by a divergence factor D. Finally, the heights of the transmitting and receiving antennas h_t' and h_r', above the plane which is tangent to the surface of the earth at the point of reflection of the ground-reflected wave, are less than the antenna heights h_t and h_r, above the surface of the earth, as shown in Fig. 8.

Under these conditions Eq. 6, which applies to larger distances within the line of sight and to antennas of sufficient height that the surface component can be neglected, becomes

$$E = E_0 (1 + DR' e^{i\Delta}) \qquad [10]$$

Similar substitutions of the values which correspond in Figs. 5 and 8 may be made in Eqs. 7 through 9. However, under practical conditions, it is generally satisfactory to use the plane-earth formulas for the purpose of calculating smooth-earth values. An exception to this is usually made in the preparation of standard reference curves, which are

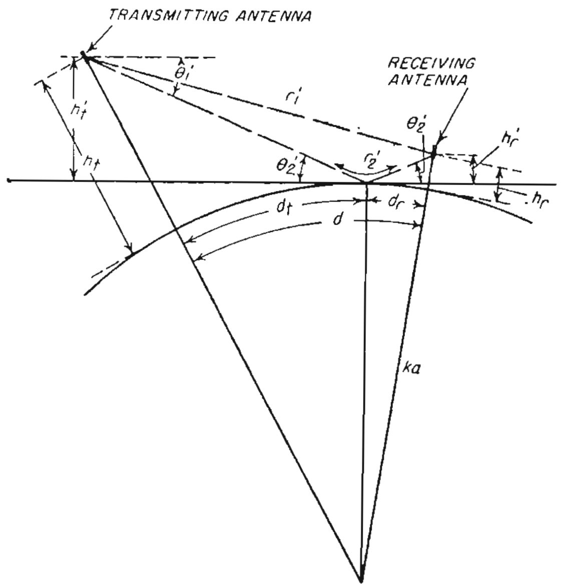


Fig. 8. Ray paths for antennas above spherical earth.

generally calculated by the use of the more exact formulas.[4-10]

Propagation beyond the Line of Sight

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 wave optics, each point on the wavefront is considered to act as a radiating source. When the wavefront is coherent or undisturbed, the resultant is a progression of the front in a direction perpendicular thereto, along a path which constitutes the ray. When the front is disturbed, the resultant front may be changed in both magnitude and direction with resulting attenuation and bending of the ray. Thus all shadows are somewhat "fuzzy" on the edges and the transition from "light" to "dark" areas is gradual, rather than infinitely sharp.

The effect of diffraction around the earth's curvature is to make possible transmission beyond the line of sight, with somewhat greater loss than is incurred in free space or over plane earth. 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 calculation of the field strength to be expected at any particular point in space beyond the line of sight around a spherical earth is rather complex, so that individual calculations are seldom made. Rather, nomograms or families of curves are usually prepared for general application to large numbers of cases. The original wave equations of van der Pol and Bremmer[4] have been modified by Burrows[6] and by Norton[5,7] so as to make them more readily usable and particularly adaptable to the production of families of curves. Such curves have been prepared, but have not been included herein, in view of the large number of curves which are required to satisfy the possible variations in frequency, electrical characteristics of the earth, polarization, and antenna height. Also, the values of field strength indicated by smooth-earth curves are subject to considerable modification under actual conditions found in practice. For VHF and UHF broadcast purposes, the smooth-earth curves have been to a great extent superseded by curves modified to reflect average conditions of terrain.

Fig. 9 is a nomogram to determine the additional loss caused by the curvature of the earth.[9] This loss must be added to the free-space loss found from Fig. 3. A scale is included to provide for the effect of changes in the effective radius of the earth, caused by atmospheric refraction. Fig. 9 gives the loss relative to free space 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 between the horizons. The total distance between antennas is $d = d_1 + d_2 + d_3$.

The horizon distances d_1 and d_2 for the respective antenna heights h_1 and h_2 and for any assumed value of the earth's radius factor k can be determined from Fig. 10.

EFFECTS OF HILLS, BUILDINGS, VEGETATION, AND THE ATMOSPHERE

The preceding discussion assumes that the earth is a perfectly smooth sphere with a uniform or a simple atmosphere, for which condition calculations of expected field strengths or transmission losses can be computed for the regions within the line of sight and regions well beyond the line of sight, and interpolations can be made for intermediate distances. The presence of hills, buildings, and trees has such complex effects on propagation that it is impossible to compute in detail the field strengths to be expected at discrete points in the immediate vicinity of such obstructions or even the median values over very small areas. However, by the examination of the earth profile over the path of propagation and by the use of certain simplifying assumptions, predictions which are more accurate than smooth-earth calculations can be made of the median values to be expected over areas representative of the gross features of terrain.

Effects of Hills

The profile of the earth between the transmitting and receiving points is taken from available topogra-

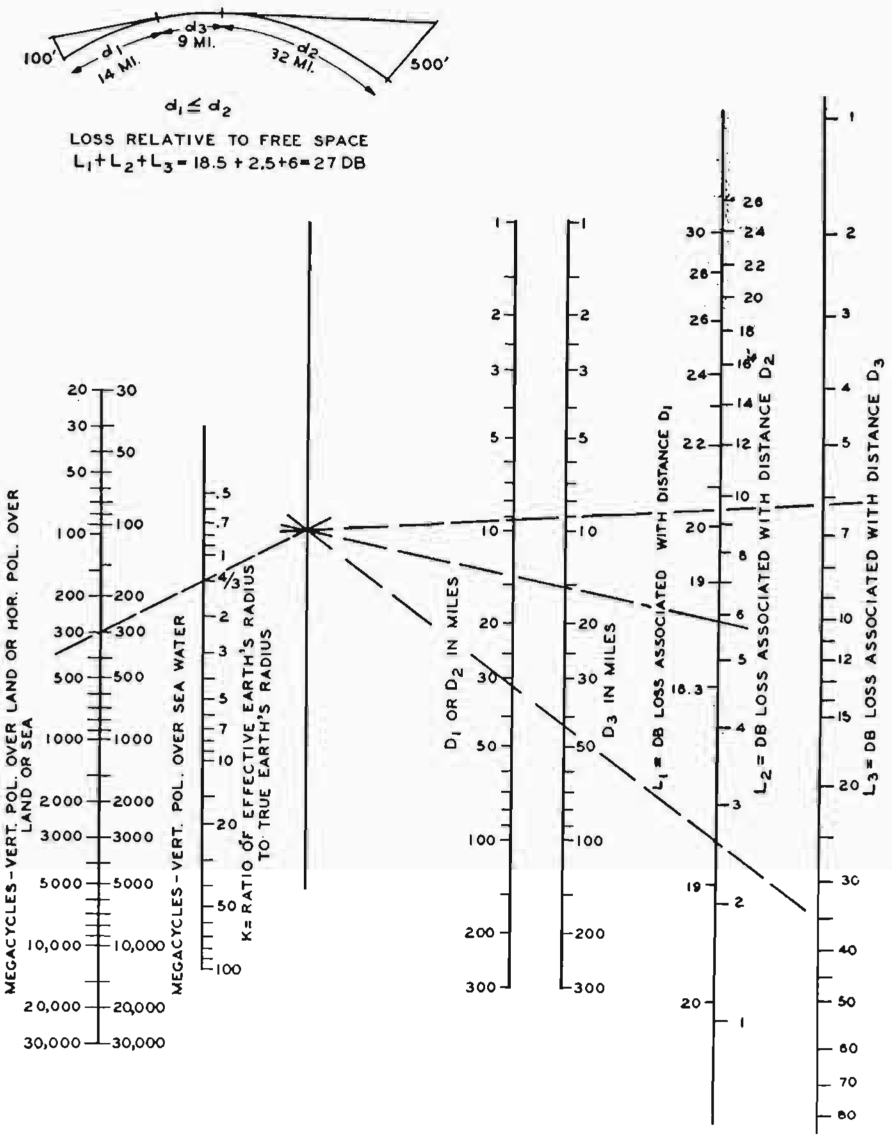


Fig. 9. Decibel loss beyond line of sight.

phic maps (available from the U.S. Geological Survey, Department of the Interior, Washington, D.C.) and is plotted on a special chart which provides for average air refraction by the use of a four-thirds earth radius, as shown in Fig. 11. The vertical scale is greatly exaggerated for convenience in displaying significant angles and path differences. Under these conditions vertical dimensions are measured along vertical parallel lines rather than along radii normal to the curved surface, and the propagation paths appear as straight lines. The field to be expected at a low receiving antenna at *A* from a high transmitting antenna at *B* can be predicted by plane-earth methods, by drawing a tangent to the profile at the point at which reflection appears to occur with equal incident and reflection angles. The heights of the transmitting and receiving antennas above the tangent are used in conjunction with Fig. 7 to compute the transmission loss or with Eq. 8c to compute the field strength. A similar procedure can be used for more distantly spaced high antennas when the line of sight does not clear the profile by at least the first Fresnel zone.[11]

Propagation over a sharp ridge or over a hill when both the transmitting and receiving antenna locations are distant from the hill may be treated as diffraction over a knife edge, shown schematically in Fig. 12a.[9-15] The height of the obstruction *H* is measured from the line joining the centers of the two antennas to the top of the ridge. As shown in Fig. 13, the shadow loss approaches 6 dB as *H* approaches 0, grazing incidence, and it increases with increasing positive values of *H*. When the direct ray clears the obstruction, *H* is negative, and the shadow loss approaches 0 dB in an oscillatory manner as the clearance is increased. Thus, a

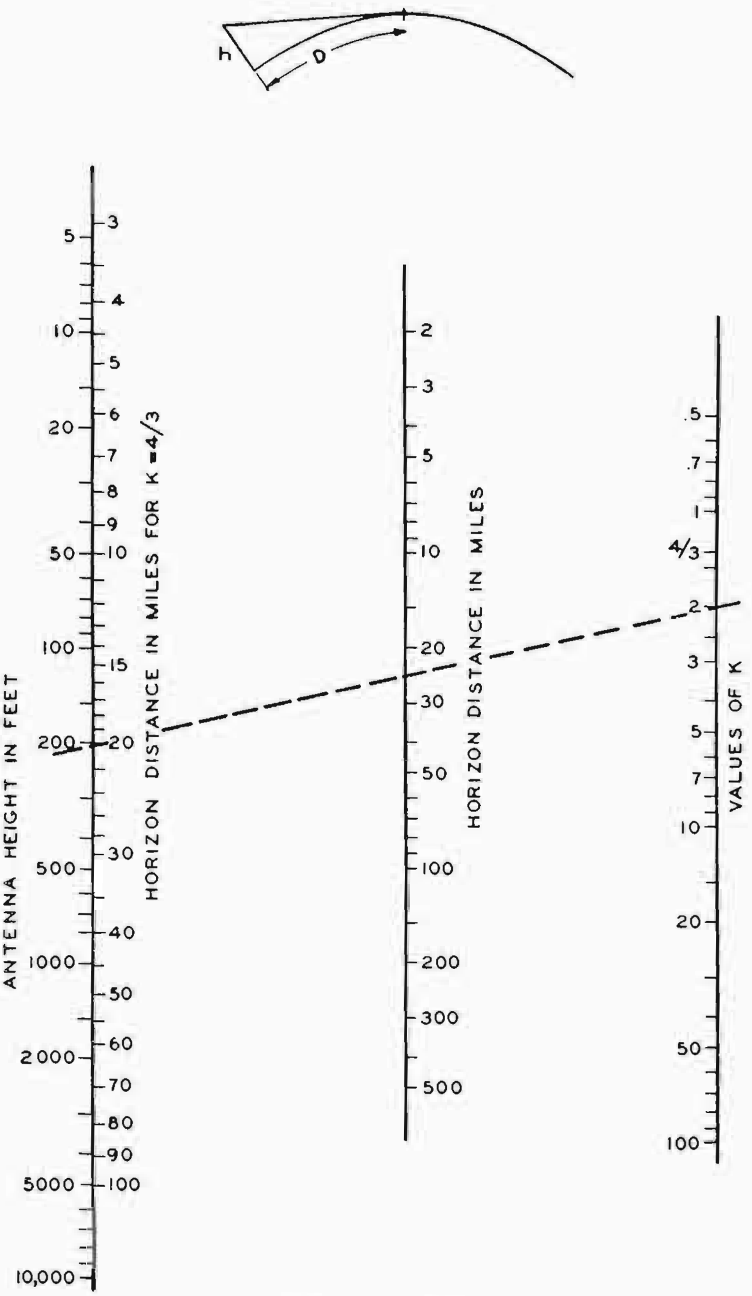


Fig. 10. Distance to horizon.

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 dB better than in free space. Physically, 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 one-half wavelength greater than the phase shift of the direct path between antennas.

The locations of the first three Fresnel zones are indicated on the right-hand scale on Fig. 13, and by means of this chart the required clearances can be obtained. At 3,000 MHz, for example, the direct ray should clear all obstructions in the center of a 40-mile path by about 120 ft., to obtain full first-zone clearance, as shown at *C* in Fig. 11. The corresponding clearance for a ridge 100 ft. in front of either antenna is 4 ft. The locus of all points which satisfy this condition for all distances is an ellipsoid of revolution with foci at the two antennas.

When there are two or more knife-edge obstructions or hills between the transmitting and receiving antennas, an equivalent knife edge may be repre-

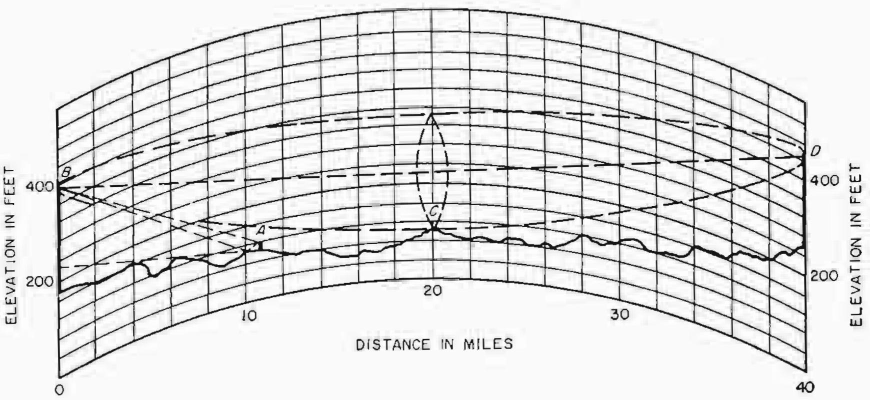


Fig. 11. Ray paths for antennas over rough terrain.

sented by drawing a line from each antenna through the top of the peak that blocks the line of sight, as in Fig. 12b.

Alternatively, the transmission loss may be computed by adding the losses incurred when passing over each of the successive hills, as in Fig. 12c. The height H_1 is measured from the top of hill 1 to the line connecting antenna 1 and the top of hill 2. Similarly, H_2 is measured from the top of hill 2 to the line connecting antenna 2 and the top of hill

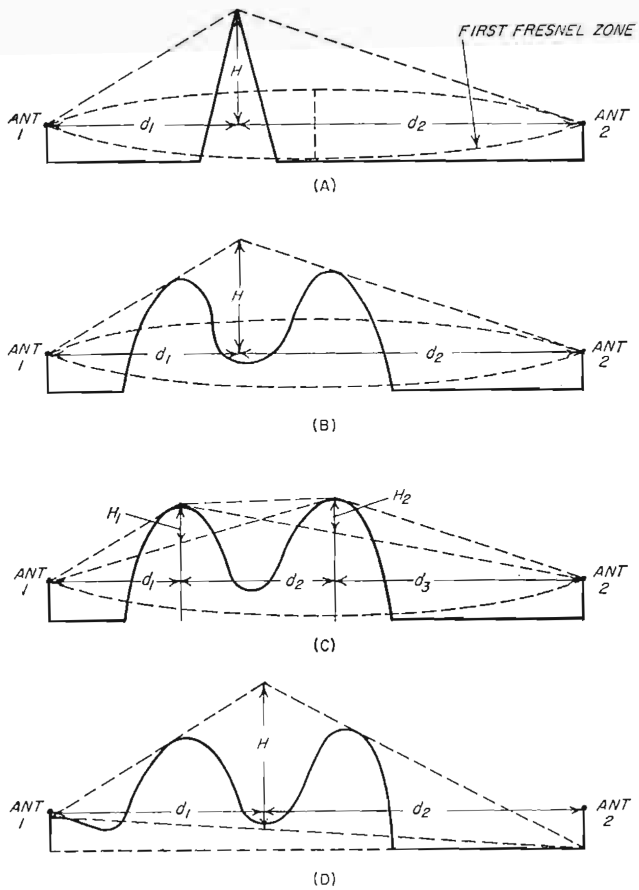


Fig. 12. Ray path for antennas behind hills.

1. The nomogram in Fig. 13 is used for calculating the losses for terrain conditions represented by Fig. 12a, b, and c.

The above procedure applies to conditions for which the earth-reflected wave can be neglected, such as the presence of rough earth, trees, or structures at locations along the profile at points where earth reflection would otherwise take place at the frequency under consideration or where first Fresnel-zone clearance is obtained in the foreground of each antenna and the geometry is such that reflected components do not contribute to the field within the first Fresnel zone above the obstruction. If conditions are favorable to earth reflection, the base line of the diffraction triangle should not be drawn through the antennas, but through the points of earth reflection, as in Fig. 12d. H is measured vertically from this base line to the top of the hill, while d_1 and d_2 are measured to the antennas as before. In this case Fig. 14 is used to estimate the shadow loss to be added to the plane-earth attenuation.[9]

Under conditions where the earth-reflected components reinforce the direct components at the transmitting and receiving antenna locations, paths may be found for which the transmission loss over an obstacle is less than the loss over spherical earth. This effect may be useful in establishing VHF relay circuits where line-of-sight operation is not practical. Little utility may be expected for mobile or broadcast services.[15]

An alternate method for predicting the median value for all measurements in a completely shadowed area is as follows:[16] (1) The roughness of the terrain is assumed to be represented by height H, shown on the profile at the top of Fig. 15. (2) This height is the difference in elevation between the bottom of the valley and the elevation necessary to

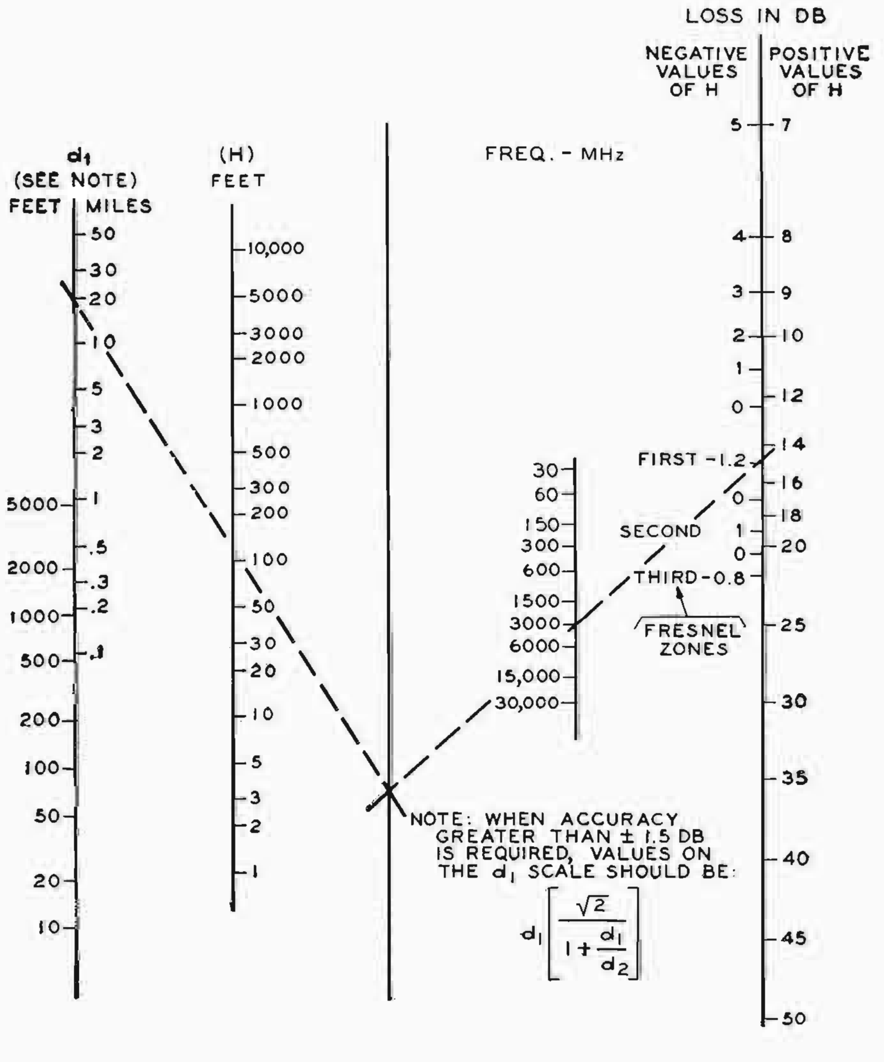
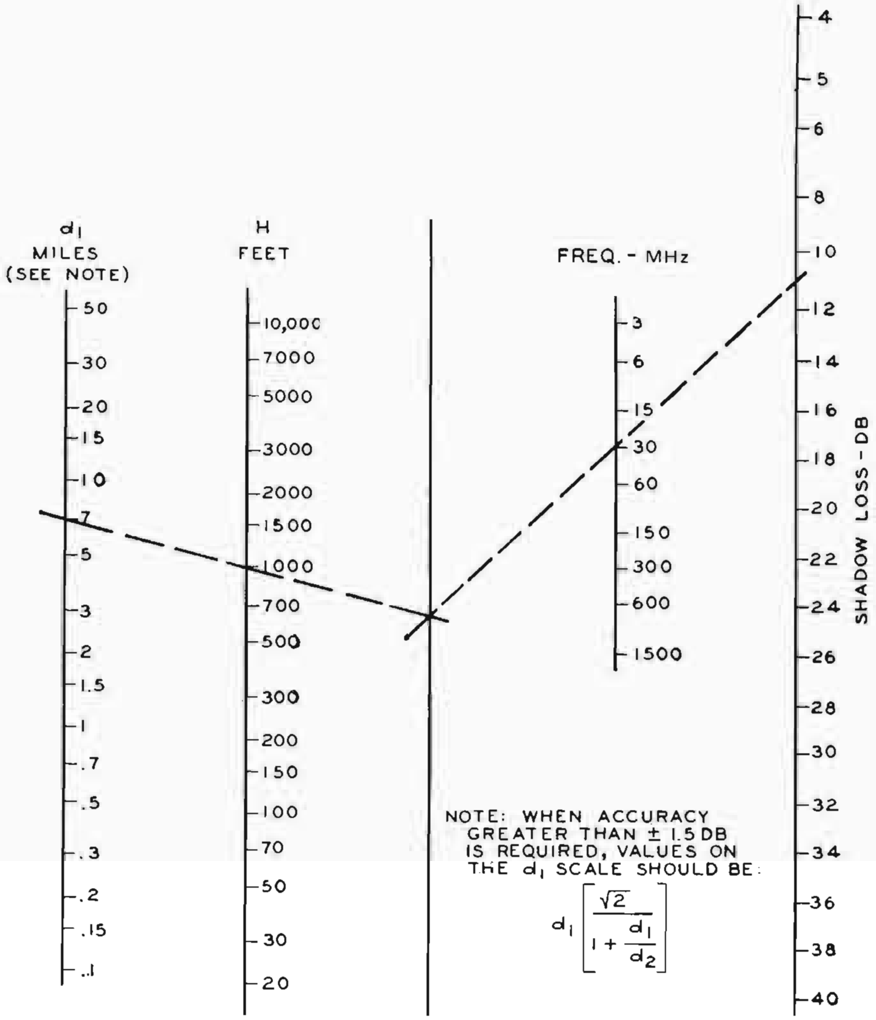


Fig. 13. Shadow loss relative to free space.



$$d_1\left[\frac{\sqrt{2}}{1+\frac{d_1}{d_2}}\right]$$

Fig. 14. Shadow loss relative to plane earth.

obtain line of sight with the transmitting antenna. (3) The difference between the measured value of field intensity and the value to be expected over plane earth is computed for each point of measurement within the shadowed area. (4) The median value for each of several such locations is plotted as a function of $\sqrt{H/\lambda}$.

These empirical relationships are summarized in the nomogram shown in Fig. 15. The scales on the right-hand line indicate the median value of shadow loss, compared with plane-earth values, and the difference in shadow loss to be expected between the median and the 90 percent values. For example, with variations in terrain of 500 ft. the estimated median shadow loss at 4,500 MHz is about 20 dB and the shadow loss exceeded in 90 percent of the possible locations is about 20 + 15 = 35 dB. This analysis is based on large-scale variations in field intensity and does not include the standing-wave effects which sometimes cause the field intensity to vary considerably in a matter of a few feet.

Effects of Buildings

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 MHz 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 dB at 30 MHz and from 10 to 40 dB at 3,000 MHz, depending on whether the wall is dry or wet. Consequently, most buildings are rather opaque at

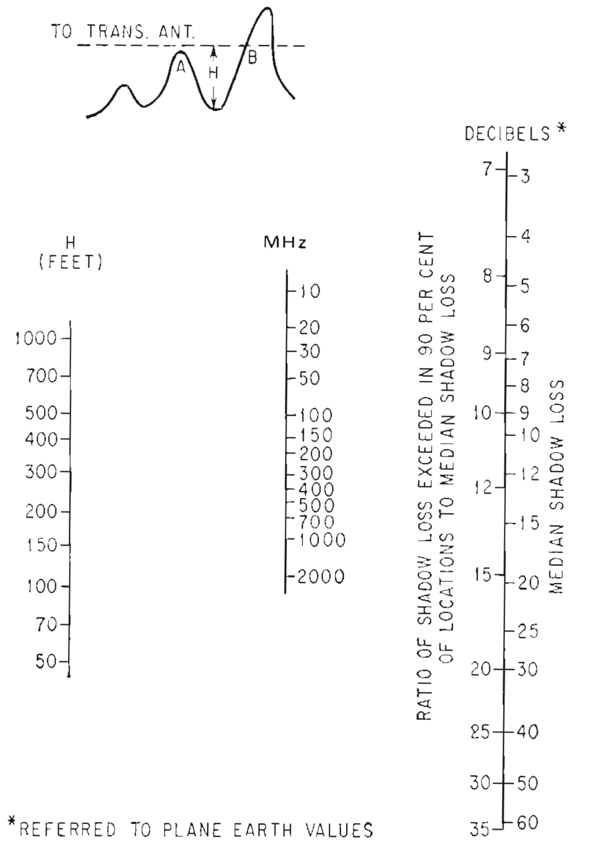


Fig. 15. Estimated distribution of shadow loss for random locations.

frequencies of the order of thousands of megacycles.

For radio-relay purposes, it is the usual practice to select clear sites, but where this is not feasible the expected fields behind large buildings may be predicted by the preceding diffraction methods. In the engineering of mobile- and broadcast-radio systems it has not been found practical in general to relate measurements made in built-up areas to the particular geometry of buildings, so that it is conventional to treat them statistically. However, measurements have been divided according to general categories into which buildings can readily be classified, namely, the tall buildings typical of the centers of cities on the one hand, and typical two-story residential areas on the other.

Buildings are more transparent to radio waves than the solid earth, and there is ordinarily much more back scatter in the city than in the open country. Both of these factors tend to reduce the shadow losses caused by the buildings. On the other hand, the angles of diffraction over or around the buildings are usually greater than for natural terrain, and this factor tends to increase the loss resulting from the presence of buildings. The quantitative data on the effects of buildings indicate that in the range of 40 to 450 MHz there is no significant change with frequency, or at least the variation with frequency is somewhat less than the square-root relationship noted in the case of hills. The median field strength at street level for random locations in Manhattan (New York City) is about 25 dB below the corresponding plane-earth value. The corresponding values for the 10 and 90 percent points are about −15 and −35 dB, respectively.[9,16,37,38]

Measurements in congested residential areas indicate somewhat less attenuation than among large buildings. In the Report of the Ad Hoc Committee[19] measurements between 4 and 10 miles from the transmitter, which include some large building areas and some open areas but are made up principally of residential areas, shown median values of 4 to 6 dB below plane earth for frequencies below 100 MHz and about 10 dB for frequencies near 200 MHz. More recent measurements at 850 MHz[20] show values of 15 to 26 dB below free space, which appear to be about 10 to 15 dB below plane earth. These measurements were not random, however, but were the maximum values of field between 10 and 30 ft. above the earth. The Television Allocations Study Organization has recently made similar measurements and has recommended appropriate values for the application of average curves to urban conditions.[37] The average effects for measurements taken in built-up areas have been accounted for in the preparation of the modified propagation curves of Figs. 19 and 20, and in new curves proposed for adoption by the FCC.[39]

Effects of Trees and Other Vegetation

When an antenna is surrounded by moderately thick trees and below treetop level, the average loss at 30 MHz resulting from the trees is usually 2 or 3 dB for vertical polarization and negligible with horizontal polarization. However, large and rapid variations in the received field strength 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 ft. or more from the antenna. Consequently, several nearby locations should be investigated for best results. At 100 MHz the average loss from surrounding trees may be 5 to 10 dB for vertical polarization and 2 or 3 dB for horizontal polarization. The tree losses continue to increase as the frequency increases, and above 300 to 500 MHz they tend to be independent of the type of polarization. Above 1,000 MHz 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. 13 or 14.[9,10]

There is a pronounced seasonal effect in the case of deciduous trees, with less shadowing and absorption in the winter months when the leaves have fallen. However, when the path of travel through the trees is sufficiently long that it is obscured, losses of the above magnitudes may be incurred, and the principal mode of propagation may be by diffraction over the trees.

When the antenna is raised above trees and other forms of vegetation, the prediction of field strengths again depends upon the proper estimation of the height of the antenna above the areas of reflection and of the applicable reflection coefficients. For growth of fairly uniform height and for angles near grazing incidence, reflection coefficients will approach -1 at frequencies near 30 MHz. As indicated by Rayleigh's criterion of roughness, the apparent roughness for given conditions of geometry increases with frequency so that near 1,000 MHz even such low and relatively uniform growth as farm crops or tall grass may have reflection coefficients of about -0.3 for small angles of reflection.[20]

The distribution of losses in the immediate vicinity of trees does not follow normal probability law but is more accurately represented by Rayleigh's law, which is the distribution of the sum of a large number of equal vectors having random phases. This distribution is shown by the graph R of Fig. 23.

Effects of the Lower Atmosphere, or Troposphere

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 earth. Whenever the dielectric constant varies with height, a horizontally traveling wave will be refracted and the path deviated from a straight line. A general solution of the problem for any possible distribution of dielectric constant with the height 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 which will permit the calculation of radio field strengths under known meteorological conditions. The complexity of this problem, together with the facts that detailed meteorological data which would permit calculation are no more readily available than radio data and that meteorological conditions are not readily predictable over long periods of time, has led to the statistical treatment of radio data, for the purpose of predicting long-distance effects and for the calculation of television service and inference, as in Statistical Evaluation of Propagation.

Stratification and Ducts

In the earlier work in this field the assumption was made that the air was horizontally stratified.[22,23] A simple engineering solution for average conditions 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, to obtain an effective earth's radius, where

$$k = \frac{1}{1 + a/2\,(\Delta\epsilon/\Delta h)} \qquad [11]$$

where a is the radius of the earth and $\Delta\epsilon$ is the change in dielectric constant in going from height h to $h + \Delta h$.[9]

Meteorological measurements indicate that the actual curve of dielectric constant vs. the height above the ground is frequently complex with one or more sharp bends, rather than a straight line as required in using the concept of an effective earth's radius. 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 MHz height intervals of 600 to 1,500 ft. can be assumed. 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 MHz. However, as the frequency increases, the straight-line approximation is valid over smaller and smaller height intervals. At 3,000 MHz, for example, this interval is only 6 to 15 ft. and the concept of effective earth radius becomes inadequate for analytical use. The rate of decrease of time-median measurements with distance is relatively consistent with theoretical propagation over an equivalent knife edge rather than with values calculated from assumed earth-radius factors.[16]

The dielectric constant normally decreases with increasing height, k is greater than unity, and the radio waves are bent toward the earth. Since the earth's radius is about 2.1×10^7 ft., 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 becomes infinite. 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 which the ray is again bent toward the earth, and so on.[8,9,24] The radio energy is thus trapped in a duct or waveguide between the earth and the maximum height of the radio path. For low-layer heights, this phenomenon is variously known as trapping, duct transmission, anomalous propagation, or guided propagation. Elevated layers of this type at heights up to several thousand feet are believed to be responsible for the occurrence of high field strengths at distances somewhat beyond the horizon from the transmitter. Theoretical studies indicate that attainable values of dielectric variation could produce the field strengths which are usually observed at such distances for small percentages of the time.[23] Confirmation has also been obtained through simultaneous observations of radio field strengths and of meteorological conditions.[22] 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, in the lower segment of the duct the dielectric constant may decrease very slowly or may even increase, so that the waves travel upward into an upper segment in which the dielectric constant decreases more rapidly than 10^{-7} per foot and in which the waves are again refracted in a downward direction to encounter the lower segment again, after which the process is repeated. In the case of either of the two foregoing forms of ducts, if there were no losses of energy involved, the field strengths at any given distance would exceed the free-space fields, since the spread of energy is restrained in the vertical dimension. However, experience indicates that over land paths the losses are such that the received field strengths are seldom greater than the plane-earth values.[9]

Tropospheric Scatter

More recently a theory has been developed by Booker and Gordon[25,26] attributing the distant tropospheric fields to the scattering of the radio waves by atmospheric turbulence rather than by reflection from horizontal stratification. There is considerable activity, both theoretical and experimental, to determine whether elevated stratified layers, turbulence, residual effects from the normal gradients of dielectric constant, or contributions from all three, are responsible for the high field strengths beyond the line of sight, which are of concern in estimating the interference between television broadcast stations. In addition to these higher field strengths, which occur for small percentages of the time, there are rather consistent fields of about 80 dB below free space, which are largely independent of frequency. The rate of decrease for the median values of these fields is consistent with the theory of scatter from random turbulence.[22,28]

Atmospheric Fading

Variations in the received field strengths around the median value are caused by changes in atmospheric conditions. Field strengths tend to be higher in summer than in winter and higher at night than during the day for paths over land beyond the line of sight. As a first approximation, the distribution of long-term variations in field strength in decibels follows a normal probability law, as shown by graph N of Fig. 20.

Measurements indicate that the fading range reaches a maximum somewhat beyond the horizon and then decreases slowly with distance out to several hundred miles. Also the fading range at the distance of maximum fading increases with frequency, while at the greater distances where the fading range decreases, the range is also less dependent on frequency. Thus the slope of the graph N must be adjusted for both distance and frequency. This behavior does not lend itself to treatment as a function of the earth's radius factor k, since calculations based on the same range of k produce families of curves in which the fading range increases systematically with increasing distance and with increasing frequency. Methods for the statistical treatment of fading are described in Statistical Evaluation of Propagation.

Effects of the Upper Atmosphere, or Ionosphere

At the present time four principal layers or regions in the ionosphere are recognized. These are the E layer, the $F1$ layer, and the $F2$ layer, centered at heights of about 100, 200, and 300 km, respectively, and the D region, which is less clearly defined but lies below the E layer. These "regular" layers are produced by radiation from the sun, so that the ion density, and hence the frequency of the radio waves which can be reflected thereby, is higher in the day than at night. The characteristics of the layers are different for different geographic locations, and the geographic effects are not the same for all layers. The characteristics also differ with the seasons and with the intensity of the sun's radiation, as evidenced by the sunspot numbers, and the differences are generally more pronounced upon the $F2$ than upon the $F1$ and E layers. There are also certain random effects which are not fully explained. Some of these are associated with solar and magnetic disturbances. Other effects which occur at or just below the E layer have been established as being caused by meteors.

Briefly the presently recognized ionospheric effects can be grouped into seven major categories as follows: (1) D region, (2) regular E layer, (3) regular $F1$ layer, (4) regular $F2$ layer, (5) sporadic E layer, (6) meteoric, and (7) anomalous and irregular ionization. While categories (4), (5), and (6) may be expected to have some impact upon television service below 88 MHz, it is not expected to be serious. Moreover, the Rules of the FCC do not provide protection from this type of interference. For these reasons these effects will not be described in detail. A more extensive discussion, with references, appears in the Fifth Edition.

STATISTICAL EVALUATION OF PROPAGATION

In previous sections a partial statistical description has been given of the separate effects of terrain and of the variation of field strengths with time. Methods have been given for the prediction of the median field strengths to be expected for areas of size comparable to the gross features of the terrain, to which correction factors may be applied for the presence of buildings and vegetation and within which the fields may be described in terms of the strengths which are expected to be exceeded at a given percentage of locations. Alternatively, the distribution of field strengths as a function of the percentage of locations may be regarded as the probability, in percent, that a given field strength will be exceeded at a particular location within the area in question.

For the purpose of formulating a national plan for the assignment of television channels, it was felt to be impractical to consider in detail even the gross features of terrain, so that a statistical approach has been adopted to prepare families of propagation curves reflecting the median values found from all available data. Figs. 19 and 20 show the field strengths in decibels relative to 1 μv/m for 1 kw of effective radiated power to be expected at the best 50 percent of receiving locations for at least 50 percent of the time, for antenna heights from 100 to 10,000 ft. These field strengths are referred to as $F(50,50)$. The field strengths are based on an effective power of 1 kw radiated from a half-wave dipole in free space, which produces an unattenuated field strength at 1 mile of 102.8 dB above 1 μv/m (102.8 dBμ). The antenna height to be used with these charts in any particular case is the height of the center of the radiating element above the average height of the profile between 2 and 10 miles from the transmitter along the desired radial. Figs. 21 and 22 show the corresponding field strengths for 50 percent of the locations and 10 percent of the time $F(50,10)$. These families of curves, in conjunction with curve N of Fig. 20, may be used to estimate the service provided by television stations, in accordance with the following procedures. More recent propagation curves are available in FCC Report R 6602, but these have not yet been adopted into the FCC Rules.[39]

Prediction of Field Strengths for Television Service[19]

The field strengths required to provide television service are derived in the following manner: Test receivers of known characteristics as to sensitivity, selectivity, etc., are set up under typical home lighting and viewing conditions. Viewers then rate the relative acceptability of pictures at varying levels of input signals as obtained from a calibrated source, such as a television signal generator. The ratings are then analyzed statistically in terms of the percentages of viewers who rate the pictures as of a given quality, such as satisfactory, at each level of signal input. These results follow the normal probability law of curve N. It is impractical to satisfy 100 percent of viewers and values satisfying 50 to 70 percent are usually adopted for broadcast purposes. From the signal level thus selected and the known bandwidth and noise characteristics of the receiver, a required signal-to-noise ratio is determined. The required instantaneous fields F' to provide service of this quality are then derived by applying the proper values for the receiver-noise figure and the antenna and transmission line characteristics of the typical receiver installation. Similar procedures are used for deriving the desired to undesired ratio for various types of interfering signals. For this purpose the undesired signal is also fed into the receiver input in various ratios and at various frequencies in relation to the desired signal.[39]

The service at a particular location is said to be satisfactory if the minimum required field F', as above determined, is exceeded for some agreed percentage of the time T, such as 90 percent. This may be expressed as a T percent field strength $F'(T)$. The required time median field $F'(T = 50)$ to provide the minimum field for the desired percentage of time $F'(T)$ is given by the equation

$$F'(T) = F'(T = 50) + N'(T) \qquad [12]$$

$N'(T)$ is the time distribution factor in decibels for T percent of the time. This factor is assumed to be independent of location so that Eq. 12 can also be written

$$F'(L,T) = F(L,50) + N'(T) \qquad [12a]$$

and

$$F'(50,10) = F(50,50) + N'(T = 10) \qquad [12b]$$

Thus $N'(T = 10)$ can be determined for various frequencies, distances, and antenna heights, using the appropriate values of $F(50,10)$ shown in Fig. 18 and 19 and of $F(50,50)$ shown in Figs. 16 and 17. The distributions of field strengths for waves propagated via the troposphere are highly variable. For short periods of time during which the characteristics of the troposphere do not vary materially and the variation is due mainly to wave interference, the distribution may approach the Rayleigh distribution shown in curve R of Fig. 20. For longer periods of time the distributions of instantaneous values and of hourly median values assume complex forms of which the curve T of Fig. 20 is characteristic. Since the field strengths from which the curve was constructed have contributions from various modes of propagation and since the shape of the curve varies with such parameters as frequency, distance, transmitting antenna height, receiver location, etc., an exact expression is not

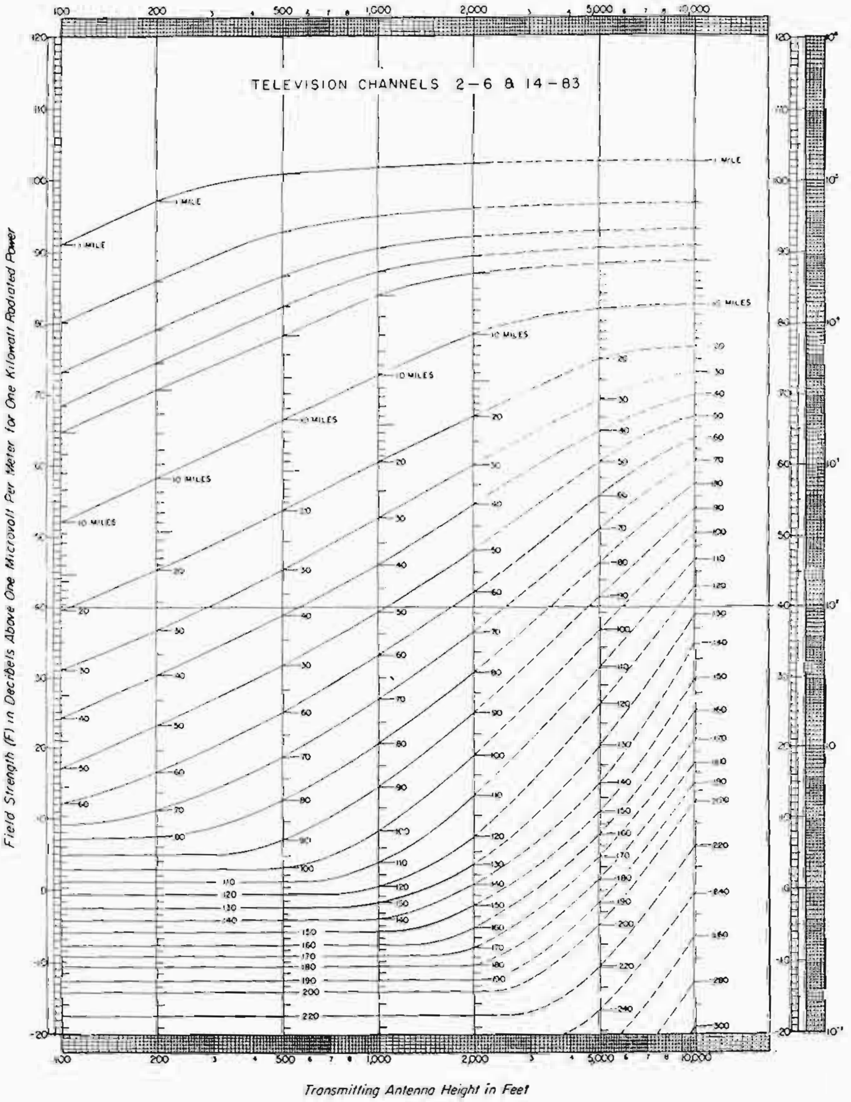


Fig. 16. $F(50,50)$ for television Channels 2 to 6, 14 to 83.

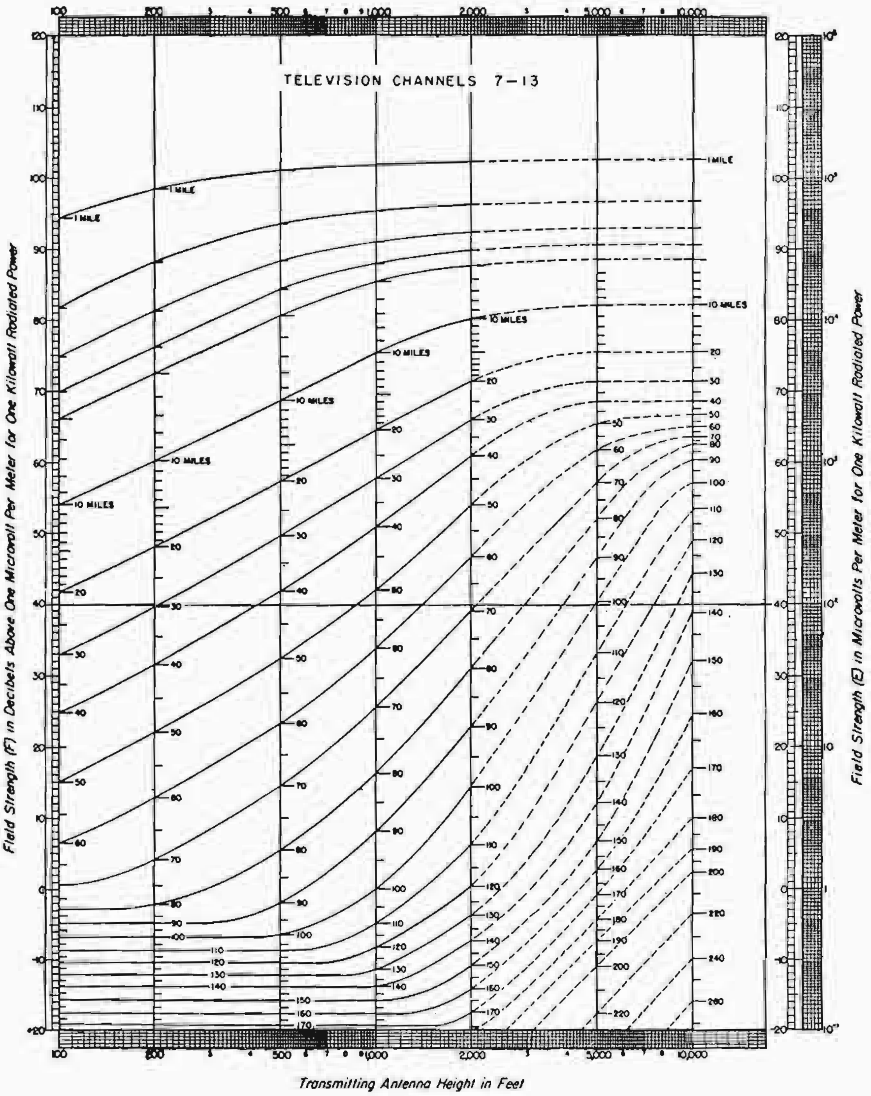


Fig. 17. $F(50,50)$ for television Channels 7 to 13.

possible. However, the curve is sufficiently close to the log normal curve N, so that with attention to the proper slope as determined by the appropriate value of $N'(T = 10)$, a log normal distribution can be used for the purposes of estimating service and interference. Thus $N'(T)$ for values of T other than 10 percent can be approximated by the formula

$$N'(T) = N'(T = 10)\,\frac{N(T)}{N(T = 10)} \qquad [13]$$

The percentage of locations L or the percentage probability L that the received fields $F'(L,T)$ will exceed the required T percent fields $F'(T)$ at a particular location within the area may be determined by the formula

$$N'(L) = F'(L,T) - P' - F(50,50) - N'(T) \qquad [14]$$

where $N'(L)$ is the location distribution factor in dB for L percent of locations or L percent probability at a particular location. For VHF television Channels 2 to 13, $N'(L)$ is equal to 0.53 times the values given by the normal probability curve N of Fig. 20, or $N'(L) = 0.53\ N(L)$. For UHF Channels 14 to 83

$$N'(L) = 0.75\,N(L)$$

$F'(L,T)$ is the minimum field strength, in dBμ, to be expected at the best L percent of locations for at least T percent of the time. P' is the effective radiated power in dB relative to 1 kw (dBk) radiated from a half-wave dipole. $F(50,50)$ is the median value of field strength in dBμ for an effective radiated power of 0 dBk for the area in question, as taken from Fig. 16 or 17, for the appropriate frequency, distance, and transmitting antenna height.

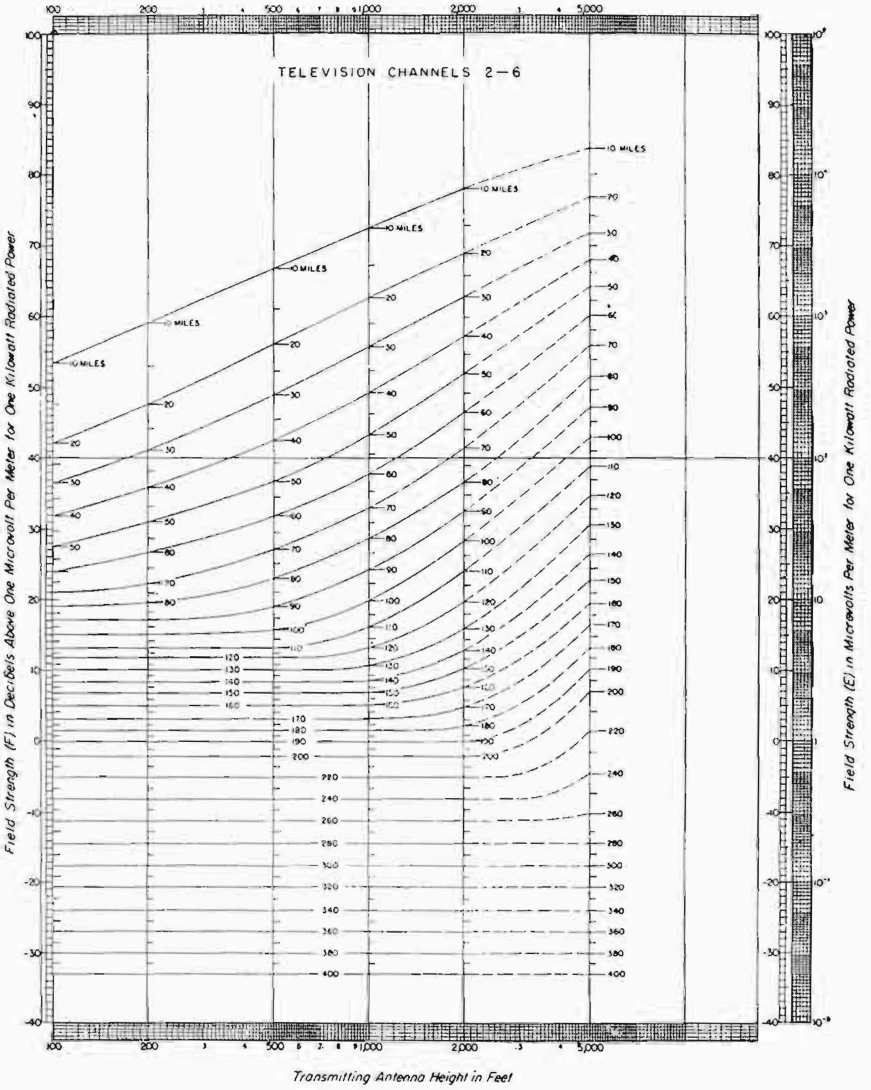


Fig. 18. *F* (50,10) for television Channels 2 to 6.

Example: For a television station operating on Channel 2, with an effective radiated power of 100 kw (20 dBk) and an average transmitting antenna height of 500 ft. for 2 to 10 miles along the radial, what percentage of locations in area 20 miles from the transmitter may be expected to have field strengths exceeding 74 dBμ for at least 90 percent of the time?

$$F'(L,90) = 74 \text{ dB}\mu$$
$$P' = 20 \text{ dBk}$$
$$F(50,50) = 54 \text{ dB}\mu \text{ (from Fig. 16)}$$
$$F(50,10) = 56 \text{ dB}\mu \text{ (from Fig. 18)}$$
$$N'(T=10) = 56 - 54 = 2 \text{ dB (from Eq. 12b)}$$
$$N'(T=90) = \frac{2(-20)}{20} = -2 \text{ dB (from Fig. 20 and Eq. 13)}$$

Substituting in Eq. 14

$$N'(L) = 74 - 20 - 54 - (-2) = +2$$
$$N(L) = \frac{N'(L)}{0.53} = 3.8$$
$$L = 41 \text{ percent (from Fig. 20)}$$

Several points at various distances along each radial can be calculated in the above manner and the distance at which desired percentages of locations, or desired probabilities, such as 50, 70, 90 percent, etc., occur may be determined by interpolation. Isoservice contours may be drawn by connecting the points having the same probability on each of the several radials.

Some analyses have been made of this problem using different characteristic slopes for values of T above and below 50 percent. Since values of T between 10 and 90 percent are usually of principal interest for broadcast purposes, a closer fit to the curve T can be made by this method within the range of interest.

Prediction of Service in the Presence of Interference from One Undesired Station[19]

The percentage of receiving locations, or the probability in percentage of L, at any given distance

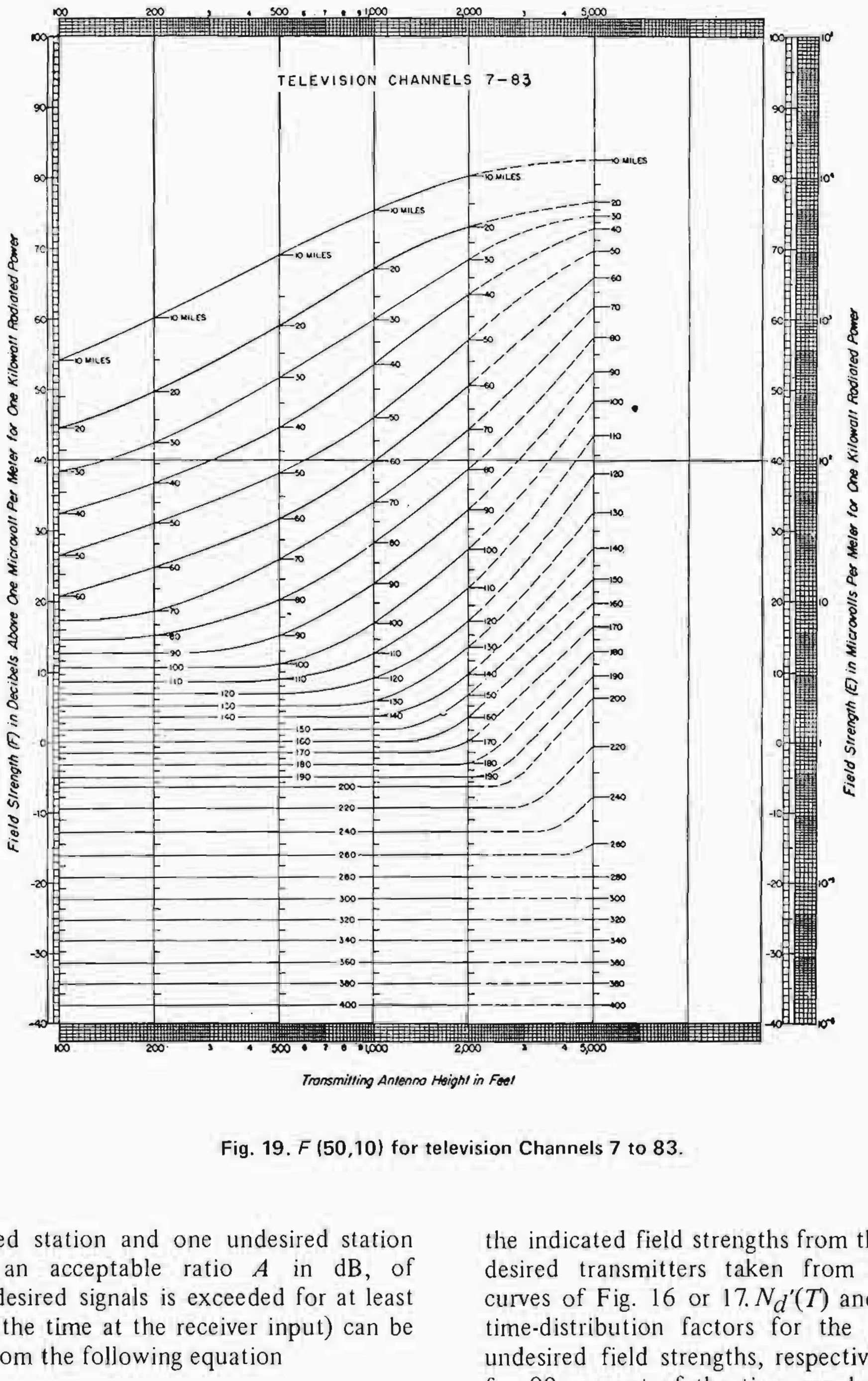


Fig. 19. *F* (50,10) for television Channels 7 to 83.

from a desired station and one undesired station (for which an acceptable ratio A in dB, of desired-to-undesired signals is exceeded for at least T percent of the time at the receiver input) can be determined from the following equation

$$n'(L) = A + P_u' - P_d' + g_{ru} - g_{rd} + F_u(50{,}50) - F_d(50{,}50) + \sqrt{N_d'(T)^2 + N_u'(T)^2} \quad [15]$$

The subscript d denotes values applicable to the desired signal, and the subscript u denotes values applicable to the undesired signal. As above, the effective radiated powers of the desired and undesired station in P_d' and P_u' are expressed in dB above 1 kw radiated from a half-wave dipole. g_{ru} and g_{rd} are, respectively, the gains of the receiving antenna in the directions of the undesired and the desired transmitters. $F_u(50{,}50)$ and $F_d(50{,}50)$ are the indicated field strengths from the undesired and desired transmitters taken from the appropriate curves of Fig. 16 or 17. $N_d'(T)$ and $N_u'(T)$ are the time-distribution factors for the desired and the undesired field strengths, respectively. The factors for 90 percent of the time can be determined by subtracting the (50,10) field strength from the (50,50) field strength for each station at the proper distances on the appropriate curves of Figs. 16 to 19, in accordance with Eq. 12b. The factors for any other desired percentage of time may be found by the use of Eq. 13 and curve N of Fig. 20.

The answer for the factor $n'(L)$ is obtained in dB. For Channels 2 through 13, $n'(L) = 0.75\ N(L)$ and the percentage of locations at which the ratio A is exceeded may be read from the probability distribution, $N(L)$, as a function of L in Fig. 20. For Channels 14 through 83, $n'(L) = 1.05N(L)$.

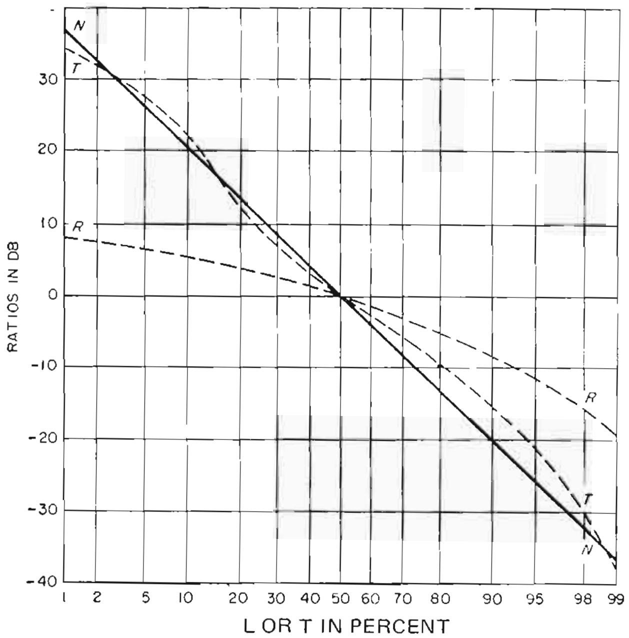


Fig. 20. Time and location distributions.

It will be seen from Eq. 15 that the time-distribution factor applicable to two fading signals combines as the root sum square of the individual factors. When the fading of the undesired signal is three or more times the fading of the desired, the latter fading may be neglected with negligible error. Thus, the charts for the desired signal $F(50,50)$ and the tropospheric charts $F(50,10)$ for the undesired, with appropriate corrections for the effective radiated powers of the two stations and the directional patterns of the receiving antennas, can be used to determine directly the isoservice contours for 90 percent of the time and 50 percent of the locations.

The approximate method, in which the fading of the desired signal is neglected, can be expressed in the following formula:

$$n'(L) = A + P_u' - P_d' + g_{ru} - g_{rd} + F_u(50,10) - F_d(50,50) \quad [16]$$

This formula permits the approximate method to be applied to the case where it is desired to locate the contour at which an acceptable ratio is exceeded for a percentage of the locations other than 50 percent.

Prediction of Service in the Presence of Interference from Several Sources

This problem was studied by the Ad Hoc Committee and four methods of calculating the combined effects of several interfering signals were reported in vol. 2 of the report of the Committee.[11] The methods involve somewhat different assumptions as to the subjective effects of interference and as to the time and space correlations of the various signals. Reference should be made to that report for details as to the assumptions made and the limitations involved in each method. The application of three of these methods is somewhat tedious, and since the results obtained by all four methods are reasonably consistent, just one relatively simple method will be described in detail.

This method involves the conclusion that the probability of a receiving location receiving satisfactory service for a particular percentage of time in the presence of a plurality of interfering signals is equal to the product of the probabilities that satisfactory service will be received for the same percentage of time in the presence of each of the interfering signals alone. Thus the values of $n'(L)$ for the desired signal and each of the interfering signals are computed individually from Eq. 15 or 16, and the resulting probability found by multiplying the individual values together. Take as an example the case of two interfering signals, the first of which yields a location probability of 0.90 (90 percent of the locations), and the second of which yields a location probability of 0.70, at a given point. The probability of receiving satisfactory service of the same time availability at the same point is 0.90 X 0.70 = 0.63, or 63 percent.

Distribution and Summation of Service

The method of describing service areas by isoservice contours, while relatively simple and useful for some purposes, is in fact a rather incomplete method which may lead to erroneous conclusions unless applied with understanding. Contours are frequently used to describe the outer limits of recognized grades of service for administrative purposes. The treatment of an isoservice contour as a limit of service, rather than as a contour of equal service availability, leads to errors in estimating service availability as well as the number of people who are expected to receive service. The foregoing analysis shows that in any small area only a percentage of the residents is expected to have service of a given quality available and assuming that a typical receiving set and antenna will be used, only a percentage of the population, rather than the total population of the area, should be included in a population count. Also, the percentage varies from area to area within the contour, increasing generally with decreasing distance from the desired transmitter, so that to obtain a fairly reliable count, variable percentages should be used for different areas.

As the distance from the desired transmitter increases, the quality of available service does not change abruptly as might be inferred from the drawing of service contours but shades gradually from service of generally high quality to service of low quality. Thus it is proper to represent the expected quality of service as a continuous function of distance. Fig. 21 shows the percentages of locations at various radii from a television station, at 63 MHz, with 100 kw ($P' = 20$ dBk) radiated from a 500-ft. antenna, which would be expected to receive service for at least 90 percent of the time in the presence of receiver and cosmic noise only. In Fig. 22 the percentages of locations in each annular ring at the radius r from the transmitter have been multiplied by the area of the ring, to produce service distributions in terms of integrated service area Y, as a function of distance from the transmitter. The thickness of each ring has been taken as $1/2\pi$ so that the ring area is equal to the radius in each case. The curve labeled $P' = 20$ dBk corresponds to the conditions of Fig. 21. Curves for powers of $P' = 0$ dBk, $P' = 10$ dBk, and $P' = 30$ dBk are also shown to illustrate how the service varies with changes in the effective radiated power. In order to estimate the equivalent service area provided by the station, the area under the curve is integrated by the use of a planimeter or in accordance with the formula

$$\text{Service area} = 2\pi \int_0^\infty Yr\,dr$$

As an additional step, the integrated service area may be represented graphically by a circle of equivalent radius. These radii are indicated for each power on Fig. 22 by the dashed lines labeled d_{SO}.

A similar approach can be used for cases in which it is desired to estimate the resulting service areas in the presence of interference from other television stations and other sources. Needless to say, the procedure becomes exceedingly complex in particular cases where there is a lack of symmetry between the sources of interference and the various radials along which service is to be estimated. In addition, as stated above, the available propagation data are subject to large probable errors when used to estimate service for any particular station. For these reasons, application of the procedures has so far been limited to broad studies of channel utilization, which are useful in developing station assignment plans and rules.

As illustrative of the methods of estimating service in the presence of several sources of interference, assume a case in which co-channel and adjacent-channel stations are assigned in a saturated triangular lattice, as shown in the inset of Fig. 23. The probability of receiving service of a given quality for a specified percentage of time from the desired station in the presence of the several sources of interference can be calculated for particular receiving locations along a radial in accordance with

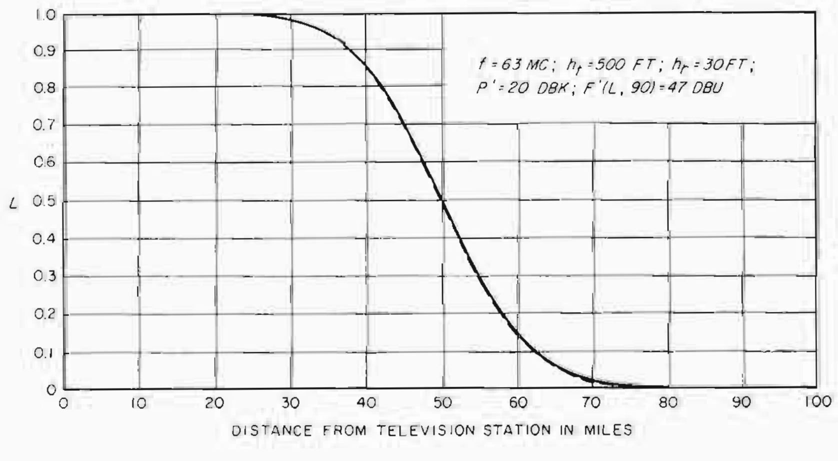


Fig. 21. Distribution of noise-limited service probability.

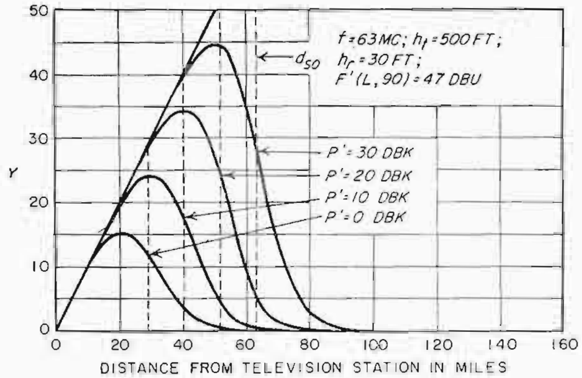


Fig. 22. Distribution of noise-limited service.

the four methods. The resulting distributions are shown in Fig. 23. Fig. 24 shows the corresponding area probability and total areas for the four methods. It can be seen that the simple method described in Appendix C of vol. 2 of the Ad Hoc Report, and described previously herein, yields smaller estimates of service than do the other three methods.

Using this concept of total area it is possible to estimate the probable efficiency of utilization of the available television channels for various combinations of station power, antenna heights, and station spacings. While it is known that as a practical matter the station assignment pattern will follow the pattern of cities rather than the idealized and somewhat more efficient lattice, from the standpoint of area coverage, useful conclusions as to station-spacing requirements have been drawn from such studies.[19] Subsequent studies, however, by the Television Allocations Study Organization (TASO)[37] have indicated that some modification of the concept of using a standard receiving installation is appropriate for studies such as the foregoing. That within reasonable limits the quality of the receiving installation will be upgraded to the point where the observer is receiving a picture which he considers to be satisfactory. This tends to flatten out the lower end of the location distribution curve as well as the rate of decay in picture quality with increasing distance from the transmitter, with a more rapid decay as the locations of very poor signal are reached, at which it is no longer economically feasible to upgrade the installation to the extent required. This effect tends to increase the validity of the use of field strength contours to specify service limits.

SELECTION OF STATION SITES

The sites for the antennas of permanent relay stations and for television broadcast stations should be selected carefully, as the success of the operation depends to a great extent upon the care and foresight used in selecting the sites. In previous sections, quantitative information has been given which will assist in estimating the transmission loss incurred over television relay links under specified conditions and in estimating the probable service obtained from a television broadcast station. The purpose of this section is to give a few guides which engineers have found to be of assistance in selecting sites which will yield optimum results for the area in question.

Selection of Sites for Radio Relay Stations

A large amount of preliminary work is necessary in laying out a radio relay system. For microwave

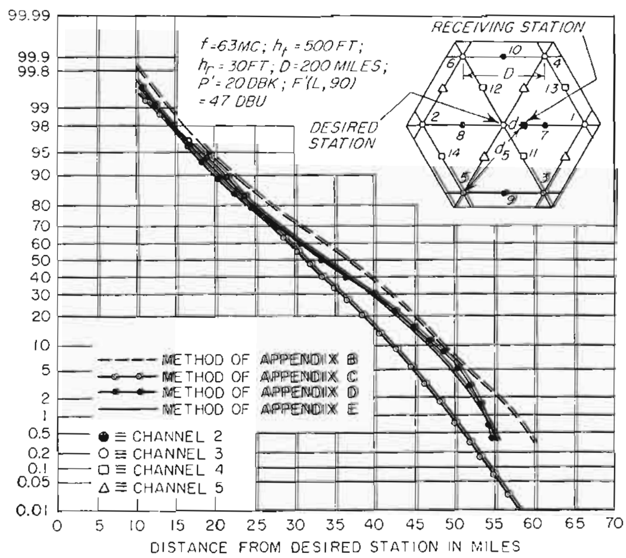


Fig. 23 Distribution of service probability limited by interference.

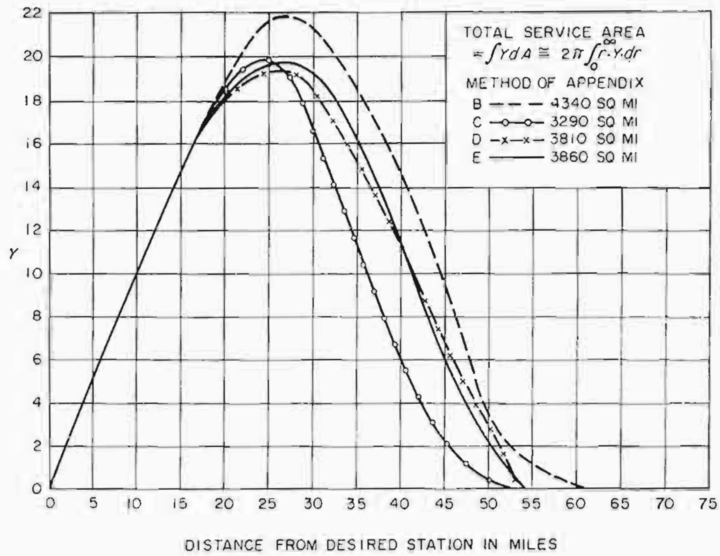


Fig. 24. Distribution of service limited by interference.

systems it is usual that adjacent sites have a clear line-of-sight path between their antennas. To determine station locations, the best available topographical maps should be used. These, however, usually will not be adequate for final station location, particularly since for some areas no maps are available and for others existing maps may be found to be inaccurate. In some cases, aerial surveys have been used. Before finally selecting a site, radio transmission tests should be made with the adjacent sites. For these tests, portable towers with parabolic antennas and transmitters mounted on carriages which can be moved up and down the towers are used.

If the intervening terrain is rough and the intermediate clearances satisfactory, no large change in received signal will be found as the antennas are raised and lowered on the towers, until the antennas are lowered so far that clearance of the first Fresnel zone no longer exists.

In some cases, however, substantial earth reflection may be encountered, and this will be evidenced by substantial variations in received signal strength as the antennas travel up and down. It is desirable that transmission be largely confined to a single ray arriving from the distant station. If one or more additional rays are present, owing to reflection from the earth at some intervening point or points, the resultant signal will be that due to the combination of rays and will depend on their relative phase relations. Sites showing such earth reflection are not desirable, as substantial amounts of fading may be expected at times when changes in the atmosphere cause the amount of bending of the waves to change with consequent changes in phase relation of the arriving rays. If such variations are observed in these path tests, the intervening terrain should be inspected with a view to determining whether by moving one or both sites a short distance the reflecting earth surface can be avoided.

It is usually difficult to recognize the areas which are responsible for earth reflection, but a few guides can be given to assist in inspection at the site. If the suspected area is fairly flat, areas of a size equivalent to an ellipse capable of reflecting the wavefront over the first Fresnel zone should be inspected. Smaller areas are capable of supporting a reflection, but in general the strength of the reflected component will be decreased. When the intervening area is rolling or irregular, the determination of the location and size of the responsible area is still more difficult. It will also be necessary to decide whether the surface roughness is too great to support reflection at the frequency of interest. For this purpose, Rayleigh's criterion of roughness is used. The surface is considered to be smooth if $h \sin \theta < \lambda/8$, where h is the average height of the features of roughness, θ is the angle of incidence of the wave to the reflecting surface, and λ is the wavelength expressed in the same units as h.

In one case where transmission was to take place over extensive salt flats which are smooth and of high conductivity, it was not possible to avoid earth reflection by any reasonable change in the station locations. The fading due to such reflection was minimized in this case by employing very low antennas at one end of the section and high mountain-top antennas at the adjacent station. With this arrangement, the earth-reflection point was close to one of the stations thereby minimizing the change in phase relations between the direct and reflected rays during periods of varying transmission conditions.[17]

Selection of Sites for Television Broadcast Stations

Sites for the antennas of television broadcast stations should be so chosen that at least first Fresnel-zone clearance is obtained over all near obstructions in the directions of the areas to be served. Thus hills with gentle slopes or with foothills which prevent such clearance should be avoided. Not only will the field strengths be reduced in the shadows of foothills and along the slope of the hill, owing to the low height of the antenna above the effective plane of reflection, but also nonuniform fields and ghosts may occur in distant areas which are within the line of sight of the transmitting antenna. Similarly, sites in the midst of tall buildings should be avoided unless the antenna can be placed well above them.

If relief maps of the proposed site are available or can be made, small grain-of-wheat lamps placed at the antenna location will assist in locating shadowed areas. Both theory and experience indicate that the radio shadows are of lesser length than the optical shadows.[37]

Profiles, taken from topographic maps, should be drawn for at least eight radials from the antenna site, and for any additional radials which from inspection appear to present particular problems, in the manner shown in Fig. 11. Estimates of the areas of service should be made, both by the above methods and the methods provided by the Rules of the FCC.[40]

In doubtful areas, actual measurements should be made over these radials, either from existing transmitters at or near the chosen site which have frequencies near the chosen frequency or from test transmitters installed for the purpose. If test transmitters are pulsed and mobile measurements are to be made, the pulse repetition rate should be sufficiently rapid so that the peak detector of the field-strength meter can distinguish between the pulse peaks and the peaks caused by standing-wave patterns through which the meter will pass. Otherwise the meter will indicate the peaks of such standing-wave patterns rather than the desired average value which is indicative of the strength of the incident fields.

There is as yet no unanimity among engineers as to the preferred method of making field-strength surveys for television broadcast stations. Because of the relative ease and dispatch with which the area may be covered, some prefer the taking of mobile measurements with a simple nondirectional antenna mounted on the vehicle at about 10 ft. above ground. Because of the difficulty of estimating height gain and antenna gain of the typical receiving antenna in a typical location as compared with the simple mobile measuring antenna under the nonideal conditions to be found in all service areas, many engineers prefer to obtain relatively fewer measurements under conditions which they consider to be more nearly typical for broadcast receiving installations. For this purpose a collapsible mast carrying a typical antenna is mounted on a vehicle and measurements are made at various accessible locations along each of the radials. Several techniques have been employed with this type of measuring equipment: (1) maintaining the antenna at a fixed height during a short run,[33] (2) clusters of spot-sampling measurements with the antenna at a fixed height,[34] or (3) moving the antenna vertically at a fixed location.[20] All three techniques have specific advantages and disadvantages. Spot sampling, which is most nearly analogous to the typical receiver situation, also presents the most difficulty in obtaining a significant sampling of the existing fields. All measurements should be made in accordance with the standards of the Institute of Radio Engineers.[41]

REFERENCES

1. Kraus, J. D.: "Antennas," 1st ed., McGraw-Hill Book Company, Inc., 1950.
2. Reference Data for Radio Engineers, 4th ed., Federal Telephone and Radio Corporation, 1956.
3. Eckersley, T. L.: Ultra-short-wave Refraction and Diffraction, *J. Inst. Elec. Engrs.*, p. 286, March, 1937.
4. van der Pol, Balth, and H. Bremmer: The Diffraction of Electromagnetic Waves form an Electrical Point Source Round a Finitely Conducting Sphere, with Applications to Radiotelegraphy and to Theory of the Rainbow, part 1, *Phil. Mag.*, July, 1937; part 2, *Phil. Mag.*, November, 1937.
5. Norton, K. A.: The Propagation of Radio Waves over a Finitely Conducting Spherical Earth, *Phil. Mag.*, June, 1938.
6. Burrows, C. R., and M. C. Gray: The Effect of the Earth's Curvature on Groundwave Propagation, *Proc. IRE*, p. 16, January, 1941.
7. Norton, K. A.: Ground Wave Intensity over a Finitely Conducting Spherical Earth, *Proc. IRE*, p. 623, December, 1941.
8. "The Propagation of Radio Waves through the Standard Atmosphere," Summary Technical Report of the Committee on Propagation, vol. 3, National Defense Research Council, Washington, D.C., 1946, published by Academic Press.
9. Bullington, K.: Radio Propagation at Frequencies above 30 Mc, *Proc. IRE*, p. 1122, October, 1947.
10. "Radio Wave Propagation," Summary Technical Report of the Committee on Propagation of the National Defense Research Committee, Academic Press, Inc., New York, 1949.

11. de Lisle, E. W.: "Computations of VHF and UHF Propagation for Radio Relay Applications," RCA, Report by International Division, New York.
12. Selvidge, H.: Diffraction Measurements at Ultra High Frequencies, *Proc. IRE,* p. 10, January, 1941.
13. McPetrie, J. S., and L. H. Ford: An Experimental Investigation on the Propagation of Radio Waves over Bare Ridges in the Wavelength Range 10 cm. to 10 m, *J. Inst. Elec. Engrs.,* part 3, vol. 93, p. 527, 1946.
14. Megaw, E. C. S.: Some Effects of Obstacles on the Propagation of Very Short Radio Waves, *J. Inst. Elec. Engrs.,* part 3, vol. 95, no. 34, p. 97, March, 1948.
15. Dickson, F. H., J. J. Egli, J. W. Herbstreit, and G. S. Wickizer: Large Reductions of VHF Transmission Loss and Fading by the Presence of a Mountain Obstacle in Beyond-Line-of-Sight Paths, *Proc. IRE,* vol. 41, no. 8, p. 96, August, 1953.
16. Bullington, K.: Radio Propagation Variations at VHF and UHF, *Proc. IRE,* p. 27, January, 1950.
17. CCIR: Documents of the XIth Plenary Assembly, Oslo, 1966; vol. 2, Propagation; Recommendation 370-1; Reports 228-1, 239-1, 244-1, and 264-1.
18. Young, Jr., W. R.: Comparison of Mobile Radio Transmission at 150, 450, 900 and 3700 Mc, *Bell System Tech. J.,* p. 1068, November, 1952.
19. "Report of the Ad Hoc Committee, Federal Communications Commission," vol. 1, May, 1949; vol. 2, July, 1950.
20. Epstein, J., and D. Peterson: An Experimental Study of Wave Propagation at 850 Mc, *Proc. IRE,* p. 595, May, 1953.
21. Smith-Rose, R. L.: A Survey of British Research on Wave Propagation with Particular Reference to Television, *J. Inst. Elec. Engrs.,* part 3A, vol. 99, no. 18, p. 270, 1952.
22. Schelling, J. C., C. R. Burrows, and E. B. Ferrell: *Proc. IRE,* pp. 427-463, March, 1933.
23. Norton, K.: "A Theory of Tropospheric Wave Propagation," FCC Technical Research Division, Report No. 40003, March, 1940.
24. "Tropospheric Propagation and Radio-Meteorology," Central Radio Propagation Laboratory, CRPL-T3, October, 1946.
25. Booker, H. G.: "Elements of Radio Meteorology," *J. Inst. Elec. Engrs.,* part 3A, vol. 93, no. 1, p. 69, 1946.
26. Booker, H. C., and W. E. Gordon: A Theory of Radio Scattering in the Troposphere, *Proc. IRE,* p. 401, April, 1950.
27. Gordon, W. E.: "The Scattering on Radio Waves by Turbulence in the Troposphere," Cornell University Research Report EE 163, September, 1953.
28. Herbstreit, J. W., K. A. Norton, P. L. Rice, and G. E. Schafer: Radio Wave Scattering in Tropospheric Propagation, *Conv. Rec. IRE,* part 2, pp. 85-93, 1953.
29. Barsis, Bean, Herbstreit, Hornberg, and Norton: Propagation of Radio Waves over Land at 1046 Mc, *Natl. Bur. Standards Rept.* 2494.
30. Rice, Longley, Norton, and Barsis: "Transmission Loss Predictions for Tropospheric Communication Circuits," National Bureau of Standards Technical Note 101 (Rev.).
31. "The Effect of Irregular Terrain and Atmospheric on Correlation between Transmission Loss Values," ESSA Report ERL 84.
32. Bean, B. R., and E. J. Dutton: "Radio Meteorology," National Bureau of Standards Monograph 92.
33. Taylor, J. P.: UHF in Portland, *Broadcast News,* p. 16-33, September-October, 1952.
34. Taylor, J. P. More Reports on UHF Coverage, *Broadcast News,* pp. 8-11, January-February 1953.
35. Fink, D. G., J. V. L. Hogan, E. K. Jett, P. F. Siling, and D. B. Smith: Comments on the Proposed Allocation of Television Broadcast Services, *Proc. JTAC,* vol. 4, Sept. 26, 1949.
36. "Radio Spectrum Utilization," Report of the Joint Technical Advisory Committee of the IEEE and EIA. (IEEE 345˙E. 47 St., NYC)
37. "Engineering Aspects of Television Allocations" (with supplement), Report of the Television Allocations Study Organization to the FCC.
38. Waldo, G. V.: "Analysis of Measurements and Observations, NYC UHF-TV Project," FCC Report No. R-6303.
39. Damelin, Daniel, Fine, and Waldo: "Development of VHF and UHF Propagation Curves for TV and FM Broadcasting," FCC Report No. R-6602.
40. Federal Communications Commission, Rules and Regulations, Section 3.683(*d*).
41. Standards on Radio Wave Propagation, Measuring Methods, *Proc. IRE.* 1942.