Chapter

1.2

Propagation

William Daniel, Edward W. Allen, Donald G. Fink

1.2.1 Introduction

The portion of the electromagnetic spectrum commonly used for radio transmissions lies between approximately 10 kHz and 40 GHz. The influence on radio waves of the medium through which they propagate is frequency-dependent. The lower frequencies are greatly influenced by the characteristics of the earth's surface and the ionosphere, while the highest frequencies are greatly affected by the atmosphere, especially rain. There are no clear-cut boundaries between frequency ranges but instead considerable overlap in propagation modes and effects of the path medium.

In the U.S., those frequencies allocated for broadcast-related use include the following:

- 550–1640 kHz: AM radio
- 54–72 MHz: TV channels 2–4
- 76–88 MHz: TV channels 5–6
- 88–108 MHz: FM radio
- 174–216 MHz: TV channels 7–13
- 470–806 MHz: TV channels 14–69
- 0.9–12.2 GHz: nonexclusive TV terrestrial and satellite ancillary services
- 12.2–12.7 GHz: direct satellite broadcasting
- 12.7–40 GHz: nonexclusive direct satellite broadcasting

1.2.2 Propagation in Free Space

For simplicity and ease of explanation, propagation in space and under certain conditions involving simple geometry, in which the wave fronts 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 are often 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 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 and W is represented in W/m^2. 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 density W. The power density is equal to the square of the field strength divided by the impedance of the medium, so for free space

$$W = \frac{E_o^2}{120\pi} \tag{1.2.1}$$

and

$$P_t = \frac{4\pi r^2 E_o^2}{120\pi} \tag{1.2.2}$$

or

$$P_t = \frac{r^2 E_o^2}{30} \tag{1.2.3}$$

Where:
P_t = watts radiated
E_o = the free space field in volts per meter
r = the radius in meters

A more conventional and useful form of this equation, which applies also to antennas other than isotropic radiators, is

$$E_o = \frac{\sqrt{30 g_t P_t}}{r} \tag{1.2.4}$$

where g_t is the power gain of the antenna in the pertinent direction compared to 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 that 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

$$E_o = \frac{\sqrt{45P_t}}{r} \tag{1.2.5}$$

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

$$E_o = \frac{7\sqrt{P_t}}{r} \tag{1.2.6}$$

From the foregoing equations it can be seen that for free space:

- 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.
- The electric field strength is proportional to the square root of the radiated power and inversely proportional to the distance from the radiator.

1.2.2a Transmission Loss Between Antennas in Free Space

The maximum useful power P_r that can be delivered to a matched receiver is given by [1]

$$P_r = \left(\frac{E\lambda}{2\pi}\right)^2 \frac{g_r}{120} \text{ W} \tag{1.2.7}$$

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 relationship between received power and the received field strength is shown by scales 2, 3, and 4 in Figure 1.2.1 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/m is 95 dB below 1 W.

A general relation for the ratio of the received power to the radiated power obtained from Equations (1.2.4) and (1.2.7) is

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi r}\right)^2 g_t g_r \left(\frac{E}{E_o}\right)^2 \tag{1.2.8}$$

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

$$\frac{P_r}{P_t} = \left(\frac{1.64\lambda}{4\pi r}\right)^2 \left(\frac{E}{E_o}\right)^2 = \left(\frac{0.13\lambda}{r}\right)^2 \left(\frac{E}{E_o}\right)^2 \tag{1.2.9}$$

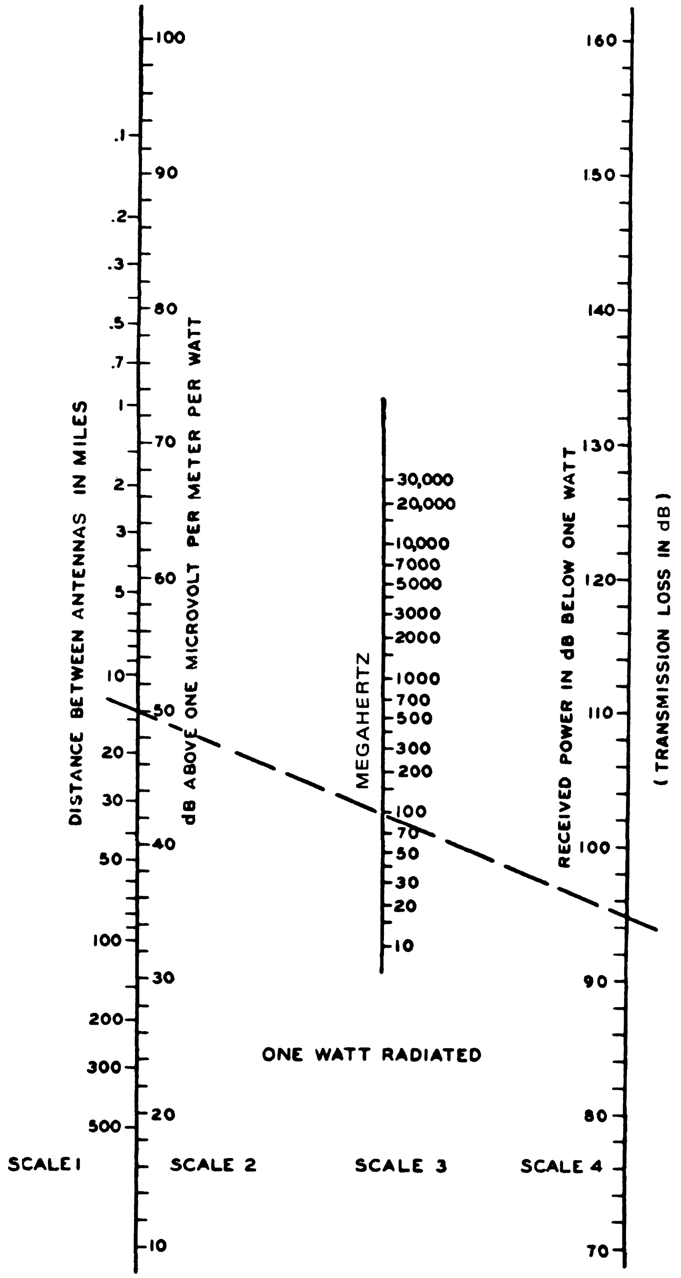

Figure 1.2.1 Free-space field intensity and received power between half-wave dipoles. (*From* [2]. *Used with permission.*)

and is shown on scales 1 to 4 of Figure 1.2.2. For free-space transmission, $E/E_o = 1$.

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

$$\frac{P_r}{P_t} = \frac{B_t B_r}{(\lambda r)^2}\left(\frac{E}{E_o}\right)^2 \quad (1.2.10)$$

where B_t and B_r are the effective areas of the transmitting and receiving antennas, respectively. This relation is obtained from Equation (1.2.8) by substituting as follows

$$g = \frac{4\pi B}{\lambda^2} \quad (1.2.11)$$

This is shown in Figure 1.2.2 for free-space transmission when $B_t = B_r$. For example, the free-space loss at 4000 MHz between two antennas of 10 ft^2 (0.93 m^2) effective area is about 72 dB for a distance of 30 mi (48 km).

1.2.3 Propagation Over Plane Earth

The presence of the ground modifies the generation and propagation of radio waves so that the received field strength is ordinarily different than would be expected in free space [3, 4]. The ground acts as a partial reflector and as a partial absorber, and both of these properties affect the distribution of energy in the region above the earth.

1.2.3a 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 Figure 1.2.3. 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 [4, 5]

$$E = \frac{E_o d}{r_1} + \frac{E_o d R e^{j\Delta}}{r_2} = E_o(\cos\theta_1 + R\cos\theta_2 e^{j\Delta}) \quad (1.2.12)$$

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

$$E = E_o(\cos^3\theta_1 + R\cos^3\theta_2 e^{j\Delta}) \quad (1.2.13)$$

Where:

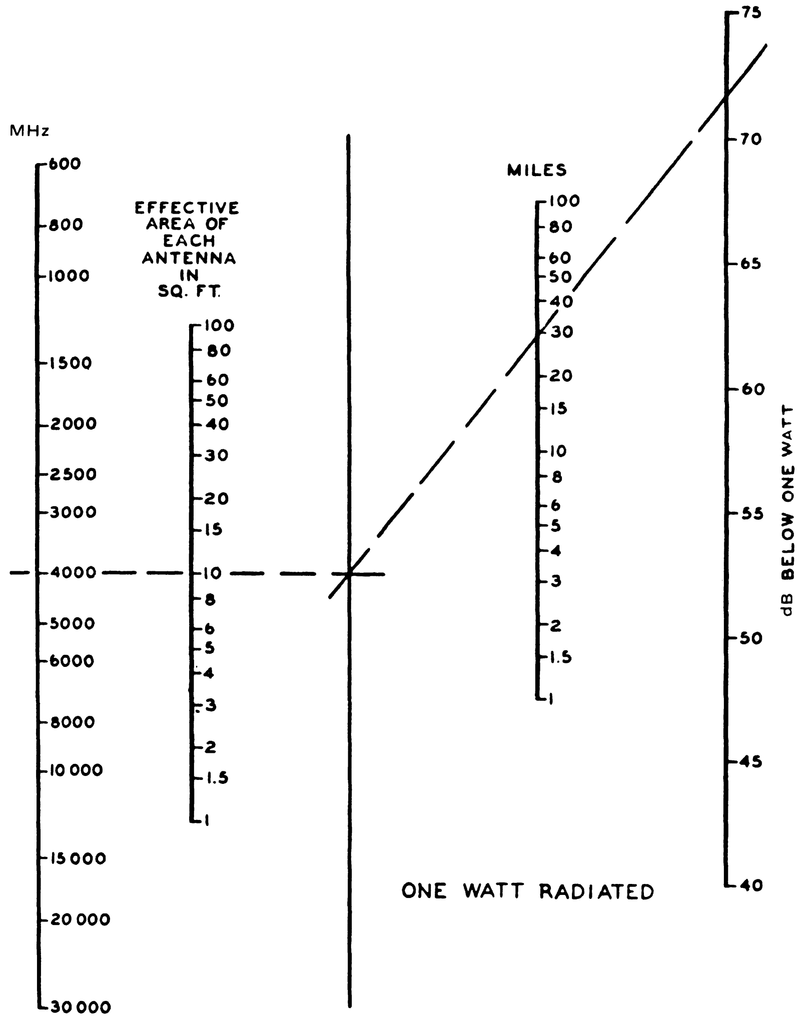

Figure 1.2.2 Received power in free space between two antennas of equal effective areas. (*From* [2]. *Used with permission.*)

E_o = the free-space field at distance d in the equatorial plane of the doublet
R = the complex reflection coefficient of the earth
j = the square root of -1
$e^{j\Delta} = \cos \Delta + j \sin \Delta$
Δ = 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

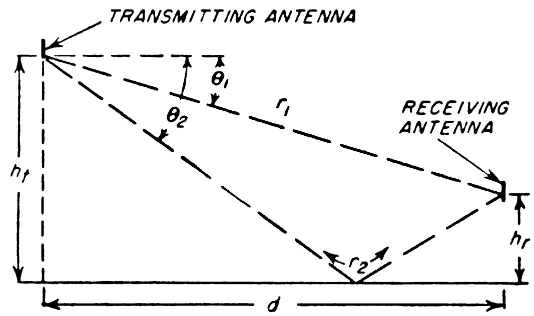

Figure 1.2.3 Ray paths for antennas above plane earth. (*From* [2]. *Used with permission.*)

For distances such that θ is small and the differences between d and r_1 and r_2 can be neglected, Equations (1.2.12) and (1.2.13) become

$$E = E_o(1 + Re^{j\Delta}) \qquad (1.2.14)$$

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 and Equation (1.2.14) becomes [3, 6]

$$E = E_o[1 + Re^{j\Delta} + (1 - R)Ae^{j\Delta}] \qquad (1.2.15)$$

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 [1]

$$A \cong \frac{-1}{1 + j\left(\frac{2\pi d}{\lambda}\right)(\sin\theta + z)^2} \qquad (1.2.16)$$

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 [3] where, in his nomenclature, $A = f(P,B)\, e^{i\phi}$.

The equation (1.2.15) for the absolute value of field strength has been developed from the successive consideration of the various components that make up the ground wave, but the following equivalent expressions may be found more convenient for rapid calculation

$$E = E_o \left\{ 2\sin\frac{\Delta}{2} + j\left[(1+R)+(1-R)A\right]e^{j\Delta/2} \right\} \tag{1.2.17}$$

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 (rad) is

$$\Delta = \frac{4\pi h_t h_r}{\lambda d} \tag{1.2.18}$$

Also, when the angle Δ is greater than about 0.5 rad, the terms inside the brackets of Equation (1.2.17)—which include the surface wave—are usually negligible, and a sufficiently accurate expression is given by

$$E = E_o \left(2\sin\frac{2\pi h_t h_r}{\lambda d} \right) \tag{1.2.19}$$

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 rad, there is a region in which the surface wave may be important but not controlling. In this region, sin Δ/2 is approximately equal to Δ/2 and

$$E = E_o \frac{4\pi h'_t h'_r}{\lambda d} \tag{1.2.20}$$

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 Figure 1.2.4 for seawater and for "good" and "poor" soil. "Good" soil corresponds roughly to clay, loam, marsh, or swamp, while "poor" soil means rocky or sandy ground [1].

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. It is ordinarily sufficiently accurate to assume that h' is equal to the actual antenna height or the minimum effective antenna height, whichever is the larger.

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 megahertz, Equation (1.2.20) 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

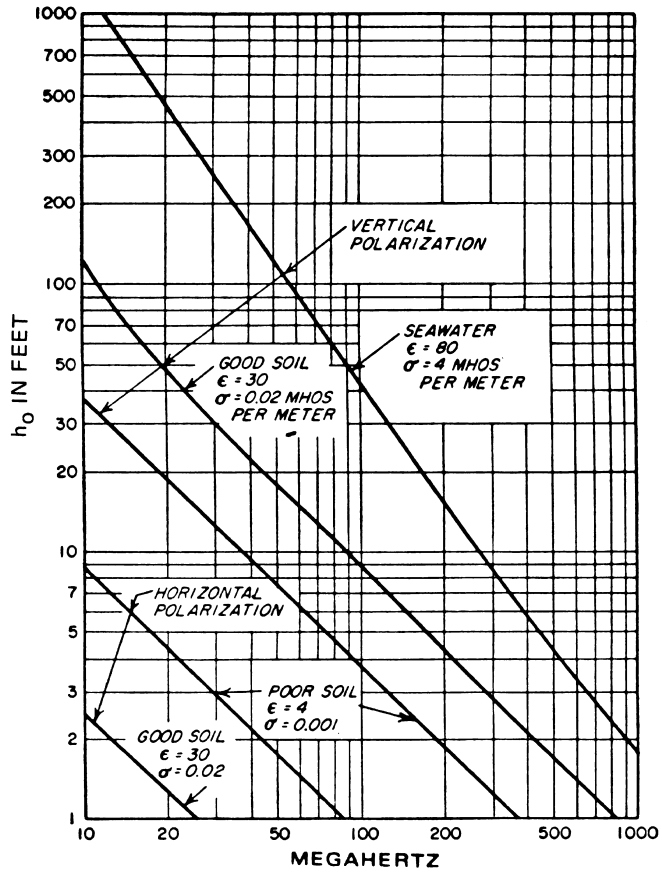

Figure 1.2.4 Minimum effective antenna height. (*From* [2]. *Used with permission.*)

$$E \cong F \frac{h_t' h_r' \sqrt{P_t}}{3 d^2} \tag{1.2.21}$$

1.2.3b 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 Equation (1.2.20) into (1.2.8), resulting in

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi d}\right)^2 g_t\, g_r \left(\frac{4\pi h_t' h_r'}{\lambda d}\right) = \left(\frac{h_t' h_r'}{d^2}\right)^2 g_t\, g_r \tag{1.2.22}$$

This relationship is independent of frequency, and is shown on Figure 1.2.5 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 W radiated. When the received field strength is desired, the power indicated on Figure 1.2.5 can be transferred to scale 4 of Figure 1.2.1, and a line through the frequency on scale 3 indicates the received field strength on scale 2. The results shown on Figure 1.2.5 are valid as long as the value of received power indicated is lower than that shown on Figure 1.2.3 for free-space transmission. When this condition is not met, it means that the angle Δ is too large for Equation (1.2.20) to be accurate and that the received field strength or power oscillates around the free-space value as indicated by Equation (1.2.19) [1].

1.2.3c Propagation Over Smooth Spherical Earth

The curvature of the earth has three effects on the propagation of radio waves at points within the line of sight:

- The *reflection coefficient* of the ground-reflected wave differs for the curved surface of the earth from that for a plane surface. This effect is of little importance, however, under the circumstances normally encountered in practice.
- Because 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.
- The heights of the transmitting and receiving antennas h_t' and h_r' , above the plane that 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 Figure 1.2.6.

Under these conditions, Equation (1.2.14), which applies to larger distances within the line of sight and to antennas of sufficient height that the surface component may be neglected, becomes

$$E = E_o\,(1 + DR'\,e^{j\Delta}) \tag{1.2.23}$$

Similar substitutions of the values that correspond in Figures 1.2.3 and 1.2.6 can be made in Equations (1.2.15 through (1.2.22). 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 generally calculated by the use of the more exact formulas [1, 4–9].

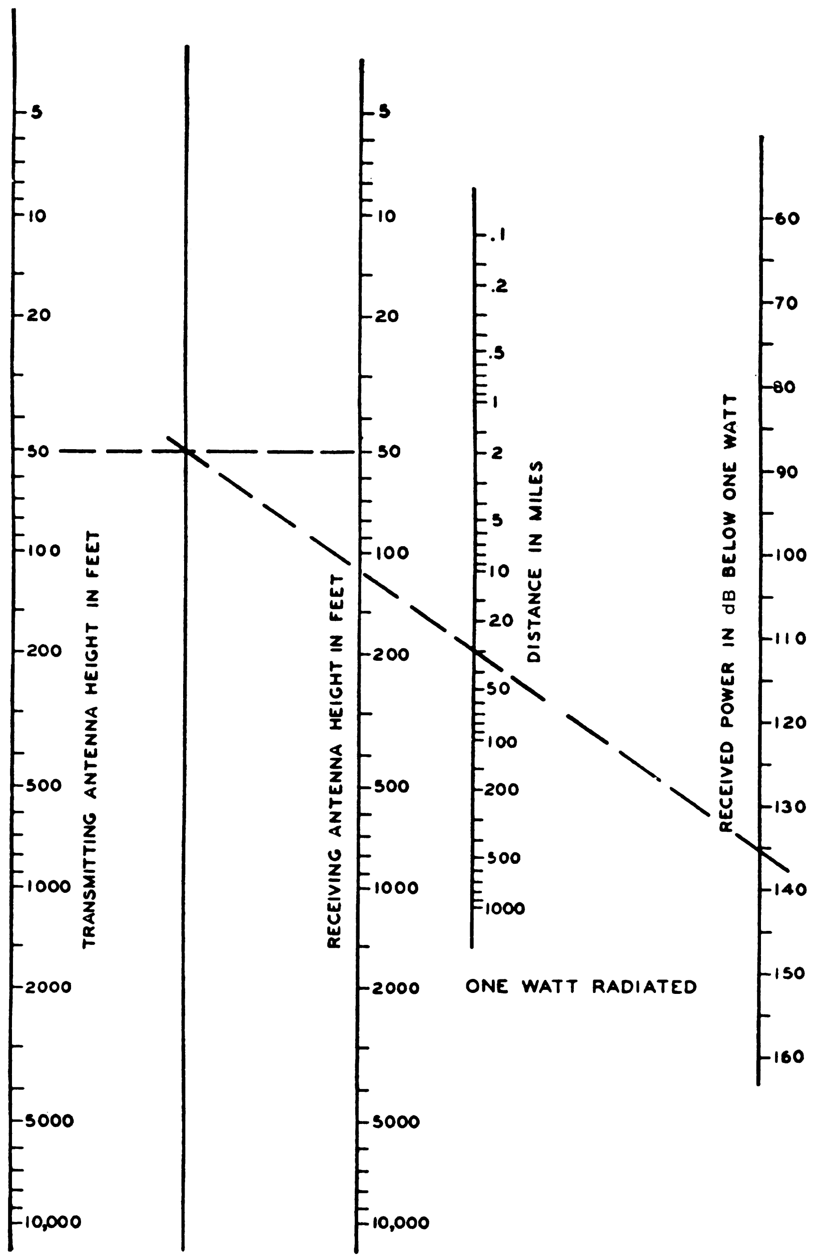

Figure 1.2.5 Received power over plane earth between half-wave dipoles. *Notes:* (1) This chart is not valid when the indicated received power is greater than the free space power shown in Figure 1.2.1. (2) Use the actual antenna height or the minimum effective height shown in Figure 1.2.4, whichever is the larger. (*From* [2]. *Used with permission.*)

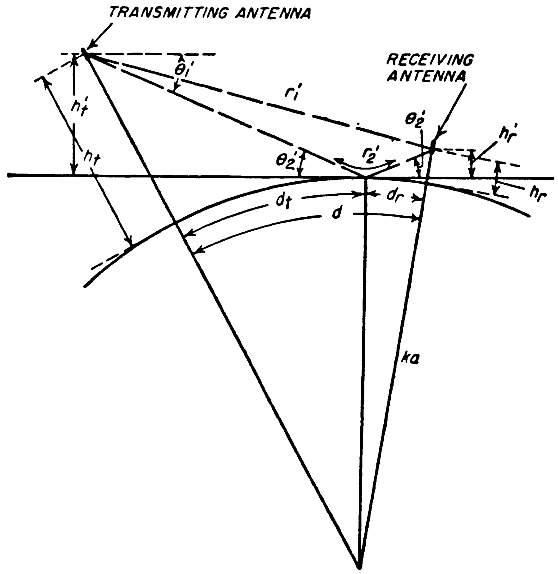

Figure 1.2.6 Ray paths for antennas above spherical earth. (*From* [2]. *Used with permission.*)

1.2.3d 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 wave front is considered to act as a radiating source. When the wave front is coherent or undisturbed, the resultant is a progression of the front in a direction perpendicular thereto, along a path that constitutes the ray. When the front is disturbed, the resultant front can 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 except with specially designed software. 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 [6] have been modified by Burrows [7] and by Norton [3, 5] so as to make them more readily usable and particularly adaptable to the production of families of curves. Such curves have been prepared by a variety of organizations. These curves have not been included herein, in view of the large number of curves that are required to satisfy the possi-

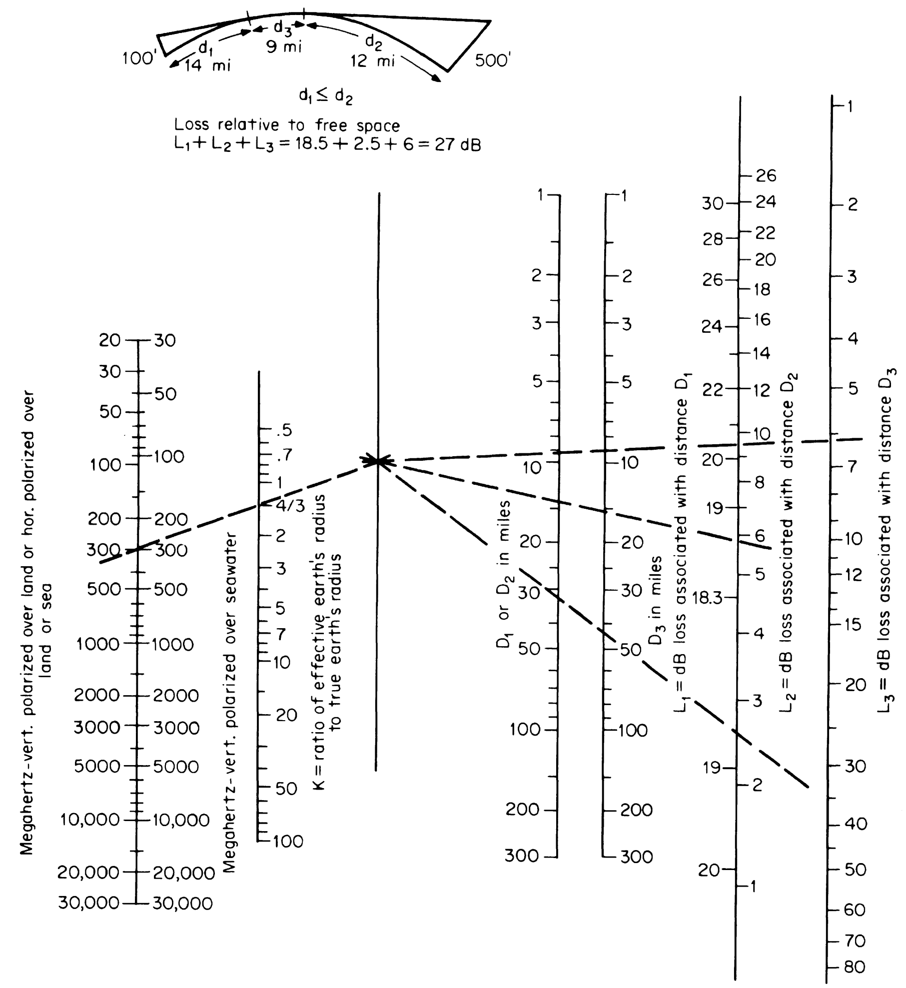

Figure 1.2.7 Loss beyond line of sight in decibels. (*From* [2]. *Used with permission.*)

ble 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.

Figure 1.2.7 is a nomogram to determine the additional loss caused by the curvature of the earth [1]. This loss must be added to the free-space loss found from Figure 1.2.1. A scale is included to provide for the effect of changes in the effective radius of the earth, caused by atmospheric refraction. Figure 1.2.7 gives the loss relative to free space as a function of three dis-

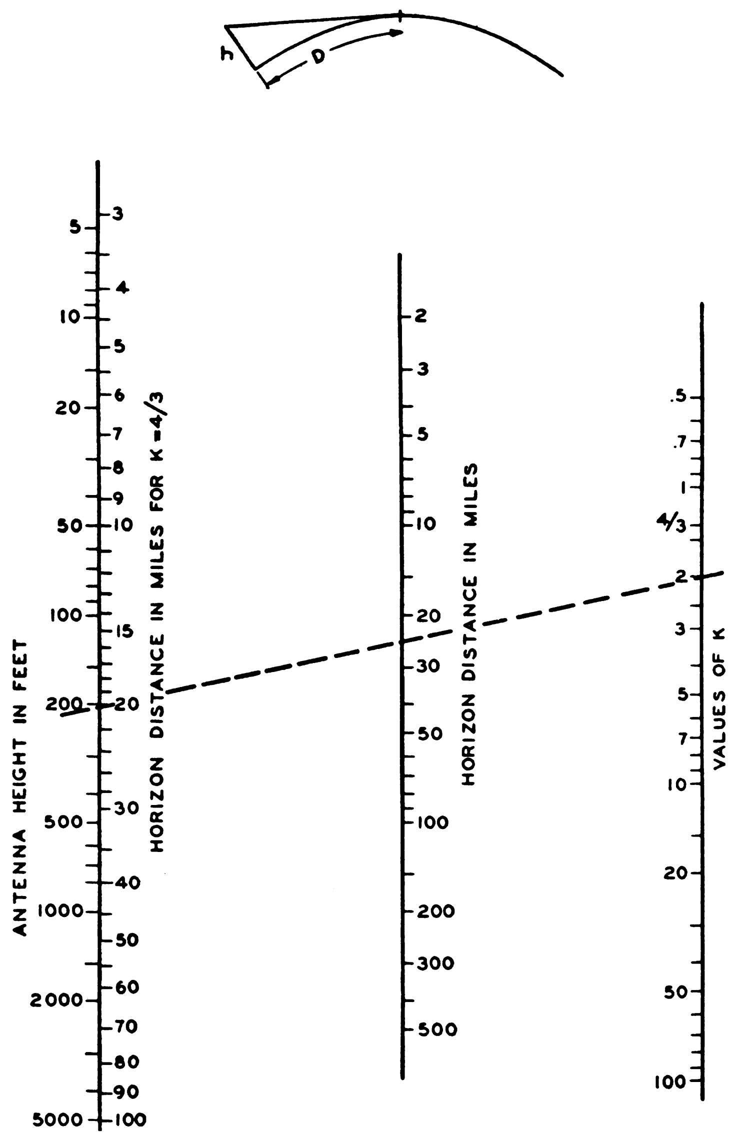

Figure 1.2.8 Distance to the horizon. (*From* [2]. *Used with permission.*)

tances; 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 $d = d_1 + d_2 + d_3$.

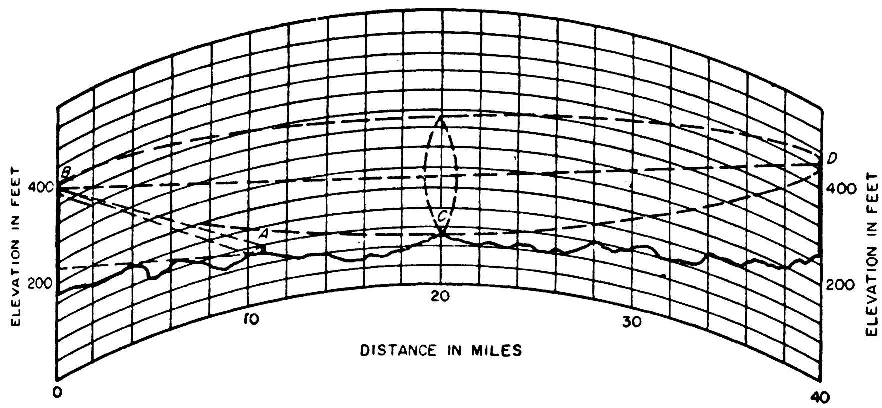

Figure 1.2.9 Ray paths for antennas over rough terrain. (*From* [2]. *Used with permission.*)

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 Figure 1.2.8 [1].

1.2.3e 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 that 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 topographic maps and is plotted on a chart that provides for average air refraction by the use of a 4/3 earth radius, as shown in Figure 1.2.9. 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 Figure 1.2.5 to compute the transmission loss, or with Equation (1.2.21) to compute the field strength. A similar procedure can be used for more

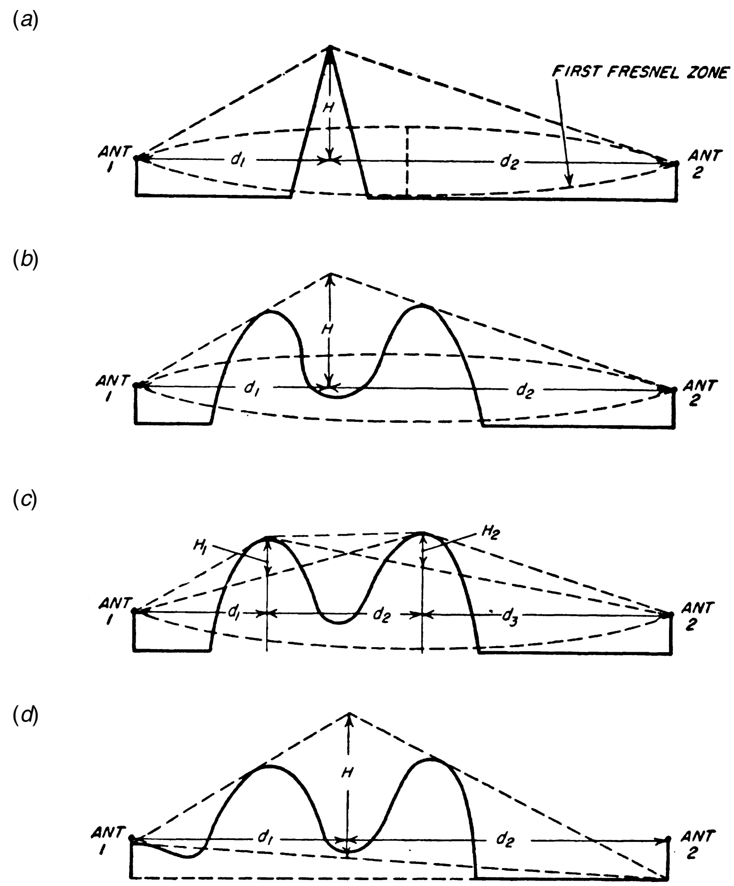

Figure 1.2.10 Ray paths for antennas behind hills: (*a–d*), see text. (*From* [2]. *Used with permission.*)

distantly spaced high antennas when the line of sight does not clear the profile by at least the first *Fresnel zone* [10].

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 Figure 1.2.10*a* [1, 9–14]. 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 Figure 1.2.11, 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 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 magni-

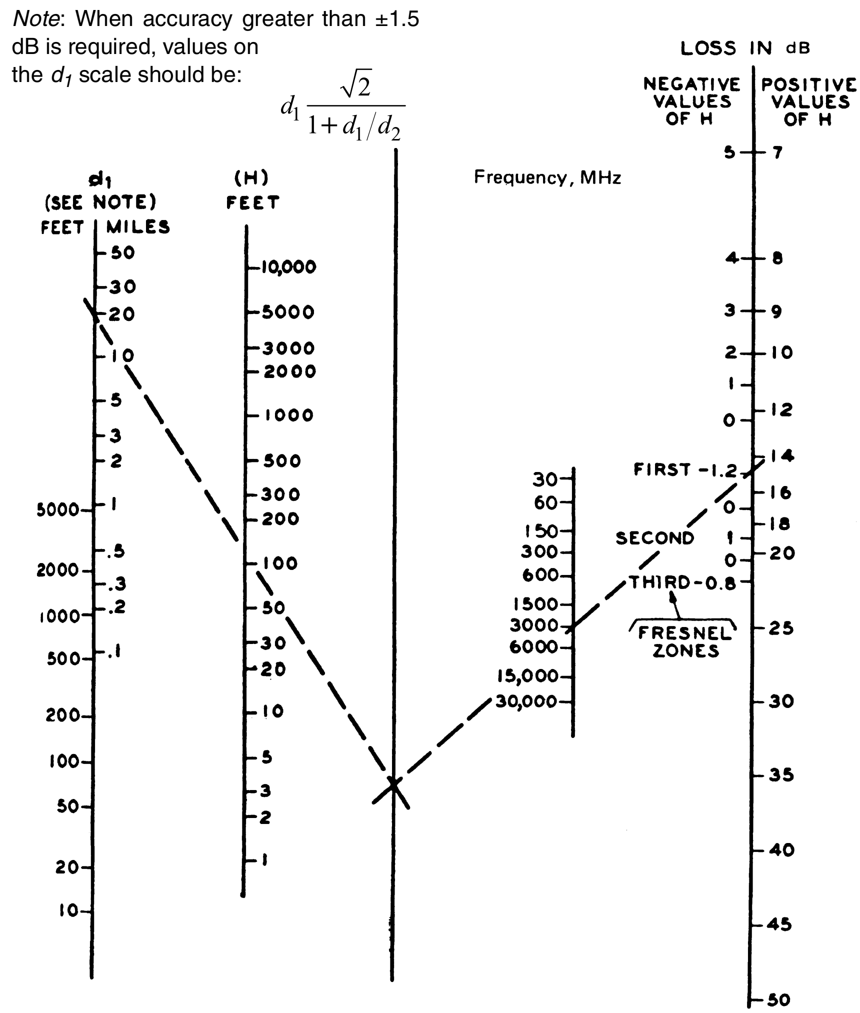

Figure 1.2.11 Shadow loss relative to free space. (*From* [2]. *Used with permission.*)

tude 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 Figure 1.2.11, and by means of this chart the required clearances can be obtained. At 3000 MHz, for example, the direct ray should clear all obstructions in the center of a 40 mi (64 km) path by about 120 ft (36 m) to obtain full first-zone clearance, as shown at "C" in Figure 1.2.9. The corresponding clearance for a ridge 100 ft (30 m) in front of either antenna is 4 ft (1.2 m). The locus of all points that 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 can be represented by drawing a line from each antenna through the top of the peak that blocks the line of sight, as in Figure 1.2.10*b*.

Alternatively, the transmission loss can be computed by adding the losses incurred when passing over each of the successive hills, as in Figure 1.2.10*c*. 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 1. The nomogram given in Figure 1.2.11 is used for calculating the losses for terrain conditions represented by Figure 1.2.10*a–c*.

This 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 Figure 1.2.10*d*. *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, Figure 1.2.12 is used to estimate the shadow loss to be added to the plane-earth attenuation [1].

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, however, can be expected for mobile or broadcast services [14].

An alternative method for predicting the median value for all measurements in a completely shadowed area is as follows [15]:

1. The roughness of the terrain is assumed to be represented by height *H*, shown on the profile at the top of Figure 1.2.13.
2. This height is the difference in elevation between the bottom of the valley and the elevation necessary to 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 sq. rt. (H/λ).

These empirical relationships are summarized in the nomogram shown in Figure 1.2.13. 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 (150 m), the estimated median shadow loss at 4500 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 that sometimes cause the field intensity to vary considerably within a matter of a few feet.

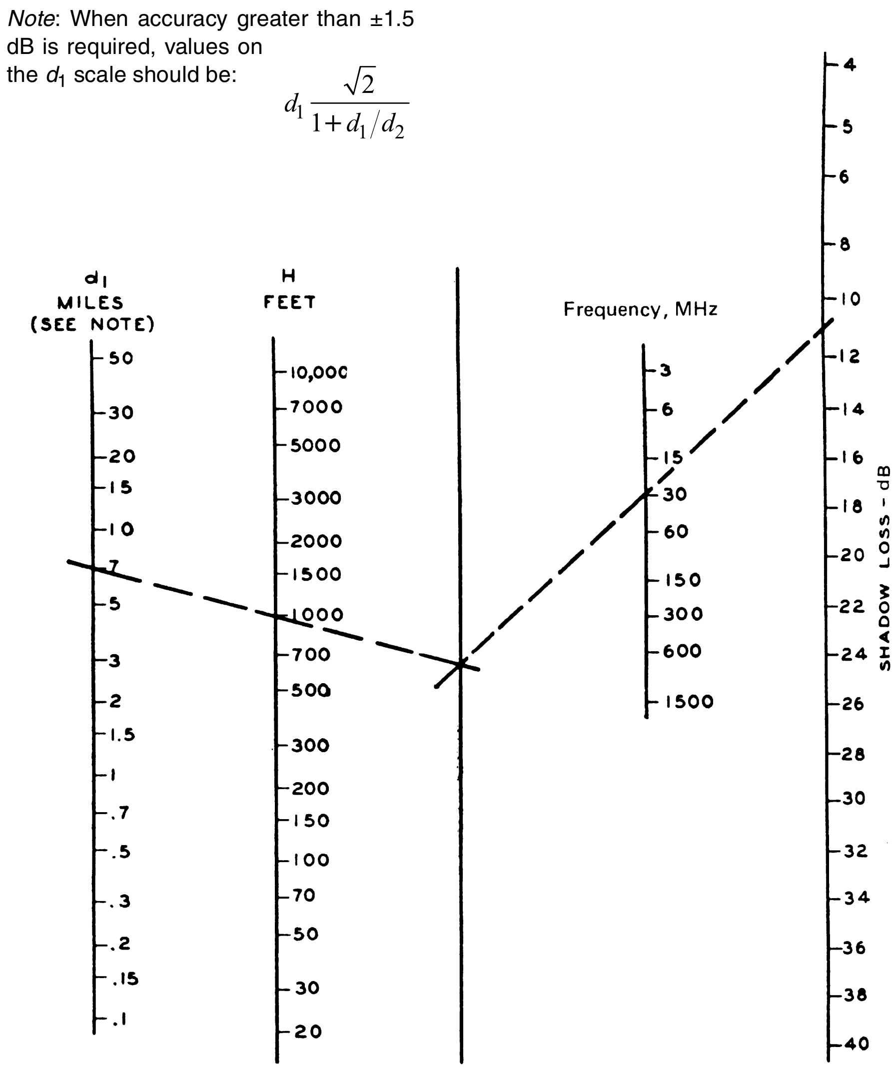

Figure 1.2.12 Shadow loss relative to plane earth. (*From* [2]. *Used with permission.*)

Effects of Buildings

Built-up areas have little effect on radio transmission at frequencies below a few megahertz, 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, can

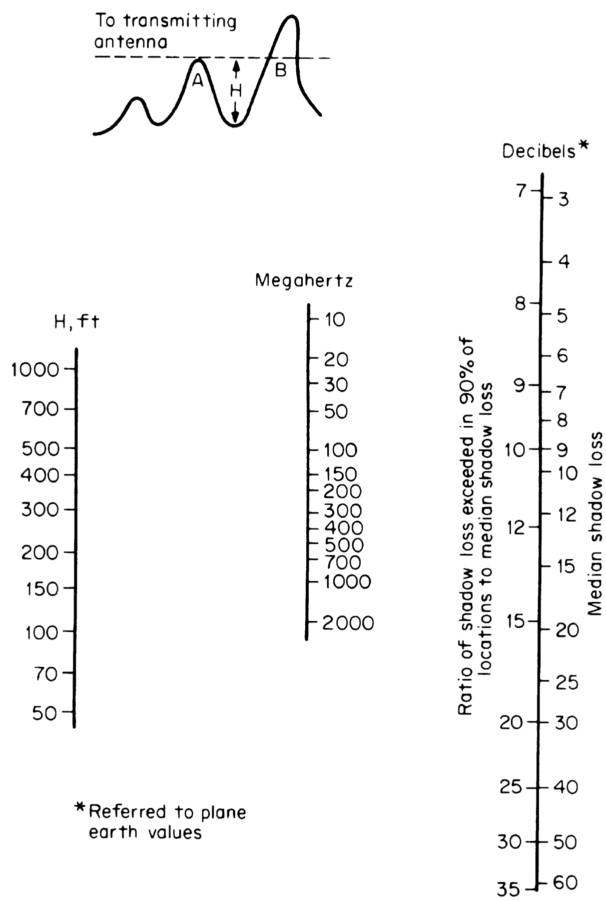

Figure 1.2.13 Estimated distribution of shadow loss for random locations (referred to plane-earth values). (*From* [2]. *Used with permission.*)

vary from 2 to 5 dB at 30 MHz and from 10 to 40 dB at 3000 MHz, depending on whether the wall is dry or wet. Consequently, most buildings are rather opaque at frequencies of the order of thousands of megahertz.

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 can 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 backscatter 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. 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 New York City is about 25 dB below the corresponding plane-earth value. The corresponding values for the 10 percent and 90 percent points are about –15 and –35 dB, respectively [1, 15]. Measurements in congested residential areas indicate somewhat less attenuation than among large buildings.

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 can 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 (30 m) 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 1000 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 Figures 1.2.9 or 1.2.11.

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 can 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 1000 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 [17].

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.

1.2.3f Effects of the Lower Atmosphere (Troposphere)

Radio waves propagating through the lower atmosphere, or troposphere, are subject to absorption, scattering, and bending. Absorption is negligible in the VHF–UHF frequency range but becomes significant at frequencies above 10 GHz. The index of refraction of the atmosphere, *n,* is slightly greater than 1 and varies with temperature, pressure, and water vapor pressure, and therefore with height, climate, and local meteorological conditions. An exponential model showing a decrease with height to 37 to 43 mi (60 to 70 kin) is generally accepted [18, 19]. For this model, variation of *n* is approximately linear for the first kilometer above the surface in which most of the effect on radio waves traveling horizontally occurs. For average conditions, the effect of the atmosphere can be included in the expression of earth 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

$$k = \frac{1}{1 + a\left(dn/dh\right)} \tag{1.2.24}$$

Where:
a = the actual radius of the earth
dn/dh = the rate of change of the refractive index with height

Through the use of average annual values of the refractive index gradient, *k* is found to be 4/3 for temperate climates.

Stratification and Ducts

As a result of climatological and weather processes such as *subsidence*, *advection*, and surface heating and radiative cooling, the lower atmosphere tends to be stratified in layers with contrasting refractivity gradients [20]. For convenience in evaluating the effect of this stratification, *radio refractivity N* is defined as $N = (n - 1) \times 10^6$ and can be derived from

$$N = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \tag{1.2.25}$$

Where:
P = atmospheric pressure, mbar
T = absolute temperature, K
e = water vapor pressure, mbar

When the gradient of *N* is equal to –39 *N*-units per kilometer, normal propagation takes place, corresponding to the effective earth's radius *ka,* where $k = 4/3$.

When *dN*/*dh* is less than –39 *N*-units per kilometer, *subrefraction* occurs and the radio wave is bent strongly downward.

When *dN*/*dh* is less than –157 *N*-units per kilometer, the radio energy may be bent downward sufficiently to be reflected from the earth, after which the ray is again bent toward the earth, and so on. The radio energy thus is trapped in a duct or waveguide. The wave also may be trapped between two elevated layers, in which case energy is not lost at the ground reflection points and even greater enhancement occurs. Radio waves thus trapped or *ducted* can produce fields exceeding those for free-space propagation because the spread of energy in the vertical direction is eliminated as opposed to the free-space case, where the energy spreads out in two directions orthogonal to the direction of propagation. Ducting is responsible for abnormally high fields beyond the radio horizon. These enhanced fields occur for significant periods of time on overwater paths in areas where meteorological conditions are favorable. Such conditions exist for significant periods of time and over significant horizontal extent in the coastal areas of southern California and around the Gulf of Mexico. Over land, the effect is less pronounced because surface features of the earth tend to limit the horizontal dimension of ducting layers [20].

Tropospheric Scatter

The most consistent long-term mode of propagation beyond the radio horizon is that of scattering by small-scale fluctuations in the refractive index resulting from turbulence. Energy is scattered from multitudinous irregularities in the common volume which consists of that portion of troposphere visible to both the transmitting and receiving sites. There are some empirical data that show a correlation between the variations in the field beyond the horizon and ΔN, the difference between the reflectivity on the ground and at a height of 1 km [21]. Procedures have been developed for calculating scatter fields for beyond-the-horizon radio relay systems as a function of frequency and distance [22, 23]. These procedures, however, require detailed knowledge of path configuration and climate.

The effect of scatter propagation is incorporated in the statistical evaluation of propagation (considered previously in this chapter), where the attenuation of fields beyond the diffraction zone is based on empirical data and shows a linear decrease with distance of approximately 0.2 dB/mi (0.1 dB/km) for the VHF–UHF frequency band.

1.2.3g Atmospheric Fading

Variations in the received field strengths around the median values 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.

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.

Effects of the Upper Atmosphere (Ionosphere)

Four principal recognized layers or regions in the ionosphere are the E layer, the $F1$ layer, 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 that can be reflected thereby—is higher during 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 *F*2 than upon the *F*1 and *E* layers. There are also certain random effects that are associated with solar and magnetic disturbances. Other effects that occur at or just below the *E* layer have been established as being caused by meteors [24].

The greatest potential for television interference by way of the ionosphere is from *sporadic E ionization*, which consists of occasional patches of intense ionization occurring 62 to 75 mi (100 to 120 km) above the earth's surface and apparently formed by the interaction of winds in the neutral atmosphere with the earth's magnetic field. Sporadic *E* ionization can reflect VHF signals back to earth at levels capable of causing interference to analog television reception for periods lasting from 1 h or more, and in some cases totaling more than 100 h per year. In the U.S., VHF sporadic *E* propagation occurs a greater percentage of the time in the southern half of the country and during the May to August period [25].

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