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Radio Propagation Fundamentals*

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The engineering of radio systems requires an estimate of the power loss between the transmitter and the receiver. Such estimates are affected by many factors, including reflections, fading, refraction in the atmosphere, and diffraction over the earth's surface.

In this paper, radio transmission theory and experiment in all frequency bands of current interest are summarized. Ground wave and sky wave transmission are included, and both line of sight and beyond horizon transmission are considered. The principal emphasis is placed on quantitative charts that are useful for engineering purposes.

I. INTRODUCTION

The power radiated from a transmitting antenna is ordinarily spread over a relatively large area. As a result the power available at most receiving antennas is only a small fraction of the radiated power. This ratio of radiated power to received power is called the radio transmission loss and its magnitude in some cases may be as large as 10^{15} to 10^{20} (150 to 200 decibels).

The transmission loss between the transmitting and receiving antennas determines whether the received signal will be useful. Each radio

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system has a maximum allowable transmission loss which, if exceeded, results in either poor quality or poor reliability. Reasonably accurate predictions of transmission loss can be made on paths that approximate the ideals of either free space or plane earth. On many paths of interest, however, the path geometry or atmospheric conditions differ so much from the basic assumptions that absolute accuracy cannot be expected; nevertheless, worthwhile results can be obtained by using two or more different methods of analysis to "box in" the answer.

The basic concept in estimating radio transmission loss is the loss expected in free space; that is, in a region free of all objects that might absorb or reflect radio energy. This concept is essentially the inverse square law in optics applied to radio transmission. For a one wave-length separation between nondirective (isotropic) antennas, the free space loss is 22 db and it increases by 6 db each time the distance is doubled. The free space transmission ratio at a distance d is given by:

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi d}\right)^2 g_t g_r \tag{1a}$$

where:

$$\left.\begin{aligned} P_r &= \text{received power} \\ P_t &= \text{radiated power} \end{aligned}\right\} \text{measured in same units}$$

λ = wavelength in same units as d

g_t (or g_r) = power gain of transmitting (or receiving) antenna

The power gain of an ideal isotropic antenna that radiates power uniformly in all directions is unity by definition. A small doublet whose over-all physical length is short compared with one-half wavelength has a gain of $g = 1.5$ (1.76 decibels) and a one-half wave dipole has a gain of 2.15 decibels in the direction of maximum radiation. A nomogram for the free space transmission loss between isotropic antennas is given in Fig. 1.

When antenna dimensions are large compared with the wavelength, a more convenient form of the free space ratio is[1]

$$\frac{P_r}{P_t} = \frac{A_t A_r}{(\lambda d)^2} \tag{1b}$$

where $A_{t,r}$ = effective area of transmitting or receiving antennas.

Another form of expressing free space transmission is the concept of the free space field intensity E_0 which is given by:

$$E_0 = \frac{\sqrt{30 P_t g_t}}{d} \text{ volts per meter} \tag{2}$$

where d is in meters and P_t in watts.

The use of the field intensity concept is frequently more convenient than the transmission loss concept at frequencies below about 30 mc,

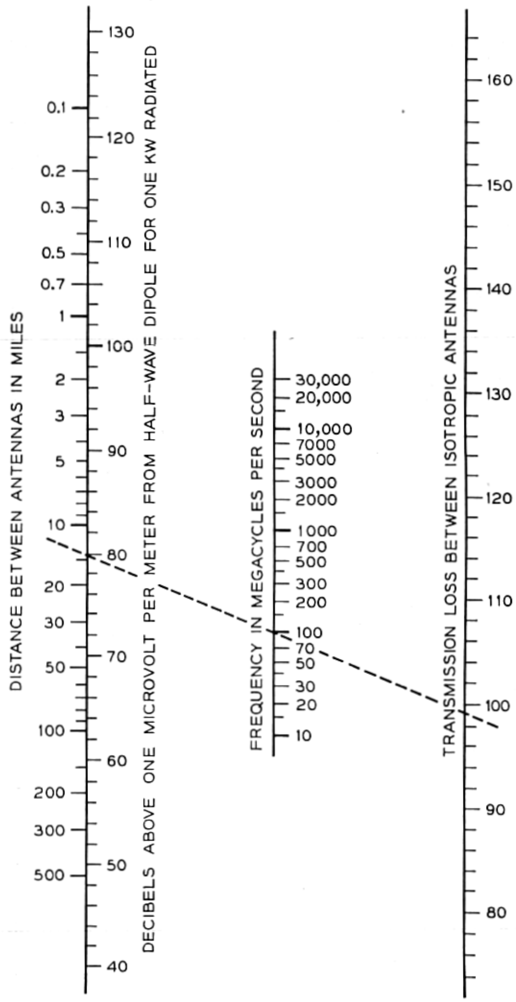

FIG. 1 — Free space transmission.

where external noise is generally controlling and where antenna dimensions and heights are comparable to or less than a wavelength. The free space field intensity is independent of frequency and its magnitude for one kilowatt radiated from a half-wave dipole is shown on the left hand scale on Fig. 1.

The concept of free space transmission assumes that the atmosphere is perfectly uniform and nonabsorbing and that the earth is either infinitely far away or its reflection coefficient is negligible. In practice, the modifying effects of the earth, the atmosphere and the ionosphere need to be considered. Both theoretical and experimental values for these effects are described in the following sections.

II. TRANSMISSION WITHIN LINE OF SIGHT

The presence of the ground modifies the generation and the propagation of radio waves so that the received power or field intensity is ordinarily less than would be expected in free space.[2] The effect of plane earth on the propagation of radio waves is given by

$$\frac{E}{E_0} = \underbrace{1}_{\substack{\text{Direct}\\ \text{Wave}}} + \underbrace{Re^{j\Delta}}_{\substack{\text{Reflected}\\ \text{Wave}}} + \underbrace{(1 - R)Ae^{j\Delta}}_{\substack{\text{“Surface}\\ \text{Wave”}}} + \underbrace{\cdots}_{\substack{\text{Induction Field}\\ \text{and Secondary}\\ \text{Effects of the}\\ \text{Ground}}} \tag{3}$$

where

R = reflection coefficient of the ground

A = "surface wave" attenuation factor

$$\Delta = \frac{4\pi h_1 h_2}{\lambda d}$$

$h_{1,2}$ = antenna heights measured in same units as the wavelength and distance

The parameters R and A vary with both polarization and the electrical constants of the ground. In addition, the term "surface wave" has led to considerable confusion since it has been used in the literature to stand for entirely different concepts. These factors are discussed more completely in Section IV. However, the important point to note in this section is that considerable simplification is possible in most practical cases, and that the variations with polarization and ground constants and the confusion about the surface wave can often be neglected. For near grazing paths, R is approximately equal to -1 and the factor A can be neglected as long as both antennas are elevated more than a wavelength above the ground (or more than 5–10 wavelengths above sea water). Under these conditions the effect of the earth is independent of polarization and ground constants and (3) reduces to

$$\left|\frac{E}{E_0}\right| = \sqrt{\frac{P_r}{P_o}} = 2 \sin \frac{\Delta}{2} = 2 \sin \frac{2\pi h_1 h_2}{\lambda d} \tag{4}$$

where P_0 is the received power expected in free space.

The above expression is the sum of the direct and ground reflected rays and shows the lobe structure of the signal as it oscillates around the free space value. In most radio applications (except air to ground) the principal interest is in the lower part of the first lobe; that is, where $\Delta/2 < \pi/4$. In this case, $\sin \Delta/2 \approx \Delta/2$ and the transmission loss over plane earth is given by:

$$\begin{aligned} \frac{P_r}{P_t} &= \left(\frac{\lambda}{4\pi d}\right)^2 \left(\frac{4\pi h_1 h_2}{\lambda d}\right)^2 g_t g_r \\ &= \left(\frac{h_1 h_2}{d^2}\right)^2 g_t g_r \end{aligned} \tag{5}$$

It will be noted that this relation is independent of frequency and it is shown in decibels in Fig. 2 for isotropic antennas. Fig. 2 is not valid when the indicated transmission loss is less than the free space loss shown in Fig. 1, because this means that Δ is too large for this approximation.

Although the transmission loss shown in (5) and in Fig. 2 has been derived from optical concepts that are not strictly valid for antenna heights less than a few wavelengths, approximate results can be obtained for lower heights by using h_1 (or h_2) as the larger of either the actual antenna height or the minimum effective antenna height shown in Fig. 3. The concept of minimum effective antenna height is discussed further in Section IV. The error that can result from the use of this artifice does not exceed ± 3 db and occurs where the actual antenna height is approximately equal to the minimum effective antenna height.

The sine function in (4) shows that the received field intensity oscillates around the free space value as the antenna heights are increased. The first maximum occurs when the difference between the direct and ground reflected waves is a half wavelength. The signal maxima have a magnitude $1 + |R|$ and the signal minima have a magnitude of $1 - |R|$.

Frequently the amount of clearance (or obstruction) is described in terms of Fresnel zones. All points from which a wave could be reflected with a path difference of one-half wavelength form the boundary of the first Fresnel zone; similarly, the boundary of the n^{th} Fresnel zone consists of all points from which the path difference is $n/2$ wavelengths. The n^{th} Fresnel zone clearance H_n at any distance d_1 is given by:

$$H_n = \sqrt{\frac{n\lambda d_1(d - d_1)}{d}} \tag{6}$$

Although the reflection coefficient is very nearly equal to -1 for

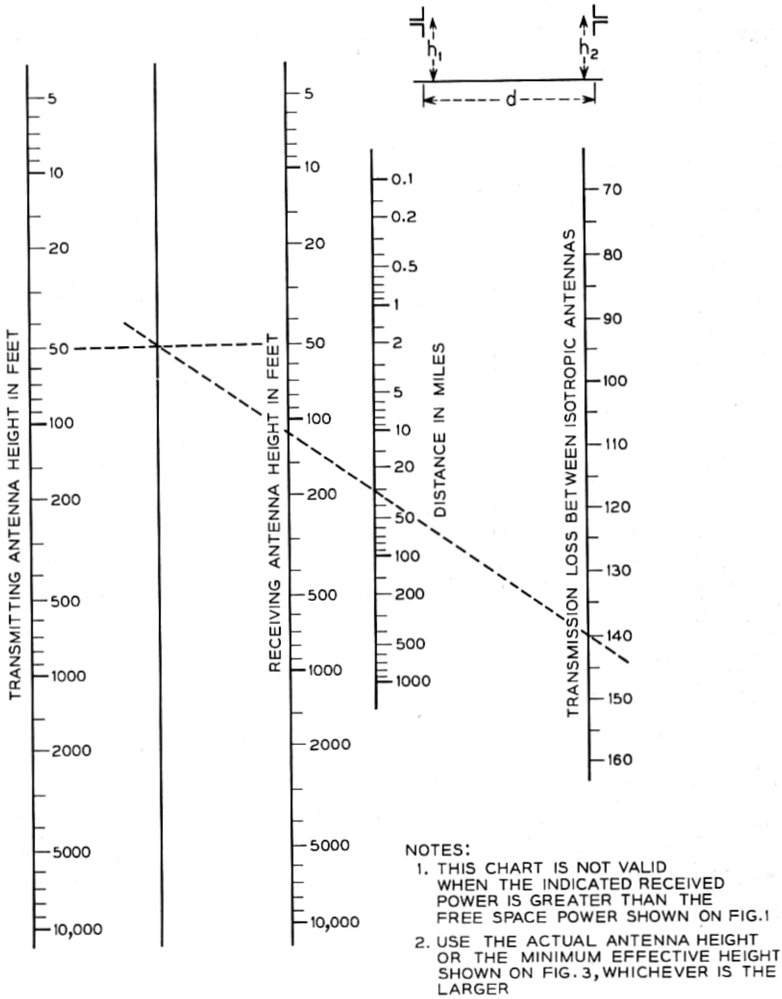

FIG. 2 — Transmission loss over plane earth.

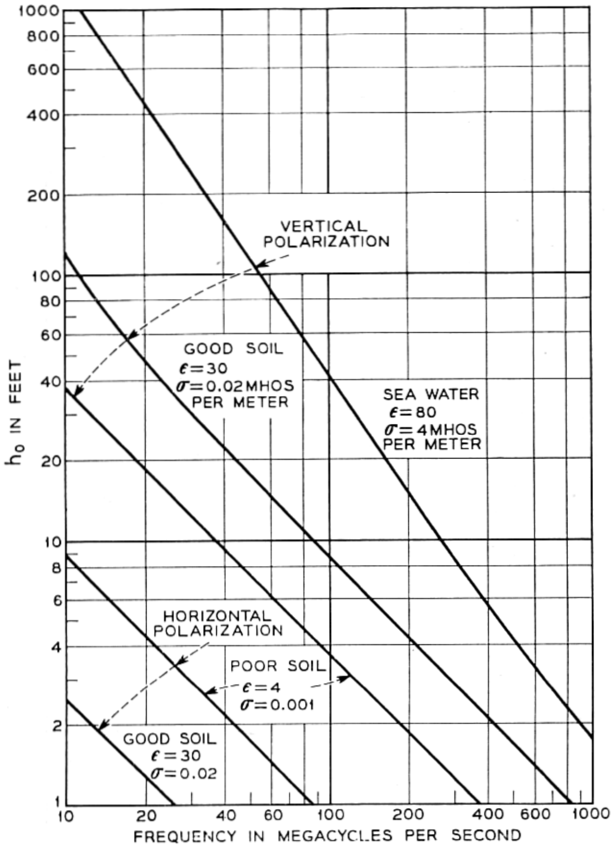

FIG. 3 — Minimum effective antenna height.

grazing angles over smooth surfaces, its magnitude may be less than unity when the terrain is rough. The classical Rayleigh criterion of roughness indicates that specular reflection occurs when the phase deviations are less than about $\pm(\pi/2)$ and that the reflection coefficient will be substantially less than unity when the phase deviations are greater than $\pm(\pi/2)$. In most cases this theoretical boundary between specular and diffuse reflection occurs when the variations in terrain exceed $\frac{1}{8}$ to $\frac{1}{4}$ of the first Fresnel zone clearance. Experimental results with microwave transmission have shown that most practical paths are "rough" and ordinarily have a reflection coefficient in the range of 0.2–0.4. In addition, experience has shown that the reflection coefficient is a statistical problem and cannot be predicted accurately from the path profile.[3]

Fading Phenomena

Variations in signal level with time are caused by changing atmospheric conditions. The severity of the fading usually increases as either the frequency or path length increases. Fading cannot be predicted accurately but it is important to distinguish between two general types: (1) inverse bending and (2) multipath effects. The latter includes the fading caused by interference between direct and ground reflected waves as well as interference between two or more separate paths in the atmosphere. Ordinarily, fading is a temporary diversion of energy to some other than the desired location; fading caused by absorption of energy is discussed in a later paragraph.

The path of a radio wave is not a straight line except for the ideal case of a uniform atmosphere. The transmission path may be bent up or down depending on atmospheric conditions. This bending may either increase or decrease the effective path clearance and inverse bending may have the effect of transforming a line of sight path into an obstructed one. This type of fading may last for several hours. The frequency of its occurrence and its depth can be reduced by increasing the path clearance, particularly in the middle of the path.

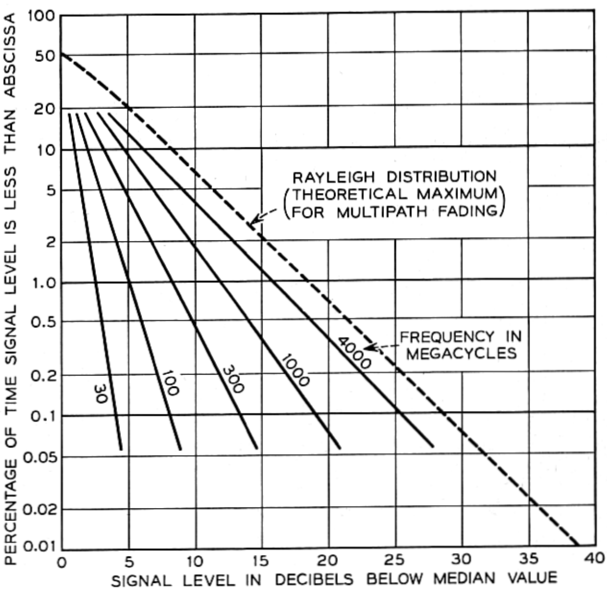

Fig. 4 — Typical fading characteristics in the worst month on 30 to 40 mile line-of-sight paths with 50 to 100 foot clearance.

Severe fading may occur over water or on other smooth paths because the phase difference between the direct and reflected rays varies with atmospheric conditions. The result is that the two rays sometimes add and sometimes tend to cancel. This type of fading can be minimized, if the terrain permits, by locating one end of the circuit high while the other end is very low. In this way the point of reflection is placed near the low antenna and the phase difference between direct and reflected rays is kept relatively steady.

Most of the fading that occurs on "rough" paths with adequate clearance is the result of interference between two or more rays traveling slightly different routes in the atmosphere. This multipath type of fading is relatively independent of path clearance and its extreme condition approaches the Rayleigh distribution. In the Rayleigh distribution, the probability that the instantaneous value of the field is greater than the value R is $\exp[-(R/R_0)]$, where R_0 is the rms value.

Representative values of fading on a path with adequate clearance are shown on Fig. 4. After the multipath fading has reached the Rayleigh distribution, a further increase in either distance or frequency increases the number of fades of a given depth but decreases the duration so that the product is the constant indicated by the Rayleigh distribution.

Miscellaneous Effects

The remainder of this Section describes some miscellaneous effects of line of sight transmission that may be important at frequencies above about 1,000 mc. These effects include variation in angles of arrival, maximum useful antenna gain, useful bandwidth, the use of frequency or space diversity, and atmospheric absorption.

On line of sight paths with adequate clearance some components of the signal may arrive with variations in angle of arrival of as much as $\frac{1}{2}°$ to $\frac{3}{4}°$ in the vertical plane, but the variations in the horizontal plane are less than 0.1°.[4, 5] Consequently, if antennas with beamwidths less than about 0.5° are used, there may occasionally be some loss in received signal because most of the incoming energy arrives outside the antenna beamwidth. Signal variations due to this effect are usually small compared with the multipath fading.

Multipath fading is selective fading and it limits both the maximum useful bandwidth and the frequency separation needed for adequate frequency diversity. For 40-db antennas on a 30-mile path the fading on frequencies separated by 100–200 mc is essentially uncorrelated regardless of the absolute frequency. With less directive antennas, uncorrelated fading can occur at frequencies separated by less than 100 mc.[6, 7]

Larger antennas (more narrow beamwidths) will decrease the fast multipath fading and widen the frequency separation between uncorrelated fading but at the risk of increasing the long term fading associated with the variations in the angle of arrival.

Optimum space diversity, when ground reflections are controlling, requires that the separation between antennas be sufficient to place one antenna on a field intensity maximum while the other is in a field intensity minimum. In practice, the best spacing is usually not known because the principal fading is caused by multipath variations in the atmosphere. However, adequate diversity can usually be achieved with a vertical separation of 100–200 wavelengths.

At frequencies above 5,000–10,000 mc, the presence of rain, snow, or fog introduces an absorption in the atmosphere which depends on the amount of moisture and on the frequency. During a rain of cloud burst proportions the attenuation at 10,000 mc may reach 5 db per mile and at 25,000 mc it may be in excess of 25 db per mile.[8] In addition to the effect of rainfall some selective absorption may result from the oxygen and water vapor in the atmosphere. The first absorption peak due to water vapor occurs at about 24,000 mc and the first absorption peak for oxygen occurs at about 60,000 mc.

III. TROPOSPHERIC TRANSMISSION BEYOND LINE OF SIGHT

A basic characteristic of electromagnetic waves is that the energy is propagated in a direction perpendicular to the surface of uniform phase. Radio waves travel in a straight line only as long as the phase front is plane and is infinite in extent.

Energy can be transmitted beyond the horizon by three principal methods: reflection, refraction and diffraction. Reflection and refraction are associated with either sudden or gradual changes in the direction of the phase front, while diffraction is an edge effect that occurs because the phase surface is not infinite. When the resulting phase front at the receiving antenna is irregular in either amplitude or position, the distinctions between reflection, refraction, and diffraction tend to break down. In this case the energy is said to be scattered. Scattering is frequently pictured as a result of irregular reflections although irregular refraction plus diffraction may be equally important.

The following paragraphs describe first the theories of refraction and of diffraction over a smooth sphere and a knife edge. This is followed by empirical data derived from experimental results on the transmission to points far beyond the horizon, on the effects of hills and trees, and on fading phenomena.

Refraction

The dielectric constant of the atmosphere normally decreases gradually with increasing altitude. The result is that the velocity of transmission increases with the height above the ground and, on the average, the radio energy is bent or refracted toward the earth. As long as the change in dielectric constant is linear with height, the net effect of refraction is the same as if the radio waves continued to travel in a straight line but over an earth whose modified radius is:

$$ka = \frac{a}{1 + \frac{a}{2}\frac{d\epsilon}{dh}} \tag{7}$$

where

a = true radius of earth

$\frac{d\epsilon}{dh}$ = rate of change of dielectric constant with height

Under certain atmospheric conditions the dielectric constant may increase ($0 < k < 1$) over a reasonable height, thereby causing the radio waves in this region to bend away from the earth. This is the cause of the inverse bending type of fading mentioned in the preceding section. It is sometimes called substandard refraction. Since the earth's radius is about 2.1×10^7 feet, a decrease in dielectric constant of only 2.4×10^{-8} per foot of height results in a value of $k = \frac{4}{3}$, which is commonly assumed to be a good average value.[9] When the dielectric constant decreases about four times as rapidly (or by about 10^{-7} per foot of height), the value of $k = \infty$. Under such a condition, as far as radio propagation is concerned, the earth can then be considered flat, since any ray that starts parallel to the earth will remain parallel.

When the dielectric constant decreases more rapidly than 10^{-7} per foot of height, radio waves that are radiated parallel to, or at an angle above the earth's surface, may be bent downward sufficiently to be reflected from the earth. After reflection the ray is again bent toward the earth, and the path of a typical ray is similar to the path of a bouncing tennis ball. The radio energy appears to be trapped in a duct or waveguide between the earth and the maximum height of the radio path. This phenomenon is variously known as trapping, duct transmission, anomalous propagation, or guided propagation.[10, 11] It will be noted that in this case the path of a typical guided wave is similar in form to the path of sky waves, which are lower-frequency waves trapped between the earth and the ionosphere. However, there is little or no similarity between the virtual heights, the critical frequencies, or the causes of refraction in the two cases.

Duct transmission is important because it can cause long distance interference with another station operating on the same frequency; however, it does not occur often enough nor can its occurrence be predicted with enough accuracy to make it useful for radio services requiring high reliability.

Diffraction Over a Smooth Spherical Earth and Ridges

Radio waves are also transmitted around the earth by the phenomenon of diffraction. Diffraction is a fundamental property of wave motion, and in optics it is the correction to apply to geometrical optics (ray theory) to obtain the more accurate wave optics. In other words, all shadows are somewhat "fuzzy" on the edges and the transition from "light" to "dark" areas is gradual, rather than infinitely sharp. Our common experience is that light travels in straight lines and that shadows are sharp, but this is only because the diffraction effects for these very short wavelengths are too small to be noticed without the aid of special laboratory equipment. The order of magnitude of the diffraction at radio frequencies may be obtained by recalling that a 1,000-mc radio wave has about the same wavelength as a 1,000-cycle sound wave in air, so that these two types of waves may be expected to bend around absorbing obstacles with approximately equal facility.

The effect of diffraction around the earth's curvature is to make possible transmission beyond the line-of-sight. The magnitude of the loss caused by the obstruction increases as either the distance or the frequency is increased and it depends to some extent on the antenna height.[12] The loss resulting from the curvature of the earth is indicated by Fig. 5 as long as neither antenna is higher than the limiting value shown at the top of the chart. This loss is in addition to the transmission loss over plane earth obtained from Fig. 2.

When either antenna is as much as twice as high as the limiting value shown on Fig. 5, this method of correcting for the curvature of the earth indicates a loss that is too great by about 2 db, with the error increasing as the antenna height increases. An alternate method of determining the effect of the earth's curvature is given by Fig. 6. The latter method is approximately correct for any antenna height, but it is theoretically limited in distance to points at or beyond the line-of-sight, assuming that the curved earth is the only obstruction. Fig. 6 gives the loss relative to free-space transmission (and hence is used with Fig. 1) as a function of three distances: d_1 is the distance to the horizon from the lower antenna, d_2 is the distance to the horizon from the higher antenna, and d_3 is the distance beyond the line-of-sight. In other words, the total distance between antennas, $d = d_1 + d_2 + d_3$. The distance to the horizon over smooth earth is given by:

$$d_{1,2} = \sqrt{2kah_{1,2}} \tag{8}$$

where $h_{1,2}$ is the appropriate antenna height and ka is the effective earth's radius.

The preceding discussion assumes that the earth is a perfectly smooth sphere and the results are critically dependent on a smooth surface and a uniform atmosphere. The modification in these results caused by the

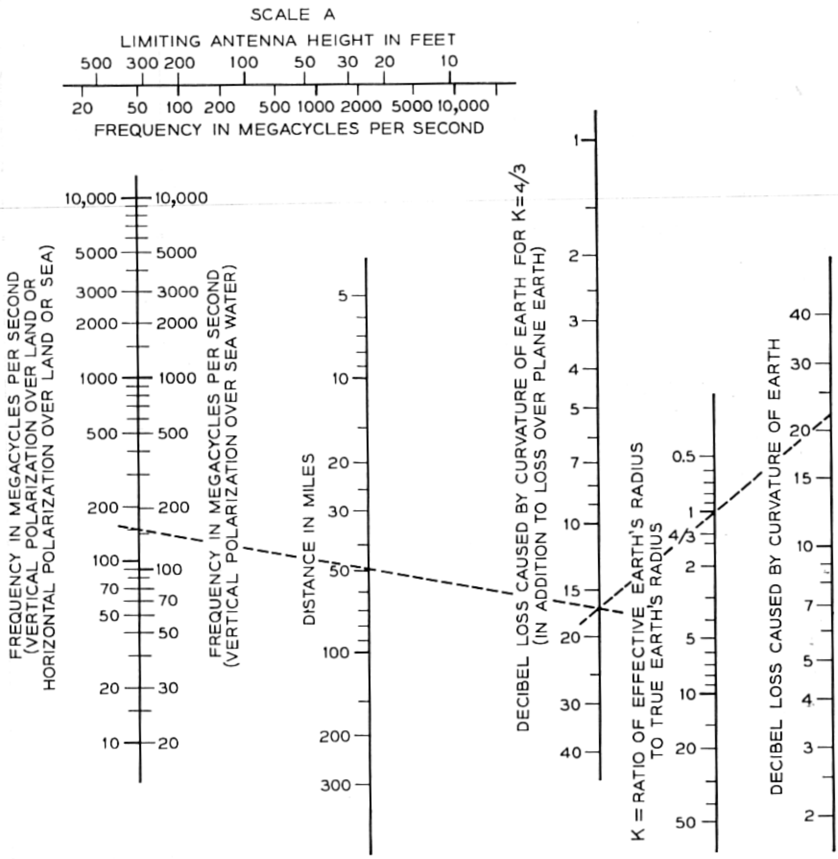

FIG. 5 — Diffraction loss around a perfect sphere.

presence of hills, trees, and buildings is difficult or impossible to compute, but the order of magnitude of these effects may be obtained from a consideration of the other extreme case, which is propagation over a perfectly absorbing knife edge.

The diffraction of plane waves over a knife edge or screen causes a shadow loss whose magnitude is shown on Fig. 7. The height of the obstruction H is measured from the line joining the two antennas to the top of the ridge. It will be noted that the shadow loss approaches 6 db

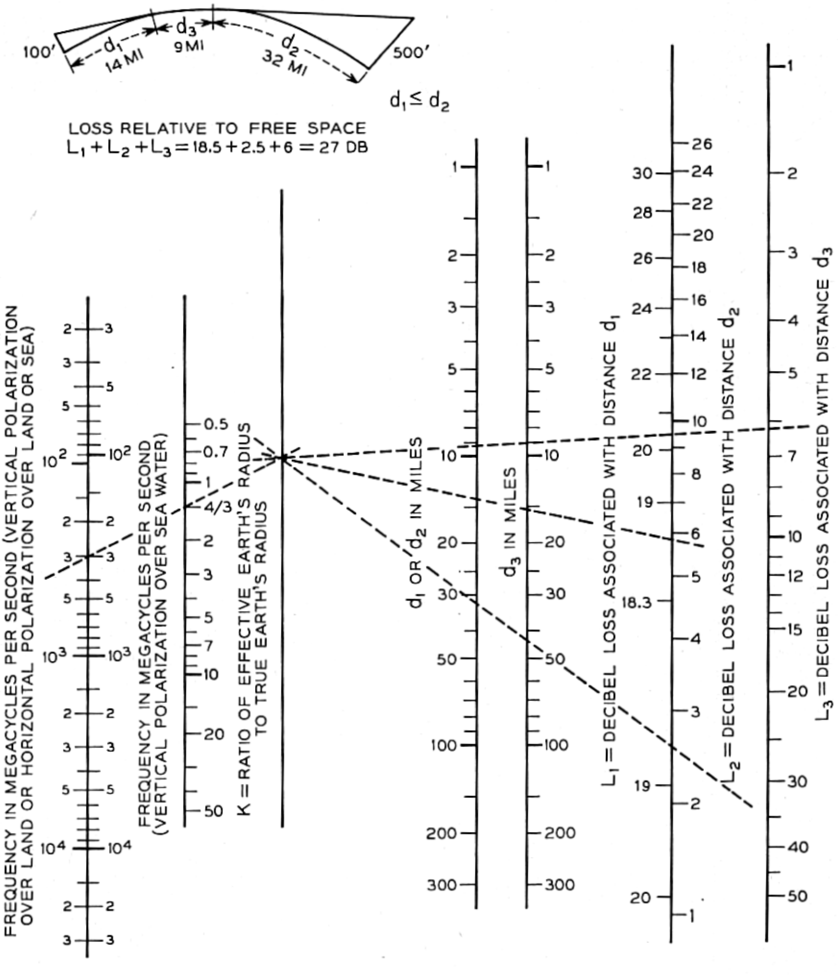

Fig. 6 — Diffraction loss relative to free space transmission at all locations beyond line-of-sight over a smooth sphere.

as H approaches 0 (grazing incidence), and that it increases with increasing positive values of H. When the direct ray clears the obstruction, H is negative, and the shadow loss approaches 0 db in an oscillatory manner as the clearance is increased. In other words, a substantial clearance is required over line-of-sight paths in order to obtain "free-space" transmission. The knife edge diffraction calculation is substantially independent of polarization as long as the distance from the edge is more than a few wavelengths.

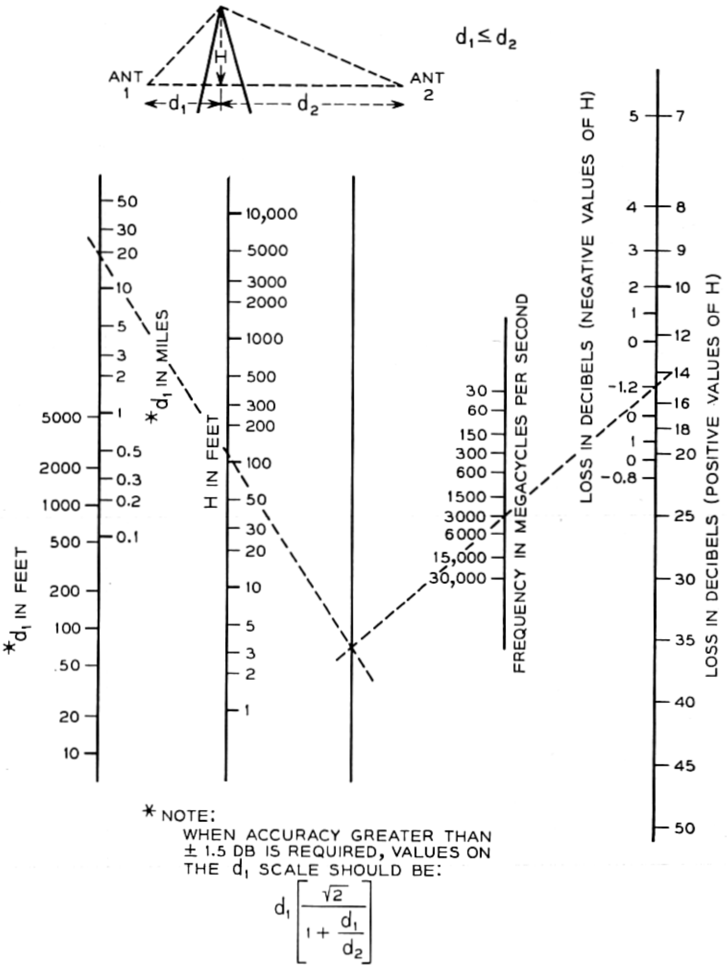

Fig. 7 — Knife-edge diffraction loss relative to free space.

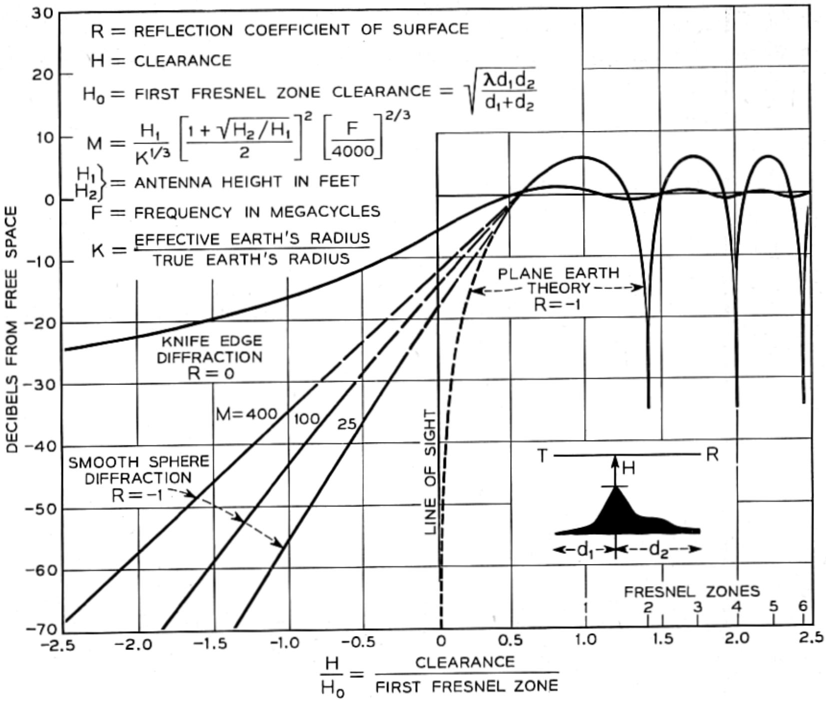

FIG. 8 — Transmission loss versus clearance.

At grazing incidence, the expected loss over a ridge is 6 db (Fig. 7) while over a smooth spherical earth Fig. 6 indicates a loss of about 20 db. More accurate results in the vicinity of the horizon can be obtained by expressing radio transmission in terms of path clearance measured in Fresnel zones as shown in Fig. 8. In this representation the plane earth theory and the ridge diffraction can be represented by single lines; but the smooth sphere theory requires a family of curves with a parameter M that depends primarily on antenna heights and frequency. The big difference in the losses predicted by diffraction around a perfect sphere and by diffraction over a knife edge indicates that diffraction losses depend critically on the assumed type of profile. A suitable solution for the intermediate problem of diffraction over a rough earth has not yet been obtained.

Experimental Data Far Beyond the Horizon

Most of the experimental data at points far beyond the horizon fall in between the theoretical curves for diffraction over a smooth sphere and for diffraction over a knife edge obstruction. Various theories have been advanced to explain these effects but none has been reduced to a simple form for every day use.[13] The explanation most commonly accepted is that energy is reflected or scattered from turbulent air masses in the volume of air that is enclosed by the intersection of the beamwidths of the transmitting and receiving antennas.[14]

The variation in the long term median signals with distance has been derived from experimental results and is shown in Fig. 9 for two frequencies.[15] The ordinate is in db below the signal that would have been expected at the same distance in free space with the same power and the same antennas. The strongest signals are obtained by pointing the antennas at the horizon along the great circle route. The values shown on Fig. 9 are essentially annual averages taken from a large number of paths, and substantial variations are to be expected with terrain, climate, and season as well as from day to day fading.

Antenna sites with sufficient clearance so that the horizon is several miles away will, on the average, provide a higher median signal (less loss) than shown on Fig. 9. Conversely, sites for which the antenna must be pointed upward to clear the horizon will ordinarily result in appreciably more loss than shown on Fig. 9. In many cases the effects of path length and angles to the horizon can be combined by plotting the experimental results as a function of the angle between the lines drawn tangent to the horizon from the transmitting and receiving sites.[16]

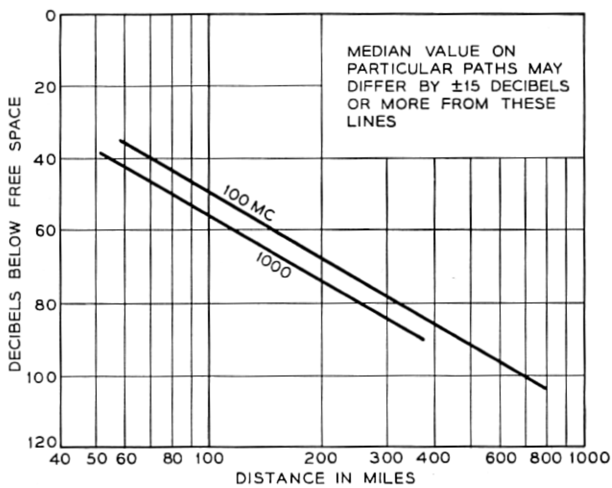

Fig. 9 — Beyond-horizon transmission — median signal level versus distance.

When the path profile consists of a single sharp obstruction that can be seen from both terminals, the signal level may approach the value predicted by the knife edge diffraction theory.[17] While several interesting and unusual cases have been recorded, the knife edge or "obstacle gain" theory is not applicable to the typical but only to the exceptional paths.

As in the case of line-of-sight transmission the fading of radio signals beyond the horizon can be divided into fast fading and slow fading. The fast fading is caused by multipath transmission in the atmosphere, and for a given size antenna, the rate of fading increases as either the frequency or the distance is increased. This type of fading is much faster than the maximum fast fading observed on line of sight paths, but the two are similar in principle. The magnitude of the fades is described by the Rayleigh distribution.

Slow fading means variations in average signal level over a period of hours or days and it is greater on beyond horizon paths than on line-of-sight paths. This type of fading is almost independent of frequency and seems to be associated with changes in the average refraction of the atmosphere. At distances of 150 to 200 miles the variations in hourly median value around the annual median seem to follow a normal probability law in db with a standard deviation of about 8 db. Typical fading distributions are shown on Fig. 10.

The median signal levels are higher in warm humid climates than in cold dry climates and seasonal variations of as much as ± 10 db or more from the annual median have been observed.[18]

Since the scattered signals arrive with considerable phase irregularities in the plane of the receiving antenna, narrow-beamed (high gain) antennas do not yield power outputs proportional to their theoretical area gains. This effect has sometimes been called loss in antenna gain, but it is a propagation effect and not an antenna effect. On 150 to 200 miles this loss in received power may amount to one or two db for a 40 db gain antenna, and perhaps six to eight db for a 50 db antenna. These extra losses vary with time but the variations seem to be uncorrelated with the actual signal level.

The bandwidth that can be used on a single radio carrier is frequently limited by the selective fading caused by multipath or echo effects. Echoes are not troublesome as long as the echo time delays are very short compared with one cycle of the highest baseband frequency. The probability of long delayed echoes can be reduced (and the rate of fast fading can be decreased) by the use of narrow beam antennas both within and beyond the horizon.[19, 20] Useful bandwidths of several megacycles appear to be feasible with the antennas that are needed to provide adequate signal-to-noise margins. Successful tests of television and of multichannel telephone transmission have been reported on a 188-mile path at 5,000 mc.[21]

The effects of fast fading can be reduced substantially by the use of either frequency or space diversity. The frequency or space separation required for diversity varies with time and with the degree of correlation that can be tolerated. A horizontal (or vertical) separation of about 100 wavelengths is ordinarily adequate for space diversity on 100- to 200-mile paths. The corresponding figure for the required frequency separation for adequate diversity seems likely to be more than 20 mc.

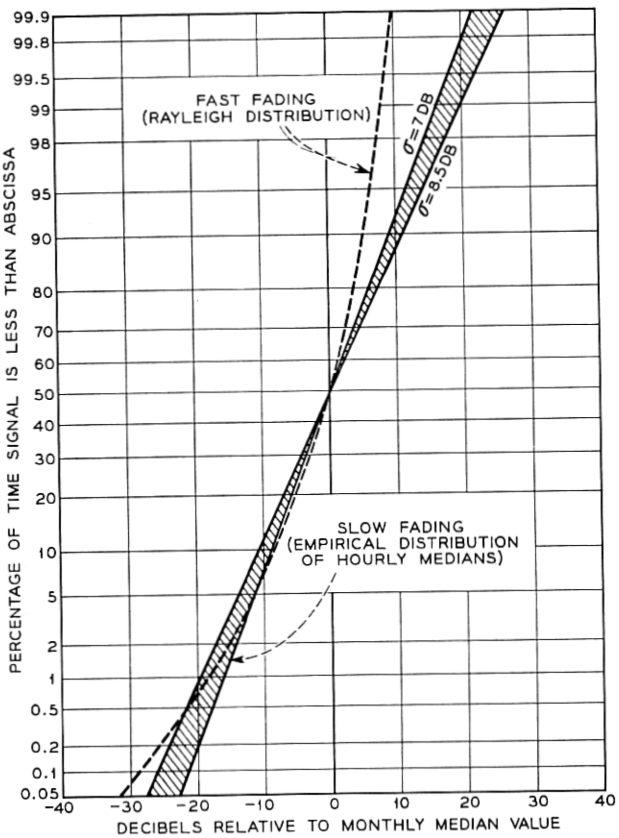

FIG. 10 — Typical fading characteristics at points far beyond the horizon.

Effects of Nearby Hills — Particularly on Short Paths

The experimental results on the effects of hills indicate that the shadow losses increase with the frequency and with the roughness of the terrain.[22]

An empirical summary of the available data is shown on Fig. 11. The roughness of the terrain is represented by the height H shown on the profile at the top of the chart. This height is the difference in elevation between the bottom of the valley and the elevation necessary to obtain line of sight from the transmitting antenna. The right hand scale in Fig. 11 indicates the additional loss above that expected over plane earth. Both the median loss and the difference between the median and the 10 per cent values are shown. For example, with variations in terrain of 500 feet, the estimated median shadow loss at 450 mc is about 20 db and the

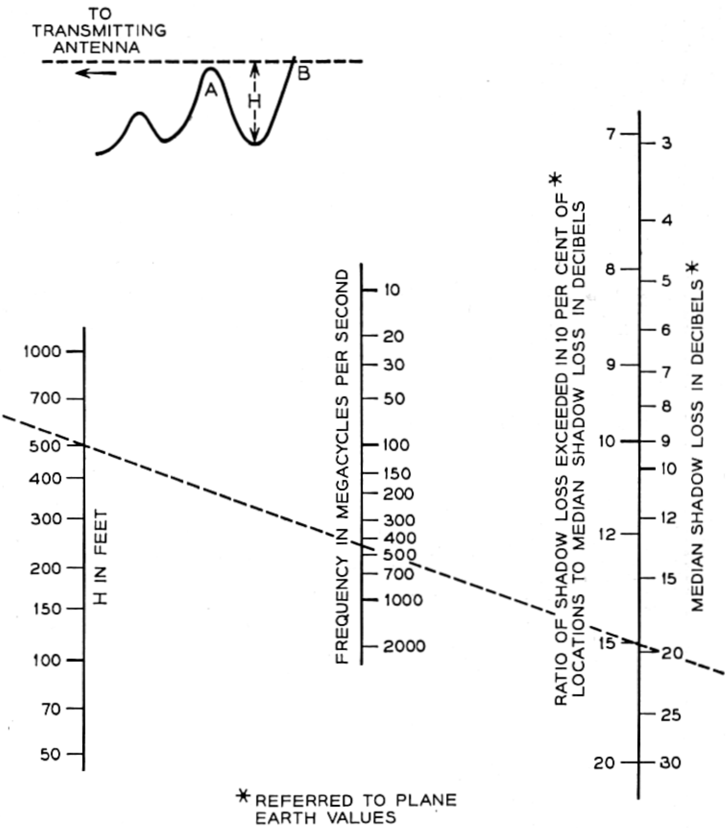

Fig. 11 — Estimated distribution of shadow losses.

shadow loss exceeded in only 10 per cent of the possible locations between points A and B is about 20 + 15 = 35 db. It will be recognized that 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 within a few feet.

Effects of Buildings and Trees

The shadow losses resulting from buildings and trees follow somewhat different laws from those caused by hills. Buildings may be 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 but, on the other hand, the angles of diffraction over or around the buildings are usually greater than for natural terrain. In other words, the artificial canyons caused by buildings are considerably narrower than natural valleys, and this factor tends to increase the loss resulting from the presence of buildings. The available quantitative data on the effects of buildings are confined primarily to New York City. These data indicate that in the range of 40 to 450 mc there is no significant change with frequency, or at least the variation with frequency is somewhat less than that noted in the case of hills.[23] The median field intensity 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 per cent and 90 per cent points are about 15 and 35 db, respectively.

Typical values of attenuation through a brick wall, are from 2 to 5 db at 30 mc and 10 to 40 db at 3,000 mc, depending on whether the wall is dry or wet. Consequently most buildings are rather opaque at frequencies of the order of thousands of megacycles.

When an antenna is surrounded by moderately thick trees and below tree-top level, the average loss at 30 mc resulting from the trees is usually 2 or 3 db for vertical polarization and is negligible with horizontal polarization. However, large and rapid variations in the received field intensity may exist within a small area, resulting from the standing-wave pattern set up by reflections from trees located at a distance of several wavelengths from the antenna. Consequently, several near-by locations should be investigated for best results. At 100 mc 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 mc they tend to be independent of the type of polarization. Above 1,000 mc, trees that are thick enough to block vision are roughly equivalent to a solid obstruction of the same over-all size.

IV. MEDIUM AND LOW FREQUENCY GROUND WAVE TRANSMISSION

Wherever the antenna heights are small compared with the wavelength, the received field intensity is ordinarily stronger with vertical polarization than with horizontal and is stronger over sea water than over poor soil. In these cases the "surface wave" term in (3) cannot be neglected. This use of the term "surface wave" follows Norton's usage and is not equivalent to the Sommerfeld or Zenneck "surface waves."

The parameter A is the plane earth attenuation factor for antennas at ground level. It 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:[24, 25]

$$A \approx \frac{-1}{1 + j\,\dfrac{2\pi d}{\lambda}\,(\sin\theta + z)^2} \tag{9}$$

where

$$z = \frac{\sqrt{\epsilon_0 - \cos^2\theta}}{\epsilon_0} \text{ for vertical polarization}$$

$$z = \sqrt{\epsilon_0 - \cos^2\theta} \text{ for horizontal polarization}$$

$\varepsilon_0 = \epsilon - j60\sigma\lambda$

θ = angle between reflected ray and the ground

= 0 for antennas at ground level

ϵ = dielectric constant of the ground relative to unity in free space

σ = conductivity of the ground in mhos per meter

λ = wavelength in meters

In terms of these same parameters the reflection coefficient of the ground is given by[26]

$$R = \frac{\sin\theta - z}{\sin\theta + z} \tag{10}$$

When $\theta \ll |z|$ the reflection coefficient approaches -1; when $\theta \gg |z|$

(which can happen only with vertical polarization) the reflection coefficient approaches +1. The angle for which the reflection coefficient is a minimum is called the pseudo-Brewster angle and it occurs for $\sin\theta = |z|$.

For antennas approaching ground level the first two terms in (3) cancel each other (h_1 and h_2 approach zero and R approaches -1) and the magnitude of the third term becomes

$$|(1 - R)A| \approx \frac{2}{\frac{2\pi d}{\lambda} z^2} = \frac{4\pi h_0^2}{\lambda d} \tag{11}$$

where h_0 = minimum effective antenna height shown in Fig. 3

$$= \left|\frac{\lambda}{2\pi z}\right|$$

The surface wave term arises because the earth is not a perfect reflector. Some energy is transmitted into the ground and sets up ground currents, which are distorted relative to what would have been the case in an ideal perfectly reflecting surface. The surface wave is defined as the vertical electric field for vertical polarization, or the horizontal electric field for horizontal polarization, that is associated with the extra components of the ground currents caused by lack of perfect reflection. Another component of the electric field associated with the ground currents is in the direction of propagation. It accounts for the success of the wave antenna at lower frequencies, but it is always smaller in magnitude than the surface wave as defined above. The components of the electric vector in three mutually perpendicular co-ordinates are given by Norton.[27]

In addition to the effect of the earth on the propagation of radio waves, the presence of the ground may also affect the impedance of low antennas and thereby may have an effect on the generation and reception of radio waves.[28] As the antenna height varies, the impedance oscillates around the free space value, but the variations in impedance are usually unimportant as long as the center of the antenna is more than a quarter-wavelength above the ground. For vertical grounded antennas (such as are used in standard AM broadcasting) the impedance is doubled and the net effect is that the maximum field intensity is 3 db above the free space value instead of 6 db as indicated in (4) for elevated antennas.

Typical values of the field intensity to be expected from a grounded quarter-wave vertical antenna are shown in Fig. 12 for transmission over poor soil and in Fig. 13 for transmission over sea water. These charts in-

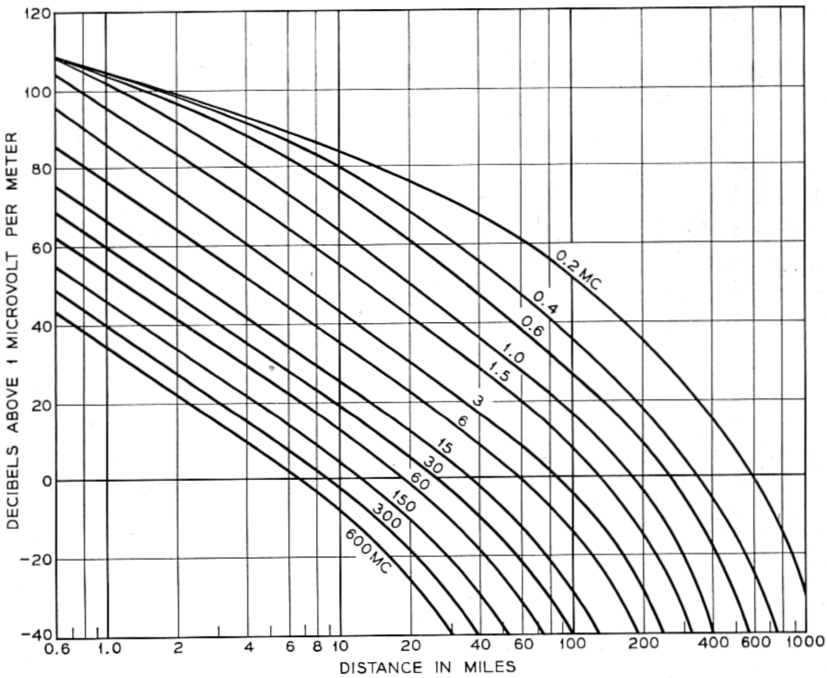

FIG. 12 — Field intensity for vertical polarization over poor soil for 1-kw radiated power from a grounded whip antenna.

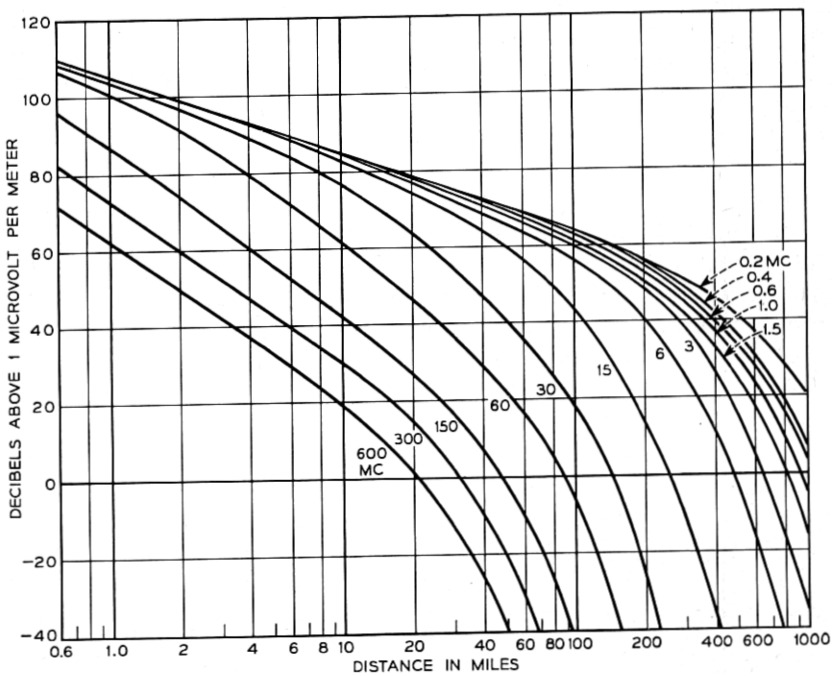

FIG. 13 — Field intensity for vertical polarization over sea water for 1-kw radiated power from a grounded whip antenna.

clude the effect of diffraction and average refraction around a smooth spherical earth as discussed in Section III, but do not include the ionospheric effects described in the next Section. The increase in signal obtained by raising either antenna height is shown in Fig. 14 for poor soil and Fig. 15 for sea water.

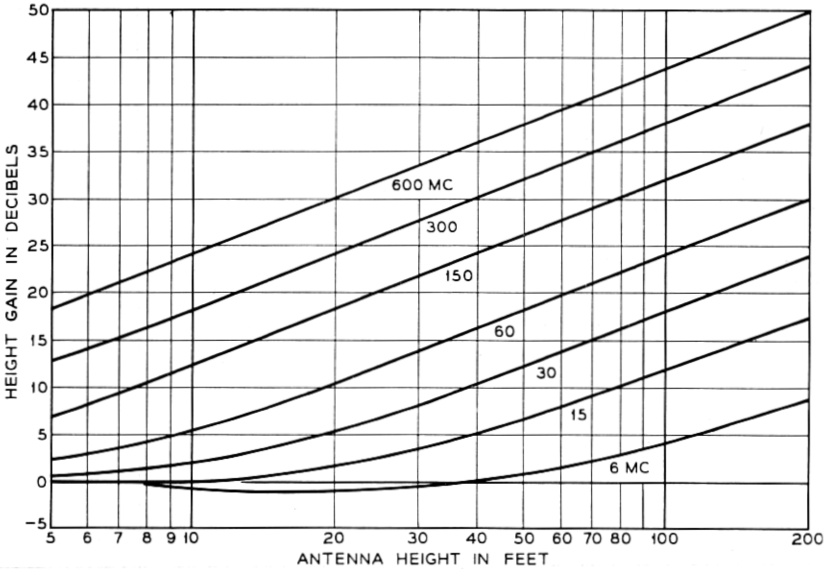

Fig. 14 — Antenna height gain factor for vertical polarization over poor soil.

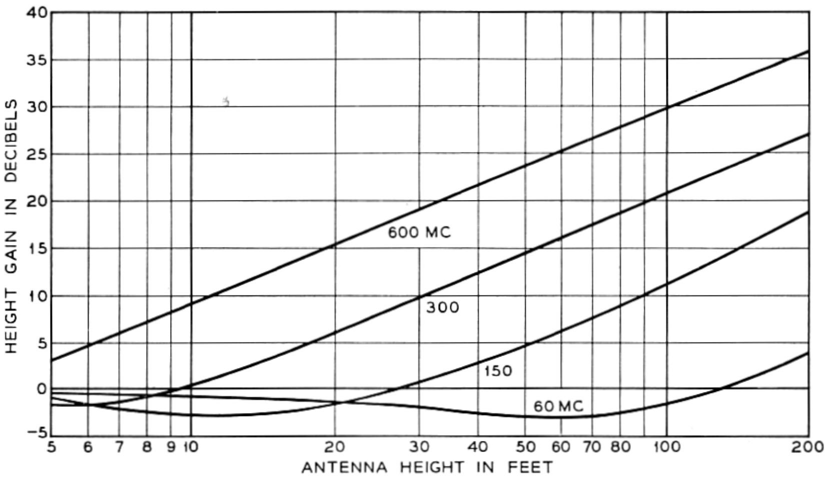

Fig. 15 — Antenna height gain factor for vertical polarization over sea water.

V. IONOSPHERIC TRANSMISSION

In addition to the tropospheric or ground wave transmission discussed in the preceding sections, useful radio energy at frequencies below about 25 to 100 mc may be returned to the earth by reflection from the ionosphere, which consists of several ionized layers located 50 to 200 miles above the earth. The relatively high density of ions and free electrons in this region provides an effective index of refraction of less than one, and the resulting transmission path is similar to that in the well known optical phenomenon of total internal reflection. The mechanism is generally spoken of as reflection from certain virtual heights.[29] Polarization is not maintained in ionospheric transmission and the choice depends on the antenna design that is most efficient at the desired elevation angles.

Regular Ionospheric Transmission

The ionosphere consists of three or more distinct layers. This does not mean that the space between layers is free of ionization but rather that the curve of ion density versus height has several distinct peaks. The E, $F1$, and $F2$ layers are present during the daytime but the F_1 and F_2 combine to form a single layer at night. A lower layer called the D layer is also present during the day, but its principal effect is to absorb rather than reflect.

Information about the nature of the inosphere has been obtained by transmitting pulsed radio signals directly overhead and by recording the signal intensity and the time delay of the echoes returned from these layers. At night all frequencies below the critical frequency f_c are returned to earth with an average signal intensity that is about 3 to 6 db below the free space signal that would be expected for the round trip distance. At frequencies higher than the critical frequency the signal intensity is very weak or undetectable. Typical values of the critical frequency for Washington, D. C., are shown in Fig. 16.

During the daytime, the critical frequency is increased 2 to 3 times over the corresponding nighttime value. This apparent increase in the useful frequency range for ionospheric transmission is largely offset by the heavy daytime absorption which reaches a maximum in the 1 to 2-mc range. This absorption is caused by interaction between the free electrons and the earth's magnetic field. The absence of appreciable absorption at night indicates that most of the free electrons disappear when the sun goes down. Charged particles traveling in a magnetic field have a resonant or gyromagnetic frequency, and for electrons in the earth's magnetic field, of about 0.5 gauss, this resonance occurs at about 1.4

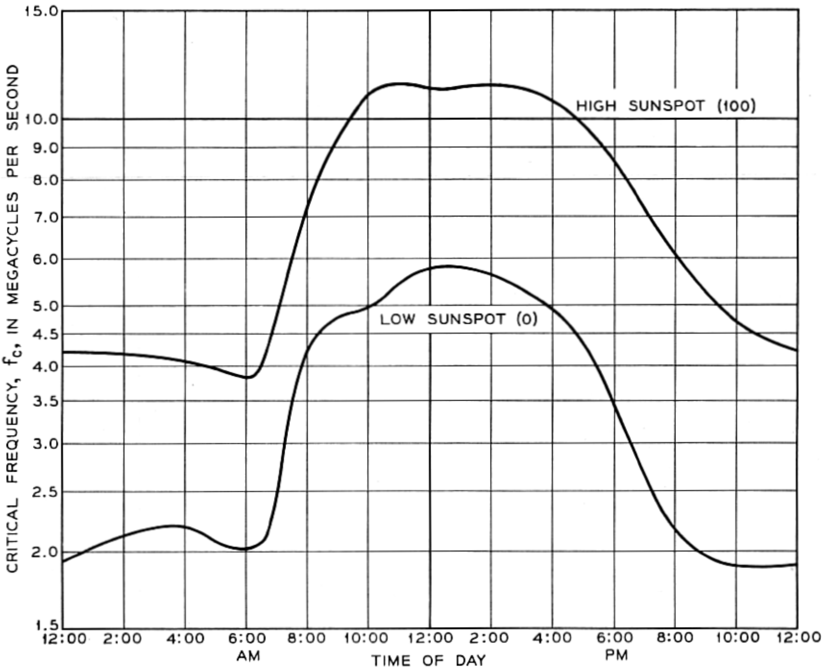

Fig. 16 — Typical diurnal variation of critical frequency for January at latitude 40 degrees.

mc. The magnitude of the absorption varies with the angle of the sun above the horizon and is a maximum about noon. The approximate midday absorption is shown on Fig. 17 in terms of db per 100 miles of path length. (On short paths this length is the actual path traveled, not the distance along the earth's surface.)

Long distance transmission requires that the signal be reflected from the ionosphere at a small angle instead of the perpendicular incidence used in obtaining the critical frequency. For angles other than directly overhead an assumption which seems to be borne out in practice is that the highest frequency for which essentially free space transmission is obtained is $f_c/\sin \alpha$, where α is the angle between the radio ray and ionospheric layer. This limiting frequency is greater than the critical frequency and is called the maximum usable frequency which is usually abbreviated muf. The curved geometry limits the distance that can be obtained with one-hop transmission to about 2,500 miles and the muf at the longer distances does not exceed 3 to 3.5 times the critical frequency.

The difference between day and night effects means that most sky-

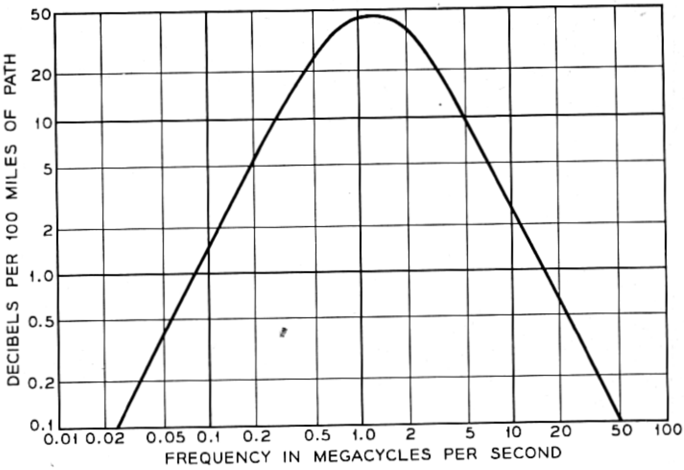

Fig. 17 — Typical values of midday ionospheric absorption.

wave paths require at least two frequencies. A relatively low frequency is needed to get under the nighttime muf and a higher frequency is needed that is below the daytime muf but above the region of high absorption. This lower limit depends on the available signal-to-noise margin and is commonly called the lowest useful high frequency.

Frequencies most suitable for transmission of 1000 miles or more will ordinarily not be reflected at the high angles needed for much shorter distances. As a result the range of skywave transmission ordinarily does not overlap the range of groundwave transmission, and the intermediate region is called the skip zone because the signal is too weak to be useful. At frequencies of a few megacycles the groundwave and skywave ranges may overlap with the result that severe fading occurs when the two signals are comparable in amplitude.

In addition to the diurnal variations in frequency and in absorption there are systematic changes with season, latitude, and with the nominally eleven-year sunspot cycle. Random changes in the critical frequency of about ± 15 per cent from the monthly median value are also to be expected from day to day.

The F layer is the principal contributor to transmission beyond 1,000 to 1,500 miles and typical values of the maximum usable frequency can be summarized as follows: The median nighttime critical frequency for F layer transmission at the latitude at Washington, D. C., is about 2 mc in the month of June during a period of low sunspot activity. All frequencies below about 2 mc are strongly reflected to earth while the higher frequencies are either greatly attenuated or are lost in outer space. The approximate maximum usable frequency for other conditions is greater than 2 mc by the ratios shown in Table I.

TABLE I

Variation With	Multiplying factor
(1) Time of Day	
Midnight	1 (Reference)
Early Afternoon—June	2
December	3
(2) Path Length	
Less than 200 Miles	1 (Reference)
Approx. 1000 Miles	2
More than 2500 Miles	3.5
(3) Sunspot Cycle	
Minimum	1 (Reference)
For one year in five—June	1.5
December	2
For one year in fifty—June	2
December	3

When all of the above variations add "in phase," transmission for distances of 2,500 miles or more is possible at frequencies up to 40 to 60 mc. For example, using the table, 2,500-mile transmission on an early December afternoon in one year out of five can be expected on a frequency of about 42 mc, which is $3 \times 3.5 \times 2 = 21$ times the reference critical frequency of 2 mc. Peaks of the sunspot cycle occurred in 1937 and in 1947–1948 so another peak is expected in 1958–1959.

The maximum usable frequency also varies with the geomagnetic latitude but, as a first approximation, the above values are typical of continental U. S. Forecasts of the muf to be expected throughout the world are issued monthly by the National Bureau of Standards.[30, 31] These estimates include the diurnal, seasonal, and sunspot effects.

Another type of absorption, over and above the usual daytime absorption, occurs both day and night on transmission paths that travel through the auroral zone. The auroral zones are centered on the north and south magnetic poles at about the same distance as the Arctic Circle is from the geographical north pole. During periods of magnetic storms these auroral zones expand over an area much larger than normal and thereby disrupt communication by introducing unexpected absorption. These conditions of poor transmission can last for hours and sometimes even for days. These periods of increased absorption are more common in the polar regions than in the temperate zones or the tropics because of the proximity of the auroral zone and are frequently called HF "blackouts." During a "blackout," the signal level is decreased considerably but the signal does not drop out completely. It appears possible that the outage time normally associated with HF transmission could be greatly reduced by the use of transmitter power and antenna size comparable to that needed in the ionospheric scatter method described below.

In addition to the auroral zone absorption, there are shorter periods of severe absorption over the entire hemisphere facing the sun. These erratic and unpredictable effects which seem to be associated with eruptions on the sun are called sudden ionospheric disturbances (SID's) or the Dellinger effect.

The preceding information is based primarily on F layer transmission. The E layer is located closer to the earth than the F layer and the maximum transmission distance for a single reflection is about 1,200 miles.

Reflections from the E layer sometimes occur at frequencies above about 20 mc but are erratic in both time and space. This phenomenon has been explained by assuming that the E layer contains clouds of ionization that are variable in size, density, and location. The maximum frequency returned to earth may at times be as high as 70 or 80 mc.[32] The high values are more likely to occur during the summer, and during the minimum of the sunspot cycle.

Rapid multipath fading exists on ionospheric circuits and is superimposed on the longer term variations discussed above. The amplitude of the fast fading follows the Rayleigh distribution and echo delays up to several milliseconds are observed. These delays are 10^4 to 10^5 times as long as for tropospheric transmission. As a result of these relatively long delays uncorrelated selective fading can occur within a few hundred cycles. This produces the distortion on voice circuits that is characteristic of "short wave" transmission.

Ionospheric Scatter

The maximum usable frequency used in conventional skywave transmission is defined as the highest frequency returned to earth for which the average transmission is within a few db of free space. As the frequency increases above the muf the signal level decreases rapidly but does not drop out completely. Although the signal level is low, reliable transmission can be obtained at frequencies up to 50 mc or higher and to distances up to at least 1,200 to 1,500 miles.[33] In this case the signal is 80 to 100 db below the free space value and its satisfactory use requires much higher power and larger antennas than are ordinarily used in ionospheric transmission. The approximate variation in median signal level with frequency is shown in Fig. 18.

Ionospheric scatter is apparently the result of reflections from many

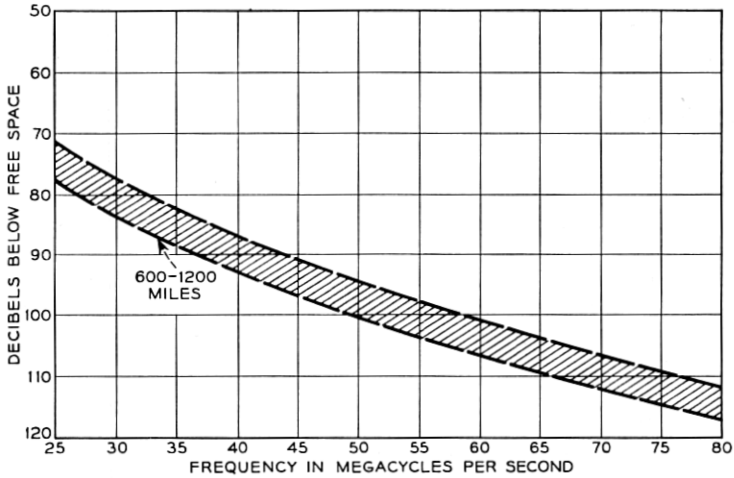

Fig. 18 — Median signal levels for ionospheric scatter transmission.

patches of ionization in the *E* layer. It is suspected that meteors are important in establishing and in maintaining this ionization but this has not been clearly determined.

In common with other types of transmission, the fast fading follows a Rayleigh distribution. The distribution of hourly median values relative to the long term median (after the high signals resulting from sporadic *E* transmission have been removed) is approximately a normal probability law with a standard deviation of about 6 to 8 db.

Ionospheric scatter transmission is suitable for several telegraph channels but the useful bandwidth is limited by the severe selective fading that is characteristic of all ionospheric transmission.

VI. NOISE LEVELS

The usefulness of a radio signal is limited by the "noise" in the receiver. This noise may be either unwanted external interference or the first circuit noise in the receiver itself.

Atmospheric static is ordinarily controlling at frequencies below a few megacycles while set noise is the primary limitation at frequencies above 200 to 500 mc. In the 10- to 200-mc band the controlling factor depends on the location, time of day, etc. and may be either atmospheric static, man made noise, cosmic noise, or set noise.

The theoretical minimum circuit noise caused by the thermal agitation of the electrons at usual atmospheric temperatures is 204 db below one watt per cycle of bandwidth; that is, the thermal noise power, in dbw is −204 + 10 log (bandwidth). The first circuit or set noise is usually higher than the theoretical minimum by a factor known as the noise figure. For example, the set noise in a receiver with a 6-kc noise bandwidth and an 8-db noise figure is 158 db below 1 watt, which is equivalent to 0.12 microvolts across 100 ohms. Variations in thermal noise and set noise follow the Rayleigh distribution, but the quantitative reference is usually the rms value (63.2 per cent point), which is 1.6 db higher than the median value shown on Figs. 4 and 10. Momentary thermal noise peaks more than 10 to 12 db above the median value occur for a small percentage of the time.

Atmospheric static is caused by lightning and other natural electrical disturbances, and is propagated over the earth by ionospheric transmission. Static levels are generally stronger at night than in the daytime. Atmospheric static is more noticeable in the warm tropical areas where the storms are most frequent than it is in the colder northern regions which are far removed from the lightning storms.

Typical average values of noise in a 6-kc band are shown on Fig. 19. The atmospheric static data are rough yearly averages for a latitude of 40°. Typical summer averages are a few db higher than the value on Fig. 19 and the corresponding winter values are a few db lower. The average noise levels in the tropics may be as much as 15 db higher than

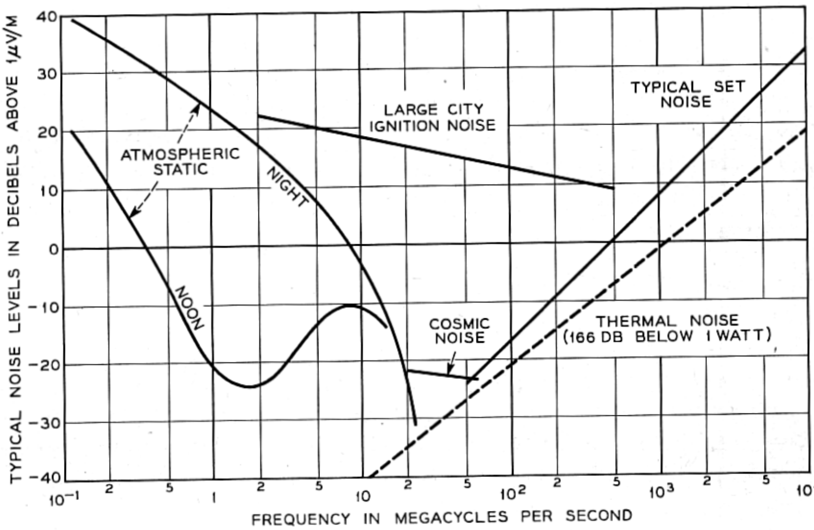

FIG. 19 — Typical average noise level in a 6-kc band.

for latitudes of 40° while in the Arctic region the noise may be 15 to 25 db lower. The corresponding values for other bandwidths can be obtained by adding 10 db for each 10-fold increase in bandwidth. More complete estimates of atmospheric noise on a world wide basis are given in the National Bureau of Standards Bulletin 462.[29] These noise data are based on measurements with a time constant of 100 to 200 milliseconds. Noise peaks, as measured on a cathode ray tube, may be considerably higher.

The man made noise shown on Fig. 19 is caused primarily by operation of electric switches, ignition noise, etc., and may be a controlling factor at frequencies below 200 to 400 mc. Since radio transmission in this frequency range is primarily tropospheric (ground wave), man made noise can be relatively unimportant beyond 10 to 20 miles from the source. In rural areas, the controlling factor can be either set noise or cosmic noise.

Cosmic and solar noise is a thermal type interference of extra-terrestial origin.[34] Its practical importance as a limitation on communication circuits seems to be in the 20- to 80-mc range. Cosmic noise has been found at much higher frequencies but its magnitude is not significantly above set noise. On the other hand, noise from the sun increases as the frequency increases and may become the controlling noise source when high gain antennas are used. The rapidly expanding science of radio astronomy is investigating the variations in both time and frequency of these extra-terrestial sources of radio energy.

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