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Scattering of Electromagnetic Waves in the Troposphere and the Use of This Technique For Communications

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Scattering of Electromagnetic Waves in the Troposphere and the Use of This Technique For Communications

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Abstract. This article is an introduction to the subject of tropospheric scatter propagation for the non-specialist. It opens with a review of various modes of propagation which may exist in a non-turbulent atmosphere, such as diffraction and ionospheric reflection. The scattering of energy in a turbulent medium is then examined, and statistical methods are introduced to describe the resultant field. Special characteristics of the signal are discussed, such as variation with distance, climatic effects, frequency dependence, fading, bandwidth, and noise level. The paper concludes with a description of methods and equipment employed in the design of a communication system operating over a distance in the range of 100 to 500 miles. It is concluded that tropospheric scatter terminals are large and costly, but that under some circumstances such a system has economic advantages over a line-of-sight relay system and can furnish comparable quality and reliability.

INTRODUCTION

It will be assumed that the reader has no specialized training in the field of wave propagation. For that reason, the following discussion will be kept largely qualitative and non-mathematical. Also, the subject will be introduced by a brief review of the more familiar propagation modes, some of which can be readily explained by the methods of geometrical optics.

Free-space propagation. When transmitting and receiving antennas are remote from reflecting or scattering objects and the medium is assumed to be homogeneous and isotropic, it is especially simple to calculate the transmission loss, or ratio of transmitted power to received power. It is convenient also to assume that the antennas are perfectly efficient, a condition which is closely approximated in practice except at low frequencies. Then the power density is

$$P = \frac{w_T \, g_T}{4\pi \, d^2} \text{ watts }/\text{m}^2 , \qquad (1)$$

where

w_T is the radiated power,

g_T is the directivity (gain) of the transmitting antenna,

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d is the distance.

The effective area of the receiving antenna is

$$A_e = g_R \lambda^2/4\pi , \qquad (2)$$

where

g_R is the directivity of the receiving antenna,

λ is the wavelength,

$\lambda^2/4\pi$ is the effective area of an isotropic antenna.

The product of (1) and (2) gives the received power (maximum available):

$$w_R = \frac{w_T\, g_T\, g_R\, \lambda^2}{(4\,\pi\, d)^2} \qquad (3)$$

This may be modified to

$$\frac{w_T}{w_R} = \frac{(4\,\pi\, d)^2}{g_T\, g_R\, \lambda^2} \qquad (4)$$

The transmission loss is usually defined as 10 times the logarithm of this ratio:

$$L = 10 \log \left(\frac{w_T}{w_R}\right) = 20 \log\, (4\pi\, d/\lambda) - G_T - G_R \text{ (decibels)} \qquad (5)$$

$$G_T = 10 \log g_T ,$$

where

$$G_R = 10 \log g_R .$$

It is seen that the transmission loss for a pair of isotropic antennas is simply 20 log $(4\pi\, d/\lambda)$ decibels. This is termed the basic transmission loss. It increases six decibels every time the distance doubles (6 db per octave). The wavelength dependence results from the fact that the effective area of the receiving antenna varies inversely with the square of the wavelength. Thus, the transmission loss increases six decibels per octave of frequency when the antennas must be essentially non-directional. On the other hand, when the antennas have fixed apertures (effective areas), the transmitted beamwidth becomes less with increasing frequency, and the transmission loss decreases six decibels per octave. This is apparent from equation (5) when we note that each term of the right member increases 6 db per octave. For isotropic antennas, G_T and G_R are zero. For an aperture antenna, such as a paraboloid or horn,

$$G_{T,\,R} \approx 10 \log\, (6A/\lambda^2), \qquad (6)$$

where A is the aperture area (valid only for an aperture more than about five wavelengths in diameter).

The free-space loss increases so slowly with distance that it is possible with currently available antennas and transmitter power levels to effect one-way communication over interplanetary distances.

Line-of-sight propagation with a non-turbulent atmosphere. We can have free-space propagation only when the waves do not pass near a reflecting or scattering object and when the medium is essentially homogeneous. This is the case of two vehicles very remote from the earth. However, the method yields approximately correct results when the path extends from a vehicle at high elevation to a sharply-beamed, ground-based antenna, so that the surface near the antenna is not effectively illuminated by the antenna. It is applicable even to the case of two antennas mounted on the surface, provided that the ray path clears the surface sufficiently and the surface is so rough that specular reflection is neglible. In the last case, however, it is usually necessary to consider the effects of the inhomogeneous character of the atmosphere. The ray normally follows a curved path because of stratification of the refractive index of the air. And when the signal bandwidth is large, it is usually not permissible to neglect the multipath effects produced by turbulence.

In the simplest case, where the earth is assumed to be smooth, the atmosphere non-turbulent, and the operating frequency high (greater than 50 mc), the problem of calculating transmission loss between antennas near the surface is still not very difficult. It is found that the negative gradient of the refractive index of the atmosphere causes a ray to be bent slightly toward the surface. This effect is often simulated in the solution by adopting an effective earth radius greater than the actual radius and then neglecting the atmosphere. A multiplier of 4/3 is found to be a good average value for the lowest layer of 1-km depth, so that the effective earth radius is changed from 3,960 miles to 5,280 miles. When a ray is traveling nearly horizontally in a stratified medium in which the refractive index gradient is dn/dh, an application of Snell's law shows that the ray path becomes straight provided that an effective earth radius ka is adopted, given by

$$\frac{1}{ka} = \frac{1}{a} + \frac{dn}{dh} \qquad (7)$$

where a is the true earth radius. Solution for k gives

$$k = \frac{1}{1 + a\, dn/dh}\,. \qquad (8)$$

When we substitute the approximate values, $a = 21 \times 10^6$ ft, $dn/dh = -12 \times 10^{-9}\ \text{ft}^{-1}$, we get the value $k = 4/3$ already mentioned. The average gradient near the surface can vary widely, however. In some uncommon meteorological conditions, the gradient near the surface can become so large numerically that k becomes infinite or even negative. This condition is known as a surface duct. It yields strong fields beyond the normal horizon. An application of simple geometry shows that the horizon distance is given by

$$d = \sqrt{2ka\,h}\,, \tag{9}$$

where h is the antenna height. For the case where k is taken as 4/3 and where h is expressed in feet and d in miles, (9) become simply

$$d = \sqrt{2h}\,. \tag{10}$$

In addition to considering the effects of coherent refraction in the atmosphere, we must also in many cases take account of reflection from the surface. The plane-wave reflection coefficient of a smooth earth surface can be calculated readily from the familiar Fresnel formula. This coefficient varies with the conductivity and dielectric constant of the earth, with the frequency and angle of incidence, and with the type of polarization. A simplification can often be made at VHF and higher frequencies when the ray path is nearly horizontal. In this case, the reflection coefficient becomes approximately equal to −1, so that the direct and ground-reflected waves tend to cancel at very small values of the grazing angle. For larger values of this angle the two waves can either reinforce or cancel each other and thus produce the familiar interference pattern. So the field strength in the optical region can vary from about 6 db above the free-space value to values which may be very small, especially for horizontal polarization. These "nulls" in the curve of field strength versus distance may prove troublesome in air-ground communication, and some form of height diversity antenna arrangement may be necessary to prevent communication failure at some values of distance.

Diffraction around a curved earth. At points where the line of sight passes close to the surface of the earth, the geometrical or ray treatment fails to give a satisfactory result. Near the limit of the optical region, the field strength may be many decibels below its free-space value. Beyond the horizon, the field strength tends to decrease exponentially with the distance. The rate of decrease becomes greater as the frequency becomes higher. The problem of determining the field strength beyond the radio horizon by analytical means has been solved for a smooth, airless earth and for the case of a constant gradient of refractive index in the atmosphere. The mathematical procedures are rather lengthy and sophisticated, but the result is in some cases relatively simple. The field strength is obtained as the evaluation of a definite integral in the form of an infinite series. Each term in the series is the product of two antenna height gain functions and an exponential function of distance.

Certain coefficients associated with these terms are themselves solutions of a differential equation and can be expressed only by infinite series. However, the solution may be restricted to one term when the distance is large compared with the optical distance, and then the evaluation of numerical results becomes quite simple.

The field existing beyond the horizon may be termed the diffraction field, since it obeys laws similar to those involved in the diffraction of light. The radiation tends to flow across the geometric boundary between the illuminated region and the shadow region. This flow occurs more readily at low frequencies than at high frequencies. Therefore, the shadow-zone field dies out more and more rapidly with increasing distance as the frequency becomes higher. If there were no propagation mechanism other than diffraction at frequencies of a few hundred megacycles per second and higher, the effective communication range would extend only a few tens of miles beyond the horizon, even with the highest practical transmitting power.

Another effect must be mentioned at this point. A surface wave, somewhat similar to that encountered on single-wire transmission lines, may be launched in the optical range and may propagate readily beyond the horizon. Surface waves are important only at relatively low frequencies and with vertical polarization. The ease with which a surface wave propagates around the earth curvature results from the tilt of the electric field lines. The E vector must must have a small forward tilt to allow power to flow downward toward the surface to supply surface losses. When the earth resistivity is too high, these surface losses become excessive and the wave soon dies out. When the earth resistivity is low, as for sea water, the surface losses are small, the wave tilt is moderate, and the surface wave can propagate far beyond the horizon with remarkably small attenuation, especially at low frequencies. Unfortunately, antennas for launching vertically polarized waves at low frequencies are either very tall and massive or they are very inefficient.

Reflection from the ionosphere. The action of sunlight and other radiation entering the atmosphere from above produces partial ionization of the air at altitudes extending upward from about 70 km. A radio wave sets the electrons into vibration and the resultant current induced in the ionosphere reacts with the wave to cause reflection and absorption.

Two effects must be distinguished. At low frequencies extending from about 10 kc to several hundred kilocycles per second, the lower portion of the ionosphere acts as a conducting surface and produces reflection in somewhat the same manner as the surface of the earth. Since the air at this level is still rather dense, the electrons collide with heavy particles and lose their directed energy to produce heat. Hence, the wave is partly absorbed in the medium. At frequencies greater than about 2 mc and less than about 30 mc, the waves pass through this lower absorbing region, called the D region, and then a new effect comes into play. At higher altitudes, electron collisions are relatively infrequent, and electron motion induced by a wave modifies the refractive index, making it less than unity. In the complete absence of collisions, the refractive index may even become zero. In this case, the medium develops an infinite phase velocity and characteristic impedance, and a wave normally incident on the ionized layer is reflected without loss. For an obliquely incident wave, the upper portion of the wave front is propagated with a higher velocity than the lower portion, and the wave may be totally reflected at a level where the refractive index is greater than zero. This is a refraction phenomenon which can be deduced from Snell's law, just as in the case of a tropospheric duct.

The effect of a given electron density in modifying the refractive index becomes less as the frequency becomes higher, so that waves of frequency greater than 50 mc are rarely reflected from the ionosphere. In fact, frequencies greater than 30 mc are rarely employed for ionospheric propagation. This fact limits the available spectrum severely. In spite of the relatively low power and simple equipment required for long-distance ionospheric communication, the limited spectrum forces expansion into higher frequency ranges where ionospheric reflection does not occur. There are other disadvantages associated with this mode, such as high atmospheric noise level and the occasional existence of excessive absoption in the D region. Ionospheric disturbances tend to be more common and the reliability of communication lower in the circumpolar (auroral) regions than at lower latitudes.

It has been found that two phenomena occurring at altitudes on the order of 100 km allow useful propagation at frequencies above the limit of normal ionospheric reflection. A persistence turbulence at altitudes of 80 to 90 km produces localized fluctuations of electron density and refractive index, so that incoherent scattering of power can occur. The scatter field strength decreases rapidly with increasing value of the angle measured from the forward direction. This effect is relatively feeble at night, when the ionizing radiation from the sun is interrupted. The scattering ability of the medium also decreases rapidly with increasing frequency, so that frequencies greater than 60 mc are of little value. A second effect is the scattering from meteor trails. Since the larger meteors, which produce strongly ionized trails, enter the atmosphere intermittently, one form of communication system is designed to transmit only when favorably oriented trails exist. Frequencies up to 70 or 80 mc have been found useful. The difficulties incident to automatic starting and stopping of transmissions and the storage of information in memory circuits have limited the application of meteor burst communication methods.

Nature of Tropospheric Fields Far Beyond the Horizon

It has been found that the assumption made with regard to the atmosphere in developing the mathematical theory of diffraction around a curved earth was over-simplified. This assumption was that the refractive index varies only with height and that the gradient observed near the surface may be assumed constant at all heights. It has been extensively demonstrated with the aid of radiosondes and refractometers that the lower troposphere is subject not only to irregular variations of vertical gradient of refractivity but also to horizontal variations of refractivity (defined as a million times the excess of refractive index over unity). The surface refractivity is on the order of 300, whereas the variations due to turbulence, measured over short distances, may range from less than 1 to 10 or more. Small as these departures of refractive index from unity may seem, a theoretical treatment shows that they can account for a great increase of field strength far beyond the horizon over the value predicted by diffraction theory.

One may invoke an optical analogy here. If the atmosphere were homogeneous over a distance corresponding to several optical wavelengths, there would be virtually no scattering of light and twilight on the earth would be of very brief duration. Also, the sky would appear black, not blue. The luminosity of the sky results principally from irregularities of molecular dimensions, whereas the colors perceived at sunrise and sunset result mainly from scattering by large particles, such as dust and water droplets. In view of the obvious and intense scattering of light by the atmosphere, it is certainly not surprising that it should also be capable of scattering radio waves. The fact that this phenomenon was identified only within the period since World War II probably results from the relatively recent advent of high-gain systems and the use of very short wavelengths.

Variation with time and distance. One of the most convincing methods for demonstrating the advantages resulting from the tropospheric scatter mode is to show graphically how the field strength varies with distance. One such graph, partly calculated and partly estimated from data available several years ago, is shown in Figure 1. The vertical coordinate represents the transmission loss between

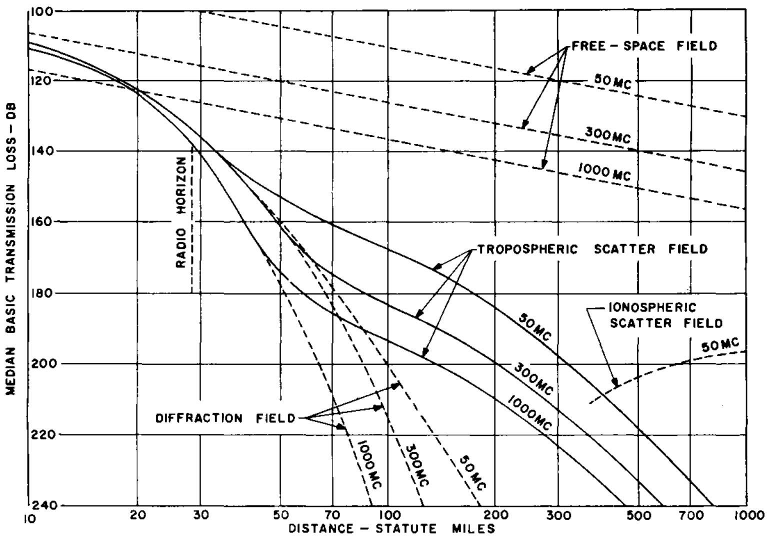

Figure 1. Approximate variation of median basic transmission loss with distance for three frequencies. Assumed height of each antenna = 100 feet. Smooth spherical earth, k = 4/3.

isotropic antennas which is exceeded 50 per cent of the time. The calculated free-space and diffraction fields are shown separately to illustrate more clearly the relative magnitude of the contribution due to scattering. The situation is depicted for three frequencies. Though the basic transmission loss increases with the frequency, it is also possible to achieve much higher antenna directivity at the higher frequencies. Therefore, there is no apparent disadvantage in using frequencies of 1000 mc and higher. It should be noted that the refractive index of the troposphere is virtually independent of the frequency, in contrast with that for the ionosphere, which is strongly frequency dependent. The curves of Figure 1 illustrate that the tropospheric scatter field becomes predominant over the diffraction field a few tens of miles beyond line of sight, that it is about 57 db below the free-space field at 100 miles, and that it falls off much more slowly with increasing distance than the diffraction field.

Figure 2 shows a recent summary of numerous measurements as compiled by National Bureau of Standards (Central Radio Propagation Laboratory). It also shows smooth curves of transmission loss versus distance for various frequencies as adopted by CRPL and by CCIR (Comité Consultatif Internationale Radio). These curves are based on definite antenna heights and on the assumption of a smooth earth and average yearly meteorological conditions. The scatter of the observed values results from variations in antenna

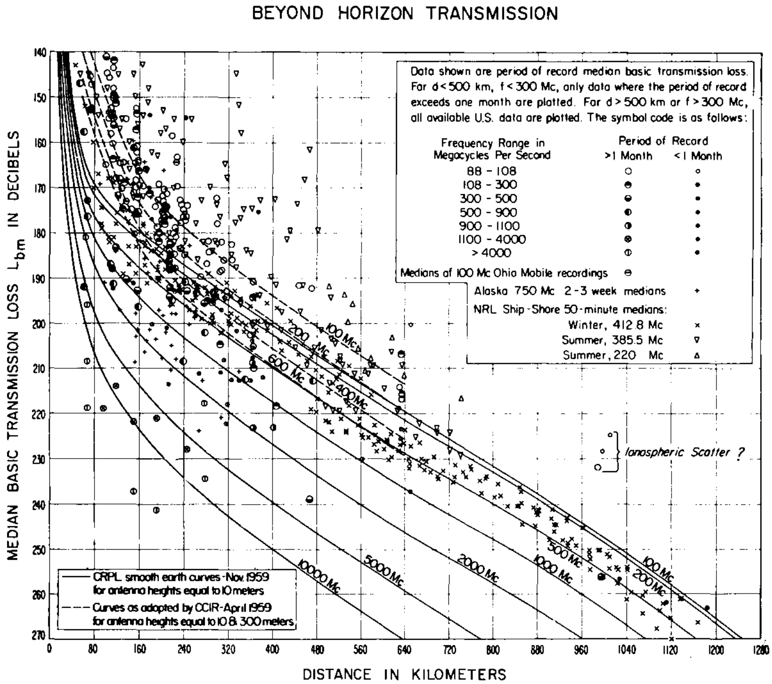

Figure 2. Experimental and theoretical relation between transmission loss and distance as compiled by National Bureau of Standards.

height, terrain, and meteorological conditions. When these conditions are carefully controlled, there is normally rather good agreement between observed and predicted fields. It may be noted that the field strength at 1000 mc and at 160 km (100 mi.) is about 58 db below the free-space value. The variation of predicted transmission loss with distance at 1000 mc is as follows (employing the CRPL curves).

d (mi)	100	200	300	400	500
L_{bm} (db)	195	211	225	237	248
$\triangle L_{bm}$ (db)		16	14	12	11

It is seen that the attenuation varies from 0.16 db per mile in the 100-200 mile range to 0.11 db per mile in the 400-500 mile range. It is also seen that above 500 mc the loss increases with frequency more than 6 db per octave or 20 db per decade, as it would in free space.

Another unique feature of the voltage induced in an antenna by virtue of scatter propagation is the fluctuation in amplitude. This fluctuation is termed fading. It is depicted for a 100-mile, 1000-mc circuit in Figure 3. This fading results from the fact that power

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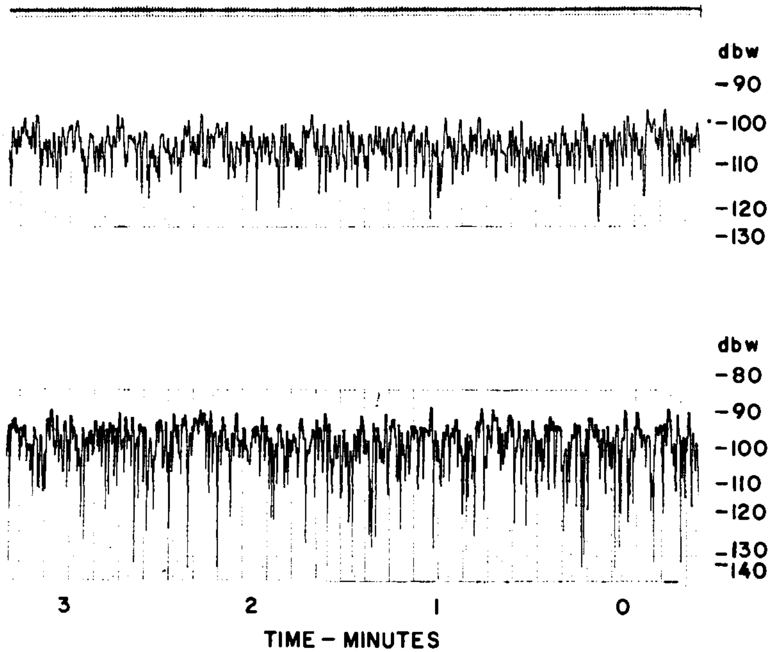

Figure 3. Fluctuation of received signal power for two typical periods. d = 100 miles, f = 900 mc.

arrives at the receiving antenna effectively over a number of paths. The relative lengths of these paths change rapidly due to atmospheric turbulence and wind motion. Therefore, interference occurs between the elementary wavelets, and the antenna voltage fluctuates in amplitude and phase as the instantaneous angles between the different components of the wave change. The resultant amplitude when many sound waves with random phase combine was investigated by Lord Rayleigh, and the amplitude distribution function is now known as the Rayleigh distribution. This function expresses the probability that the instantaneous amplitude exceeds some specific value. The value which is exceeded 50 per cent of the time is called the median value, and it is this value which is generally used to characterize the amplitude of the signal.

Explanation of scattering on basis of ray theory. Since the propagation which we are considering here is basically an atmospheric phenomenon, we must consider the nature of this medium more closely. The troposphere and lower stratosphere contain only electrically neutral particles (neglecting the minute ionizing effects of cosmic rays). The medium is therefore non-conducting. The refractive index depends upon the pressure, temperature, and water vapor pressure. The accepted formula for refractivity is

$$N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \tag{11}$$

where P is the total atmospheric pressure in millibars, e is the water-vapor pressure in millibars, and T is the absolute temperature in degrees Kelvin. The first term, representing the contribution of dry air, shows that the refractivity rises as the pressure increases or the temperature drops. The second term, representing the contribution of water vapor is most important at higher temperatures where the saturation vapor pressure is relatively high. We conclude that cool, moist air has a larger refractivity than warm, dry air. Surface ducts are commonly a result of warm, dry air overlying cool, moist air.

Aerodynamic investigations indicate that turbulence in the lower troposphere is a result principally of the wind blowing over the irregular surface of the earth and of uneven heating of the surface by sunlight. At higher altitudes, turbulence may occur at air mass boundaries, where the gradient of temperature may be abnormally large. Turbulence is also known to occur at the tropopause. It is believed that energy is fed from the causative agent, such as the wind, into the large eddies, and that these degenerate into smaller eddies until a certain limiting size is reached. The turbulent air movements are associated with random variations of temperature and water vapor pressure, and therefore with variations of refractivity.

When a radio wave with a plane or spherical wave front traverses such a turbulent medium, the electric field induces a non-uniform electric displacement density D in the medium, since $D = \epsilon E$ and ϵ, the electric permittivity, is a function of position. In effect, the wave induces a distribution of feeble dipoles in the medium, and these dipoles, being nonuniformly distributed, generate a new field which has different directional properties than the original wave. This is the scatter field. A quantitative treatment will not be attempted here. It is sufficient to state that the scattered power density is ordinarily very weak compared to that in the incident wave, and that the latter can be propagated great distances in the turbulent medium without being greatly modified.

A rough qualitative understanding of the scattering process may be gained from a consideration of the ray treatment depicted in Figure 4. Here a plane wave advances from the left as indicated by the parallel arrows. It encounters a region of increased pressure or reduced temperature, where the refractivity is higher than in the ambient air. This is indicated by the shaded area. After emerging from this region, the wave front is no longer plane because of the reduced phase velocity in the shaded area. The arrows on the emergent wave show that some rays are now propagated in new directions, so that power can reach points which are within the shadow zone. If the "blob" is large compared with a wavelength, the dimple in the wave front also covers a large area and the power can be effectively radiated in new directions. It should be noted that the distortion of the wave front is greatly exaggerated in Figure 4 in order to make it readily perceptible.

Angular dependence of scattered field. The important parameter in a quantitative treatment of scattering in a medium with a random distribution of dielectric constant, ϵ, is the space-correlation function C (R). It may be noted that $\epsilon = n^2$. If we write

$$\epsilon = \epsilon_0 + \triangle\epsilon, \tag{12}$$

then $\triangle \epsilon$ is the variation of dielectric constant from the mean value. It is only the relative variation $(\triangle\epsilon/\epsilon_0) \approx \triangle\epsilon$ which is of interest here. We are now concerned with the average manner in which $\triangle\epsilon$ varies with position. This is where the space-correlation function arises:

$$\overline{\triangle\epsilon\ (r)\ \triangle\epsilon(r + R)} = \overline{(\triangle\epsilon)^2}\ C\ (R) \tag{13}$$

where $\triangle\epsilon$ (r) is the value of $\triangle\epsilon$ at a point defined by r,

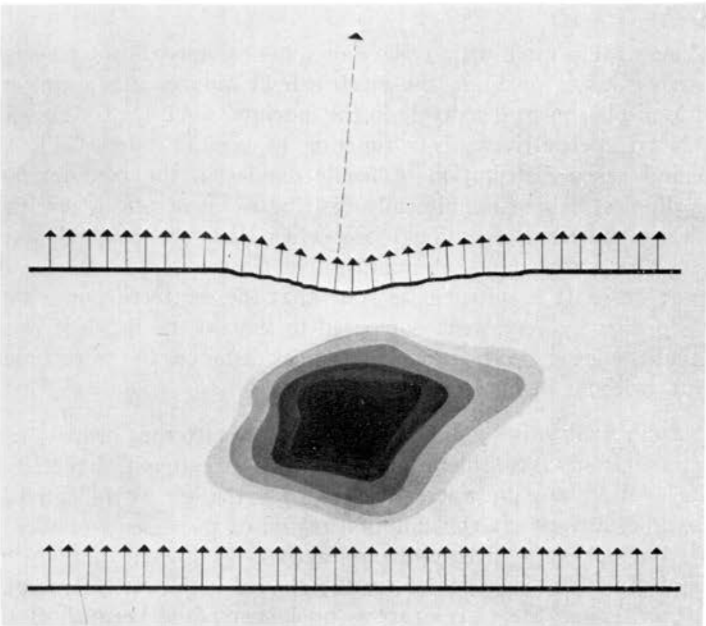

Figure 4. Sketch showing influence of refractive-index perturbation on wave front.

$\triangle\epsilon$ (r + R) is the value of $\triangle\epsilon$ at a point displaced by a distance R,

$\overline{(\triangle\epsilon)^2}$ is the mean square value of $\triangle\epsilon$ at all points of the medium.

The left member is the mean value of the product of $\triangle\epsilon$ at two points separated by a distance R. It is clear that C (O) must always be 1. The manner in which C (R) decreases as R increases determines the angular distribution of the scattered power uniquely.

The choice of the function C (R) may be based on very careful and detailed statistical measurements of the dielectric constant of the medium, or it may be chosen so that the theoretical calculations of scattered power agree in various respects with measured values. The latter method has been the more successful. The first model, proposed by Booker and Gordon (1950), is the exponential model.

$$C\,(R) = e^{-R/l_0} \qquad (14)$$

where l_0 is called the scale length or average size of the blobs in the hierarchy of decaying eddies. A more recent model proposed by Norton (1959), and generally termed the Bessel model, has yielded results more in keeping with experimental propagation measurements. This is given by

$$C\,(R) = (R/l_0)\;K_1\,(R/l_0)\,, \qquad (15)$$

where K_1 is the modified Bessel function. The functions e^{-x} and x K_1 (x) are plotted in Figure 5. Both of these functions lend themselves conveniently to subsequent treatment.

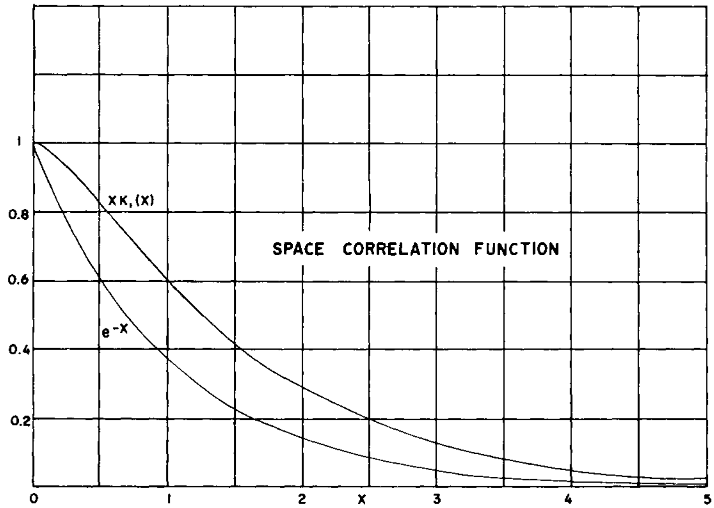

Figure 5. Plots of two space-correlation functions.

When the appropriate mathematical operations are performed, the scattering cross section of the medium, σ, is obtained. This cross section measures the power scattered per unit volume, per unit solid angle, per unit incident power density. It has the dimension cm^{-1}. It is a function of the angle θ measured between the direction of the incident wave and the direction of the scattered wave (see Figure 6). It is also a function of the scale length l_o, and generally of the wavelength, λ. The parameter, σ, is a measure of the average scattering ability of the medium on a microscopic scale.

For the case of the Bessel correlation function, it is given by

$$\sigma(\theta, \lambda) = \frac{6\pi^4}{\lambda^4} \frac{\overline{(\triangle\epsilon)^2}\, l_o^3}{[1 + (4\pi l_o/\lambda)^2 \sin^2 (\theta/2)]^{5/2}}. \tag{16}$$

It may be seen that the maximum power is scattered in the forward direction ($\theta = 0$). The power density drops to one-half of its maximum value when $\sin (\theta/2) = 0.045\ \lambda/l_o$, or $\theta \approx 0.09\ \lambda/l_o$. A typical example is: $\lambda = 1$ m, $l_o = 50$ m, $\theta \approx 0.^\circ 1$. Thus, the scattered power is sharply beamed in the forward direction. Since practical transhorizon paths require θ to be much larger than this value, the second term in the brackets in (16) becomes much greater than 1, and the formula can be simplified by dropping 1:

$$\sigma(\theta, \lambda) = \frac{3\lambda\, \overline{(\triangle\epsilon)^2}}{512\pi\, l_o^2 \sin^5 (\theta/2)}$$

$$\approx \frac{3\lambda\, \overline{(\triangle\epsilon)^2}}{16\pi\, l_o^2\, \theta^5} \tag{17}$$

This formula shows that the scattered power density varies directly with the wavelength (or inversely with the frequency) and inversely with the fifth power of the scattering angle, θ. This dependence has been found to be in reasonable agreement with measurements.

Method of determining received power. A simple geometrical model is usually adopted to determine the power available at the receiving antenna, as shown in Figure 6. The antennas employed in a tropospheric scatter system generally have large apertures and narrow beams. They are mounted near the surface and the antenna beam is directed horizontally. It is assumed that the lower edge of the beam lies on a plane tangent to the earth, and that diffraction of power into the shadow zone may be neglected. It is further assumed that only single scattering is important. The justification for the second assumption is not yet firmly established, and it is possible that multiple scattering may play a significant part, at least under some conditions. It may be seen from Figure 6 that the scattering angle, θ, increases as the height, h, of the beam intersection increases.

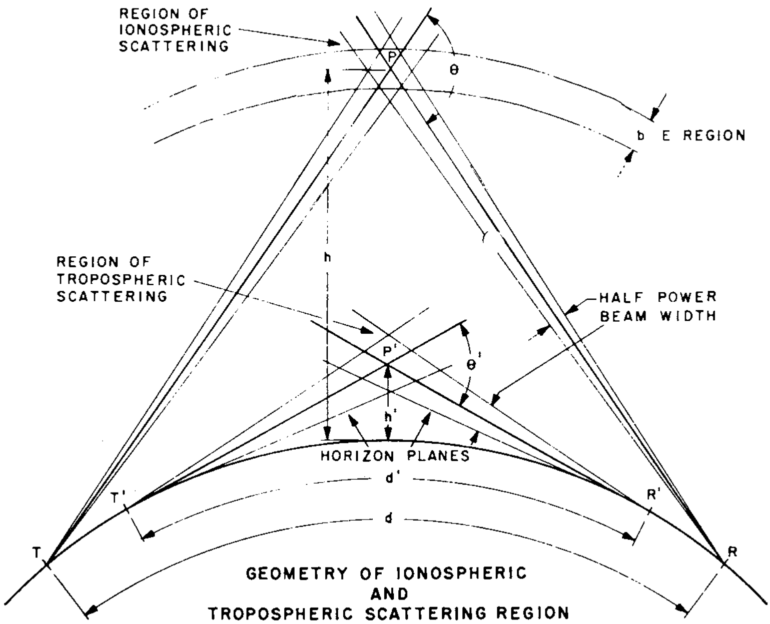

Figure 6. Sketch showing geometry of scatter propagation with narrow-beam antennas.

It is now necessary to perform an integration over the volume which is common to the two antennaa beams in order to determine the total power available to the receiving antenna. Let R_1 be the distance from the transmitting antenna to a scattering element and R_2 be the distance from this scattering element to the receiving antenna. The incident power density at the scattering element is

$$\frac{w_T\, g_T}{4\pi\, R_1^2}\,.$$

When this is multiplied by σ dv, the power scattered by the element dv into a unit solid angle is obtained. The power density at the receiver is obtained by dividing by R_2^2, and the available receiving antenna power is then equal to the power density times the antenna effective area.

$$w_T = \int_V \left(\frac{w_T\, g_T}{4\pi\, R_1^2}\right) (\sigma\, dv) \left(\frac{1}{R_2^2}\right) \left(\frac{\lambda^2\, g_R}{4\pi}\right)$$

$$= \frac{w_T\, \lambda^2}{16\, \pi^2} \int_V \frac{\sigma\, g_T\, g_R}{R_1^2\, R_2^2}\, dv \qquad (18)$$

where the integration extends over the volume which is common to the two antenna beams. It may be noted that the scatter angle θ appearing in (17) is equal to the non-optical distance, d, divided by the effective earth radius, ka, when the antenna beams are directed horizontally (smooth surface). When the line of sight is raised above the horizon by near obstacles, the angle θ must be increased accordingly.

The integration required in (18) is generally difficult. It is further complicated by the fact that $\overline{(\triangle\epsilon)^2}$ in (17) varies with height, and therefore with θ. The exact nature of this dependence is still unknown, but the assumption that $\overline{(\triangle\epsilon)^2}$ varies inversely with the square of the height has yielded reasonably good agreement with measurements. It is probable that the scale length, l_o, also varies with altiude. The integration becomes quite simple for the case where the antenna beams are so narrow that the various parameters in the integrand may be assumed constant. If we further assume that the antenna beamwidths are equal and that the antennas are at the surface, then the common volume is given approximately by $R^3\ \beta^3/\sin\theta \approx R^3\ \beta^3/\theta$, where $R_1 = R_2 = R$ and β = antenna beamwidth. For this case, (18) becomes

$$w_R = \left(\frac{w_T\ \lambda^2}{16\ \pi^2}\right)\left(\frac{\sigma\ g^2}{R^4}\right)\left(\frac{R^3\ \beta^3}{\theta}\right). \qquad (19)$$

If we now substitute for σ from (17) and write $g = 8.2/\beta^2$, we get

$$w_R = \frac{3\ (8.2)^2\ w_T\ \lambda^3\ \overline{(\triangle\epsilon)^2}}{256\ \pi^3\ l_o^2\ \beta\ R\ \theta^6}. \qquad (20)$$

For the assumed conditions, $R = ka\theta/2$, so that (20) becomes

$$w_R = 0.0508\ \frac{w_T\ \lambda^3\ \overline{(\triangle\epsilon)^2}}{l_o^2\ \beta\ ka\ \theta^7}. \qquad (21)$$

It is seen that, when the turbulence parameters are independent of height, the received power is inversely proportional to the seventh power of the scattering angle, θ, which in turn is proportional to distance. This is a much more gradual rate of decay at long distances than that predicted by diffraction theory. It may be noted, also, that the received power varies with the cube of the wavelength when the antenna beamwidth is constant. In free-space, the power would vary with the square of the wavelength. The most interesting conclusion is that the power varies inversely as the beamwidth, whereas in free space it would vary inversely as the fourth power of the beamwidth. This represents the extreme case of a penalty which is associated with large apertures and narrow beams.

Statistical methods of treating received signal. Statistical theory plays an important part in the treatment of tropospheric propagation, because the refractive index of the medium varies in a random manner with time and position. It may have been noted that the summation of the power scattered toward the receiving antenna from the common volume of the antenna beams took no account of the phase of the contribution from each volume element. The result is the mean power over a sufficiently long time interval. As mentioned earlier, the signal induced in the receiving antenna is effectively the resultant of many individual components having random phase angles. When all components have approximately equal intensities, the amplitude of the antenna voltage is Rayleigh distributed. We can specify the probability, or the percentage of time, that the amplitude exceeds a given value, but we cannot predict the antenna voltage at any one instant. When the average power is calculated, the corresponding voltage is the rms value. It is common practice to employ the median value, that is, the value which is exceeded half the time, rather than the rms value, in measurements of transmission loss, because the former is more readily determined.

When the measurement is limited to a short interval, such as a minute, and there is no strong constant voltage component present such as that which might result from diffraction or layer reflection, the voltage is Rayleigh distributed. This distribution is given by

$$P\ (V_i > V) = e^{-V^2/V_o^2} \qquad (22)$$

where V is some specified envelope voltage, V_i is the instantaneous envelope voltage, and V_o is the rms envelope voltage. The following table shows a few sets of values obtained from (22):

P	0.01	0.10	0.368	0.50	0.90	0.99
10 log (V^2/V_o^2) (db)	6.63	3.62	0	–1.59	–9.77	–19.98

The amplitude is expressed in decibels relative to the rms value. We see that the rms value is about 1.6 db above the median value, that the 1 per cent value is about 8.2 db above the median value, and that the 99 per cent value is about 18.4 db below the median value. Only two per cent of the time may the amplitude be expected to exceed an excursion of 26.6 db. A form of graph paper is often used on which (22) plots as a straight line (Rayleigh graph paper). As can be observed from the foregoing, the probability scale is unsymmetrical.

Another probability function which finds much application is the log normal distribution. This is the same as the normal, or Gaussian, distribution, but with the logarithm of the amplitude (usually expressed in decibels) replacing the amplitude. A graph of this distribution plots as a straight line on the familiar probability paper. The probability scale in this case is symmetrical. It has been observed that the distribution obtained from a large number of hourly medians, expressed in decibels, is normally distributed. The normal distribution for a zero mean value of the random variable is given by

$$P\ (x_1^2 > x^2) = \frac{1}{2}\left[1 - \text{erf}\ (\frac{x}{\sqrt{2}\ \sigma})\right], \tag{23}$$

where erf (z) is the error function of z, and σ is the standard deviation. It may be noted that $P = 0.16$ or 0.84 when $x = \pm\ \sigma$. The term "log normal" merely signifies that x in (23) in a logarithmic variable, such as transmission loss expressed in decibels.

Practical Aspects of Scatter Propagation

Variation of signal level with distance. This variation has been illustrated by Figures 1 and 2. The solid curves are drawn for a smooth earth and for antenna heights of 10 meters in accordance with the latest CRPL methods.

It was seen in an earlier section that the increase of transmission loss with distance results principally from three effects:

(1) the free-space spreading of the wave.
(2) the increase of the scattering angle, θ, with distance, and
(3) the increase in the height of the antenna beam intersection with distance.

If narrow-beam antennas are used, and if $\overline{(\triangle\epsilon)^2}$ is assumed to be inversely proportional to h^2, a distance dependence of the form $1/d^9$ may be deduced. A study of Figure 2 reveals that the inverse-ninth-power dependence is less satisfactory than an exponential dependence over much of the range. In fact, the curve for 1000 mc fits the following equation within $\pm$ 2 db from 200 km to 1100 km:

$$L_b\ (db) = 201 + 0.078\ [d\ (km) - 200]$$

It may be concluded that no simple relation between transmission loss and distance applies at all ranges. An exponential relation seems to be fairly accurate at long distances, but a more complex relation exists at short distances.

Seasonal and climatological influence. It has been definitely established that the hourly median values of field strength vary over a rather wide range with the weather. This dependence has a sound theoretical basis. When the gradient of refractivity near the surface is large, the rays undergo more refraction and the distance between radio horizons (the angular distance) is reduced. Consequently, the transmission loss is also reduced. This effect is clearly demonstrated by the tendency for radio ducts to form under suitable conditions. Such ducts are fairly common on clear, calm summer nights over moist soil, because a layer of cool, saturated air forms near the surface, whereas the air aloft tends to remain warm and dry. Ducts are also rather common in the trade wind regions over the oceans. The effect of refractivity gradient is also apparent in the fact that tropospheric fields are stronger in the summer than in the winter, and stronger in the tropics than in temperate or arctic regions.

A second theoretical relation tends to confirm the observed climatic dependence. According to one theory of turbulence, the mixing-in-gradient theory, the intensity of turbulent fluctuations should be proportional to the local gradient of the inhomogeneous mean profile. Hence, a high gradient near the surface should increase the power scattered at the lower levels, i.e., on the shorter paths. It has been observed that the variability of the signal is

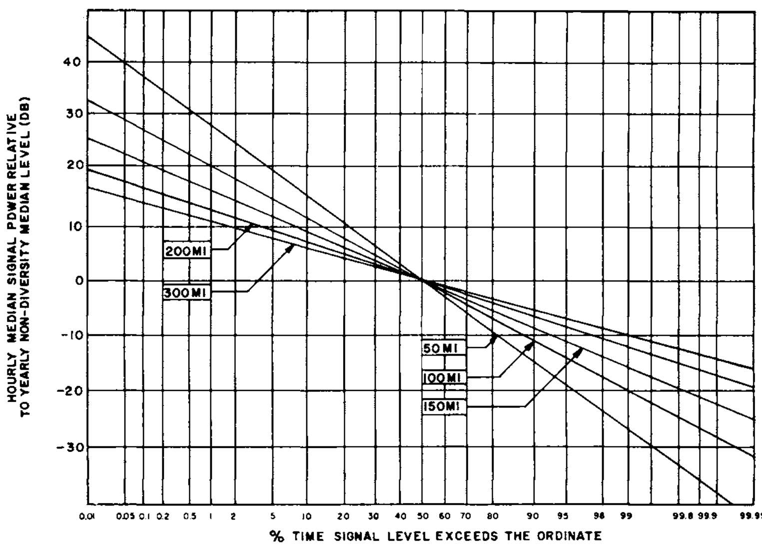

Figure 7. Long term distributions of signal levels received over circuits of various lengths.

greatest on short paths, which are not much longer than the optical value, and becomes less on longer paths, where the scattering region is high in the troposphere or even in the stratosphere. This is demonstrated by Figure 7, which shows the probability distribution of hourly medians for path lengths, of 50, 100, 150, 200, and 300 miles. The standard deviation ranges from about 12 db for the shortest path to about 4 db for the longest path. In another test, the distributions of hourly median field strengths were plotted for a 188-mile path and a 618-mile path, both for summer and for winter. The differences between the 10 and 90 percentile values in decibels are shown below:

Distance	*188 miles*	*618 miles*
Winter	12 db	3 db
Summer	32 db	10 db

Frequency dependence. It is not easy to determine the dependence of transmission loss upon frequency, because the relation may vary with the antenna beamwidth and with the length of the path. The tropospheric model based upon the Bessel correlation function was found to yield a value of received power for narrow-beam antennas porportional to λ^3. Tests made with scaled antennas at several frequencies have tended to substantiate this model. The curves of Figure 2 were also based on such a frequency dependence. It should be noted that a scaled system in free space has a transmission loss varying as λ^2, so that the scatter mechanism accounts for only a first-power dependence. This relation is probably not applicable below about 400 mc. The tendency below 400 mc is that the transmission loss varies with frequency as λ^2, just as in free space.

Another basic relation should be noted at this point. So long as free-space conditions are applicable and the antenna apertures remain fixed, the transmission loss decreases 6 db when the frequency is doubled. This fact results from the halving of the transmitting antenna beamwidth and the quadrupling of power density in the beam. On the other hand, when scaled antennas are used, so that the beamwidths remain constant, the transmission loss increases 6 db when the frequency is doubled. This results from the reduction of the receiving antenna effective area by a factor of four. This fact applies also to isotropic antennas.

When frequencies greater than about 5000 mc are being considered, it is necessary to consider absorption on long paths. This is principally a result of resonant absorption in oxygen and of isotropic scattering by rain drops. The latter effect is rarely serious as indicated by the proposed use in the Bell System of 11,000-mc line-of-sight relay systems.

Performance of antennas of large aperture. It has been shown that increasing the antenna aperture does not necessarily produce the same reduction of transmission loss as in free space. As a general rule, antennas with an aperture diameter of 100 wavelengths or more suffer a reduction in gain as compared with free-space conditions. This reduction is often called the aperture-to-medium coupling loss.

From elementary theory we deduce that, in free space, doubling the aperture diameter of both antennas halves the beamwidth, and increases both the power density and the receiving antenna effective area by a factor of four. Hence, the transmission loss is reduced by 12 db. In the theoretical treatment (eq. 21), it was shown that for very narrow-beam antennas the received power may be expected to vary only inversely with the first power of the beamwidth (3 db for a doubling of aperture diameter). The difference between 12 db and 3 db must be charged to aperture-to-medium coupling loss.

The explanation for this effect may be stated as follows. When antennas with broad beams are used, the transmitting antenna illuminates a large volume of the medium, and the receiving antenna is capable of accepting power scattered from a similar large volume. In this case, the received power is dependent only upon the angular dependence of the scattering cross-section, σ, and is independent of the antenna beamwidths except in so far as they affect the incident power density and the receiving antenna effective area. However, with very narrow-beam antennas (assumed equal), we may assume that σ is nearly constant over the common volume. Doubling the aperture diameter of each antenna reduces the common volume by a factor of eight, whereas the incident power density is increased only by a factor of four. Since the receiving antenna effective area is also increased by a factor of four, the net effect is a gain of two in received power.

Since the scattering cross section, σ, has a strong angular dependence ($1/\theta^5$ in the assumed model), it is apparent that only a limited portion of the medium which is illuminated by a broad-beam antenna can contribute effectively to the received power. The medium has an effective beamwidth of its own, which is defined by the limiting values of θ at which the cross section, σ, is reduced to one-half of its maximum value. This medium beamwidth is clearly somewhat less in the vertical direction than in the horizontal direction. If we call this beamwidth α_0, then it is apparent that the aperture-to-medium coupling loss should be a function of α_0/β, where β is the antenna beamwidth. The coupling loss should remain small until α_0/β becomes as large as 1 and should then build up more and more rapidly as α_0/β becomes larger. This concept has been verified by measurements.

It has also been argued on theoretical grounds that the coupling loss (expressed as a ratio) increases with the cube of the path length. The experimental evidence on this point is inconclusive. Certain comparative aperture and beam-swinging experiments on a 618-mile path suggest that the coupling loss on a path of this length may be much smaller than the d^3 dependence would predict. It is also probable that the scattering properties of the medium vary with frequency in such a manner that the aperture-to-medium coupling loss depends on the frequency as well as the aperture diameter measured in wavelengths. This loss seems to be more prominent at frequencies of 2000-3000 mc than at 400 mc.

Fading and diversity. As mentioned earlier, the received signal on a tropospheric scatter circuit exhibits a rapid fluctuation, which results from the multipath nature of the propagation. For most design purposes, it is satisfactory to assume that this fading is Rayleigh distributed. Evidence suggests, however, that at the lower frequencies, such as 400 mc, there may be times when the received signal results in part from another mechanism, which has many of the properties of reflection from a layer. At lower frequencies the layer appears fairly smooth, so that a relatively large specular component exists in combination with a randomly fluctuating signal. In this case, the fading is shallower than predicted by the Rayleigh model. At higher frequencies, the layer appears much rougher, and the specular component tends to disappear.

As a rough rule, the fading frequency, defined by the number of upward crossings of the median level per second, is proportional to the frequency. It may be as low as 0.1 cps at 300 mc and may rise to several cycles per second at 3000 mc. The tendency is for the fading frequency to decrease more rapidly than the wave frequency when the latter becomes relatively low. In any event, the power spectrum contains negligible power at frequencies greater than a few cycles per second at the highest operating frequencies used thus far.

The depth of fading can be reduced and the average signal power increased by diversity reception. This is based on the fact that the fading at points separated in space or on spaced frequencies is essentially incoherent. That is, a minimum field strength at one location or on one frequency may be matched by a higher field strength at another frequency or location. Hence, employing two or more receivers connected to spaced antennas or operating on spaced carrier frequencies and combining their outputs results in quite significant improvements in signal-to-noise ratio.

An illustration of this improvement for dual and triple diversity is given in Figure 8. It is assumed that each of the signals is subject to Rayleigh fading and that the fading on individual channels is uncorrelated. The non-diversity curve is a straight line on the scale which has been chosen. It is seen that the greatest improvement due to diversity reception occurs at the lowest signal levels, corresponding to large percentages of time. For example, dual diversity produces a 15 db improvement at the 99.9 per cent level and only about 3 db improvement at the 50 per cent level.

Space diversity requires the use of multiple antennas, whereas frequency diversity requires the use of multiple transmitters. The required spacing of antennas to produce the desired degree of incoherence of fading is on the order of 50 wavelength transverse to the path, and the required frequency spacing is on the order of 4 mc. Where multiple transmitters are used, it is usually necessary to connect them to separate antennas to achieve decoupling. Since the use of multiple antennas of very large aperture may greatly increase station cost, it has been proposed recently that a system of angular diversity may be employed in this case. A number of feed antennas are mounted in each parabolic reflector in such a manner that several skewed beams are produced. Corresponding transmitting and receiving beams intersect near midpath in a common volume which is different from that for another pair of beams. Therefore, the fading on the various receiving beams tends to be incoherent. Each transmitting feed is connected to a separate transmitter and each receiving feed to a separate receiver. Only a single reflector is required at each terminal. This scheme also tends to overcome some of the aperture-to-medium coupling loss which occurs with very large apertures.

Another type of fast fading occurs when an airplane passes near or through the common antenna volume. This has a more regular period than normal tropospheric fading, and the signal excursion may be very large.

The slower variations of field strength resulting from air mass movements and from diurnal and seasonal changes are often designated as long-term fading. This type of fading cannot be alleviated by diversity reception. The typical range of fading for a season or for a whole year can be represented by plotting the distribution curve of hourly medians as in Figure 7. An allowance for such fading must be made when the system design is calculated on the basis of the long-term median transmission loss.

Bandwidth limitations. When consideration is given to the transmission of information, one is concerned with the effect of the medium upon the shape of the modulating wave. The simplest form of modulation from the theoretical standpoint is an impulse of negligible duration. Such an impulse has a uniform frequency spectrum and represents very-broad-band transmission. Because of multipath propagation, the received signal will be a pulse of finite duration. Such a pulse has a spectrum width which is the reciprocal of its length. Hence, the medium can be said to be limited in bandwidth approximately to the reciprocal of the relative multipath delay.

Thus the problem of bandwidth is reduced to one of beam geometry. Relatively small bandwidth results from broad antenna beams and long transmission paths. A particularly severe source of bandwidth limitation is the scattering from airplanes. However, the multipath delays in the troposphere are many times smaller than those occurring on ionospheric paths. Generally, bandwidths of several megacycles per second are achieved, even with relatively small antennas. With large antennas having beamwidths less than 1 degree and with moderate distances such as 100-200 miles, it seems possible to achieve a bandwidth of at least 10 mc. On the whole, the signal-to-noise ratio in existing systems has rarely been high enough to allow exploiting the bandwidth of the medium fully.

Noise levels. The ultimate limit on the transmission loss which can be tolerated in any communication system is the noise level in the receiver. In an ionospheric system operating at high frequencies, the noise level is always determined by atmospheric sources, principally lightning discharges. In the VHF range, noise sources external to the receiver are still of great importance, the major one being cosmic noise originating in the galaxy. Ignition noise and other switching transients can also be severe in some locations. It is not usually necessary to exercise great care in keeping receiver noise to a minimum. However, at frequencies in excess of 300 mc, the noise introduced by the receiver itself is generally the most prominent. Only when the sun or the center of the galaxy happens to lie in the receiver antenna beam is it necessary to consider celestial noise sources. And man-made noise is also usually quite easy to avoid.

The internal noise of the receiver has its origin either in the input device or in the first stage or two of amplification. The input noise is of thermal origin and is called Johnson noise. It results from the random motion of electrons in a resistive circuit element. This may be the antenna itself, or it may be a mixer stage if this precedes the first amplifier. A lossless antenna with a sharp beam directed toward the sky has a very small noise output. However, if the antenna beam is directed horizontally, the earth radiates noise power into the antenna. Also, any losses in the antenna or the transmission line can result in additional noise power.

It is customary to rate the sensitivity of a receiver on the basis of its noise figure. This is defined as the equivalent input noise power generated by the receiver divided by the noise power generated within a resistor connected across the input terminals and matching the input impedance of the receiver. The latter, or Johnson noise, is equal to kTB watts, where k is Boltzmann's constant (1.37×10^{-23} watts/degree/cps), T is the temperature in degrees Kelvin, and B is the bandwidth in cycles per second. For a temperature of $288°K$ and a bandwidth of 1 cycle per second, the Johnson noise is -204 dbw (decibels relative to 1 watt). This number is usually taken as the starting point in noise calculations. When a highly efficient and sharply beamed antenna is directed toward the sky, the input noise may be considerably smaller than −204 dbw.

Such reduction is becoming of increasing importance as low-noise input amplifiers are developed. Until recently, a receiver noise figure of 8-10 db was considered very creditable. It is now possible to build a parametric input amplifier with a noise figure of 2 db or less. And with masers, this number can be reduced to 0.2-0.3 db. Such low noise figures are of greatest importance in radio astronomy and in space communication, where the inherent antenna noise, or antenna temperature, can be reduced to exceptionally low values.

The importance of the reduction of receiver noise figure from the economic standpoint can be appreciated when one considers that a reduction of 3 db in the receiver noise figure (often not very hard to achieve) may have the same effect on signal-to-noise ratio as increasing the transmitter power from 10 to 20 kw.

Communication System Design

Modulation techniques. The principal application of tropospheric scatter systems has been the transmission of multiple voice channels. They therefore supplement cable circuits and microwave line-of-sight relay systems. A television circuit is in operation from Miami to Havana, with the long over-water hop provided by tropospheric scatter. It is apparent that this mode of propagation is most advantageous in areas where the population density is very small or where natural barriers exist, such as mountains and bodies of water.

As in conventional telephone practice, the voice channels, ranging from 24 to 120 or more, are multiplexed by the familiar single-sideband, suppressed-carrier method. An overall bandwidth of 4 kc must be allowed per voice channel. For example, in a 24-channel system, the baseband after multiplexing extends from 12 kc to 108 kc. In most applications, the UHF carrier wave is frequency modulated by the baseband signal, with a modulation index of about 3 at the highest baseband frequency. Frequency modulation is chosen in preference to amplitude modulation because the klystron power amplifiers, which are usually employed, function much more efficiently at a constant power level, and because a wide-band system, such as FM, has better signal-to-noise properties than a narrow-band system like AM.

For a 24-channel system, the maximum frequency deviation, with an index of 3, is 336 kc. The selective circuits in the transmitter and receiver should have linear phase characteristics over a range ± 336 kc. Circuits designed to achieve this have a bandwidth of about 1.3 mc. This excess bandwidth is a penalty which must be accepted if the intermodulation distortion (crosstalk) is to be kept small.

Transmission loss requirements. This subject can perhaps be best illustrated by a typical design problem. Assume a propagation path 150 miles in length, with a 28-foot parabolic antenna for transmitting and two such antennas for receiving at each end. Actually, only two antennas need be used at each terminal, since one of them can be diplexed for simultaneous transmission and reception at two frequencies separated by 5 per cent or more. Assume an operating frequency of approximately 1000 mc. Then from Figure 2 we get a median basic transmission loss of 204 db. Each antenna has a free-space directivity of about 36 db. Since the aperture diameter is only about 28 wavelengths, the aperture-to-medium loss may be neglected. Hence, the medium path loss is 204 – 72 = 132 db.

Now assume that the transmitter power output is 10kw and that the transmission line loss is 2 db. The medium available signal power at the receiver is 40 – 132 – 2 = – 94 dbw. According to Figure 7, an allowance of about 22 db should be made for the worst 0.1 per cent of the year. Hence, the median available signal power during this worst period is – 116 dbw. Since speech is quite highly redundant, occasional short fades below the threshold of good signal-to-noise ratio can be tolerated. Consequently, we arbitrarily select the 99 per cent abscissa in Figure 8 and read the dual diversity curve. A fade allowance of 8 db is obtained. Thus, a signal

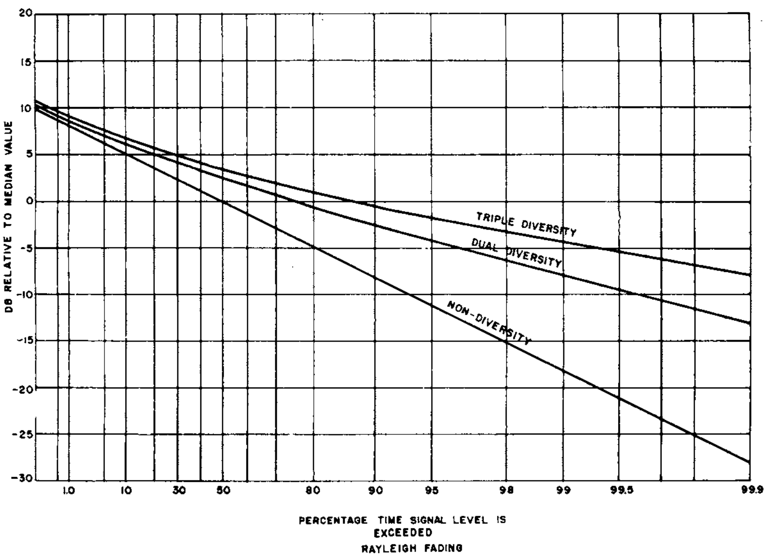

Figure 8. Short term distributions of signal levels for non-diversity, dual-diversity, and triple-diversity circuits. Rayleigh fading is assumed.

threshold of – 124 dbw is established. This means that the available receiver power should be above this threshold during 99 per cent of the worst 0.1 per cent period during the year.

We now investigate the noise power. Assume a receiver noise figure of 8 db and a noise bandwidth of 1.3 mc, corresponding to a 24-channel FM system. Then the equivalent receiver noise input is $-204 + 8 + 10 \log (1.3 \times 10^6) = -135$ dbw. The final input signal-to-noise ratio is $-124 - (-135) = 11$ db. This is approximately the minimum value of signal-to-noise ratio which will insure satisfactory FM detector operation. If the ratio does not drop below this value, the receiver output signal-to-noise ratio will be on the order of 30 db. Hence, the design is compatible with the assumed reliability of the circuit.

This problem illustrates the use of statistical procedures in choosing the correct system design. However, much gain is designed into a system, there is always a finite though small probability of the service becoming unsatisfactory. When a number of links are to be connected into a relay system, as has been done in numerous instances, the reliability of each link must be somewhat better than the expected overall reliability.

Selection of operating frequency band. The selection of operating frequency is governed partly by technical and partly by political considerations. The latter have to do with the allocation of bands for various types of services by the Federal Communications Commission. Common-carrier bands have been set up in the vicinity of 2000, 4000, and 7000 mc. The 4000-mc and 7000-mc bands have been exploited quite extensively for line-of-sight relay systems. Tropospheric scatter equipment for operation in the 2000-mc band has been developed recently, principally for military application. Older equipment has been employed for use outside the continental U. S. in the bands near 400 mc and 900 mc, and much of the experimental study program has been carried on in the range from 100 mc to 1000 mc.

On the basis of purely technical considerations, we should bear in mind that the free-space gain of a system with fixed antenna sizes increases with the frequency. A point is eventually reached at sufficiently high frequencies where much of this additional free-space gain is nullified by antenna-to-medium coupling loss. Also, the transmission line losses tend to increase with the frequency, and it is more difficult to construct high-power amplifiers at the higher frequencies. Furthermore, the λ-cubed dependence mentioned earlier tends to discriminate against the higher-frequency circuits. For operation of the longest experimental circuits, a frequency near 400 mc has been employed, mainly because of the availability of exceptionally high transmitter power. It is probable that the shorter circuits will employ frequencies in the approximate range of 2000-6000 mc.

Siting. In contrast with the practice in line-of-sight relay systems, it is not necessary to mount the antennas of a tropospheric scatter system high above the surface. It is desirable to erect the antenna on a slight rise in the surface to avoid blocking of the line of sight by near obstacles. It is also important to have the line of sight to the nearest terrain feature at a low elevation angle. A negative elevation angle is best. As a rough rule, each positive degree of elevation angle of the line of sight is equivalent to increasing the path length by about 90 miles.

Because of the very large antennas used on some circuits, it would be extremely costly to mount them 100 or 200 feet above the surface, as in a typical line-of-sight relay station. Consequently, the virtual lack of height gain in a tropospheric scatter system is a fortunate circumstance. On the other hand, it is still desirable to increase the distance to the horizon, because the scattering angle, θ, is determined only by the non-optical part of the path. When one terminal is in an airplane, the distance between terminals may be increased by nearly the increased line of sight distance when all other parameters are the same.

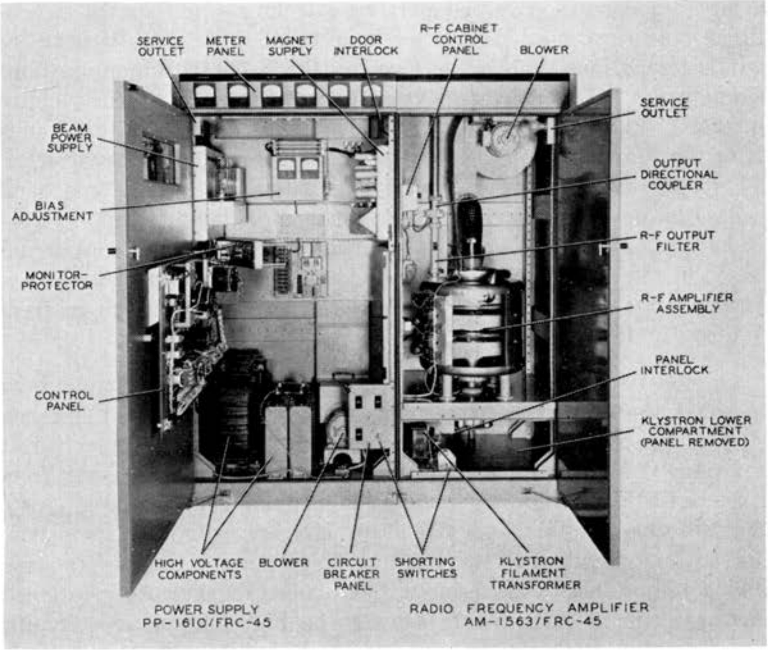

Figure 9. Typical 1-kw klystron power amplifier designed to operate over a frequency range of 750-1000 mc.

The only other important siting problem is the avoidance of high man-made noise levels. This is more important than in other modes, because of the cost of increasing system gain to over-ride noise levels is so great. A site near an airport is to be avoided because of the signal distortion which scatter from an airplane may produce.

Equipment design features. This discussion will be concluded by citing the salient characteristics of typical equipment employed on tropospheric scatter circuits (Mellen *et al.*, 1955; Morrow *et al.*, 1956).

The circut is normally duplex, i.e., transmission occurs simultaneously in both directions. The signals corresponding to the two directions are spaced in frequency sufficiently to allow separation with filters, even when one antenna is used for both transmitting and receiving. The required spacing is about five per cent.

The transmitter may be rated as high as 50 kw at 400 mc. At the higher frequencies, the power rating is usually 1 kw or 10 kw. The final amplifier is normally a klystron, with three or four cavities. The latter may have an output of 10 kw with an input of only 0.1 watt. A 1-kw klystron amplifier employs air cooling (Figure 9), whereas a 10-kw amplifier requires water cooling. The unit at the right in Figure 10 is a water-to-air heat exchanger. The anode efficiency of such a klystron amplifier in FM service is 30 to 40 per cent. For single-sideband modulation, the efficiency tends to be very

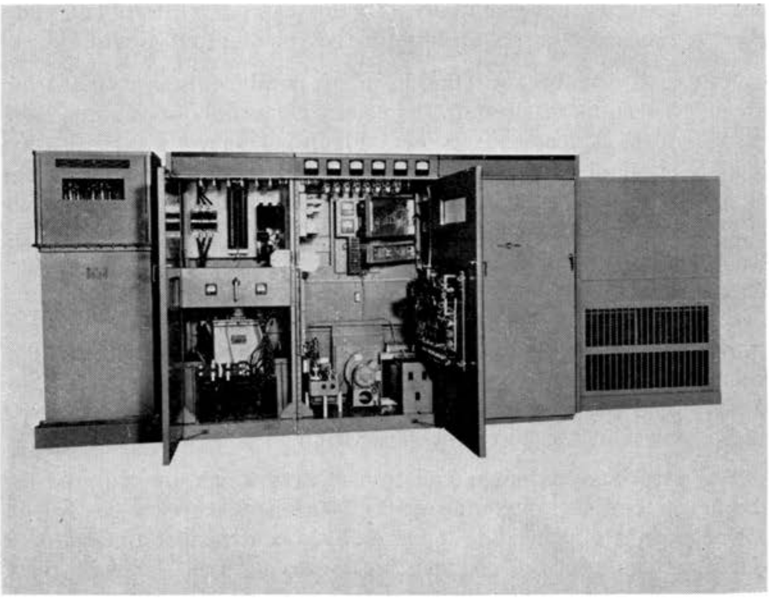

Figure 10. Typical 10-kw klystron power amplifier designed to operate over a frequency range of 750-1000 mc.

low, though it can be increased to more than 20 per cent with special design of the collector anode (Morrow *et al.*, 1956).

In a typical FM exciter, a stable voltage is generated with a quartz crystal oscillator at a relatively low frequency, this voltage is phase modulated with the intelligence, or baseband, and the resultant voltage is multiplied in frequency to an intermediate frequency of 70 mc. This IF signal is then mixed with the output of a frequency multiplier chain to produce the final output frequency. A similar heterodyning process is employed in the receiver to reduce the incoming signal to an intermediate frequency of 70 mc. This value of intermediate frequency is also employed in the Bell System TD-2 line-of-sight relay system, so that the two types of systems can be readily interconnected.

It is customary to employ two or more receivers arranged so as to provide diversity reception. Each receiver is equipped with an effective limiter or automatic gain control to hold the detector output approximately constant in the presence of fading. When the signal level drops, the receiver noise output tends to increase. In a commonly-used type of diversity combining system, the maximal-ratio type, the receiver outputs are combined in such a manner that the noisier receiver automatically furnishes a smaller proportion of the total output. It is characteristic of FM detectors that the signal-to-noise ratio in the output remains high until the signal input voltage drops to some threshold value. For a further decrease of input, the output noise level rises rapidly. In this case, fast, deep fades are observed as short bursts of noise in the voice output circuit.

Antennas usually take the form of paraboloids, varying from about 10 feet to 120 feet in diameter. Commonly used sizes have diameters of 28 feet and 60 feet. Figure 11 shows a typical 1-kw mobile terminal, with the transmitter and dual diversity receiver mounted in a trailer, and with the power supply mounted on a flat-bed trailer. Two 28-foot paraboloids are visible in the picture. The transmission line takes the form of a flexible 3⅛ inch coaxial line. Figure 12 shows a 1-kw scatter terminal, with the transmitter and two receivers mounted in a pair of military shelters. Each of the two antennas in this case is a 15-foot inflatable paraboloid. The inner face of the rear wall is aluminized to make it reflecting. The front wall is transparent for radio waves. The feed horn on the axis and a blower at the lower edge are visible.

The very large antennas and transmitters which are required for the longer circuits, extending up to 500 miles, are very costly. In ordinary, inhabited terrain, it is usually much cheaper to provide a given number of voice channels by means of a line-of-sight relay system. However, where the intermediate terrain is of such character that the installation and supply of relay stations becomes very

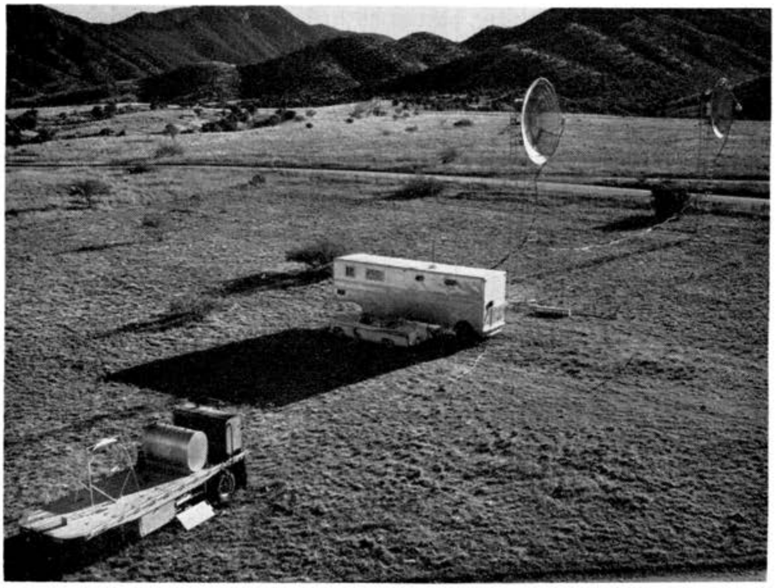

Figure 11. Typical mobile duplex 1-kw scatter terminal designed for dual-diversity reception. Antenna diameter = 15 feet.

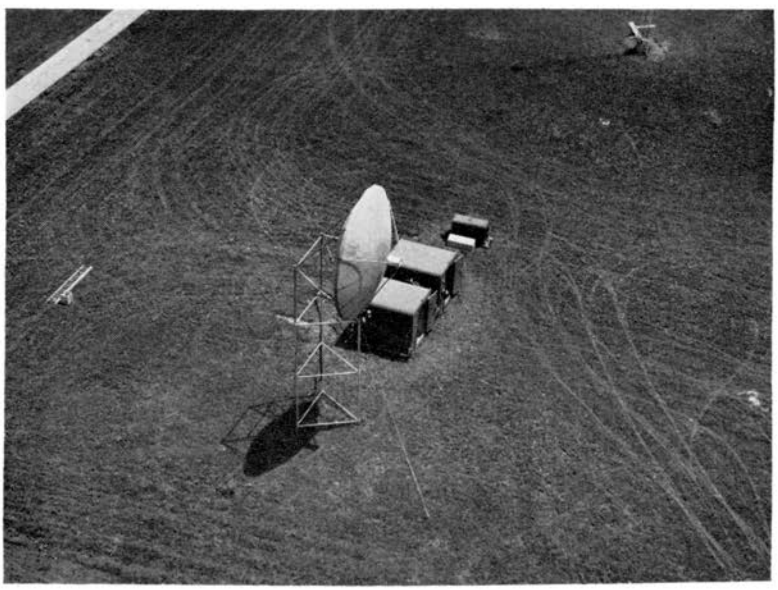

Figure 12. Typical air transportable duplex 1-kw scatter terminal designed for dual-diversity reception. One of two antennas is shown. Inflatable 15-foot paraboloid.

difficult, or where a water barrier is to be crossed, the high-power scatter link is often the most economical solution. This tends to explain why the most extensive early applications of such systems have occurred in Canada and Alaska.

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