NBS

Technical Note No. 95

Boulder Laboratories

CHARACTERISTICS OF POINT-TO-POINT TROPOSPHERIC PROPAGATION AND SITING CONSIDERATIONS

BY R. S. KIRBY, P. L. RICE, AND L. J. MALONEY

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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October 19, 1961

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1. INTRODUCTION

Since World War II there has been a tremendous development and expansion of telecommunication facilities in the frequency range above 100 Mc/s. This has come about primarily because of the vast increase in the total amount of communications required and the need for high reliability. Particularly at these frequencies, the characteristics of the atmosphere and terrain affect the propagation of radio waves. The presence of the troposphere manifests itself in many ways. One of its more important characteristics is the mechanism which causes more efficient radio wave propagation than can be accounted for by diffraction alone. There have been several different theories put forth to explain this phenomenon (all of which involve the troposphere, and in some instances the stratosphere as well) and the effect of the variations in atmospheric refractive index upon the propagation of electromagnetic waves. Layers and ducts, which are characterized by horizontally homogeneous discontinuities in the vertical gradient of refractive index, influence line-of-sight paths as well as non-line-of-sight paths. Regular fading as well as prolonged space-wave fadeouts are associated with these atmospheric conditions.

Interference to a communications system may occur as a result of favorable propagation from a remotely located transmitter operated on the same or on adjacent frequencies. Such long distance transmissions are associated with lower than average transmission loss for the propagation path between the undesired transmitting antenna and the desired receiving antenna. This is an important consideration when it is necessary to specify the service of one facility in the presence of possible interference from another facility on the same or on closely adjacent channels.

2. BASIC TELECOMMUNICATION REQUIREMENTS

A typical radio communication circuit is required to perform a function. Usually this function involves the transmission of information from one location to another. The measurement of how well the circuit performs involves both the volume of information that can be transmitted during a given period of time as well as its accuracy in faithfully reproducing at the output the same information that was inserted at the input. The information can be of various forms, either digital or analog.

Figure 1 shows a concept of a communication circuit with one propagation path. The original message is inserted in the transmitter system where it becomes part of the modulation of an RF electromagnetic wave radiated from the transmitting antenna. The receiving antenna picks up only an infinitesimal amount of the power radiated as well as unwanted radiations from many interfering sources. The ratio of the power input to the terminals of the transmitting antenna to the resulting signal power available at the receiving antenna is known as system loss.

Transmission loss is less than system loss by the amount of the antenna losses. Antenna losses are usually negligible for antennas designed for use above 100 Mc/s; an exception is the uni-directional rhombic antenna. Basic transmission loss, sometimes called path loss, is the transmission loss that would exist between isotropic antennas. The receiver itself contributes some thermal noise. At the receiver output the signal carrying the desired information must be of sufficient power relative to all of the unwanted signals and noise combined to provide for a sufficiently faithful reproduction of the original message. It can be seen that there are many sources of RF interference and noise. Some are in a sense controllable from the standpoint of adequate receiver design and siting, and others are likely to be present in all cases. After allowance for the transmission loss, sufficient transmitter power must be used to overcome the combined effect of all of the sources of unwanted RF power at the receiver. The fading characteristics of transmission loss within short periods of time such as an hour must be accounted for, and it is also necessary to estimate the hourly median values of transmission loss likely to be exceeded for a given percentage of the hours during the year.

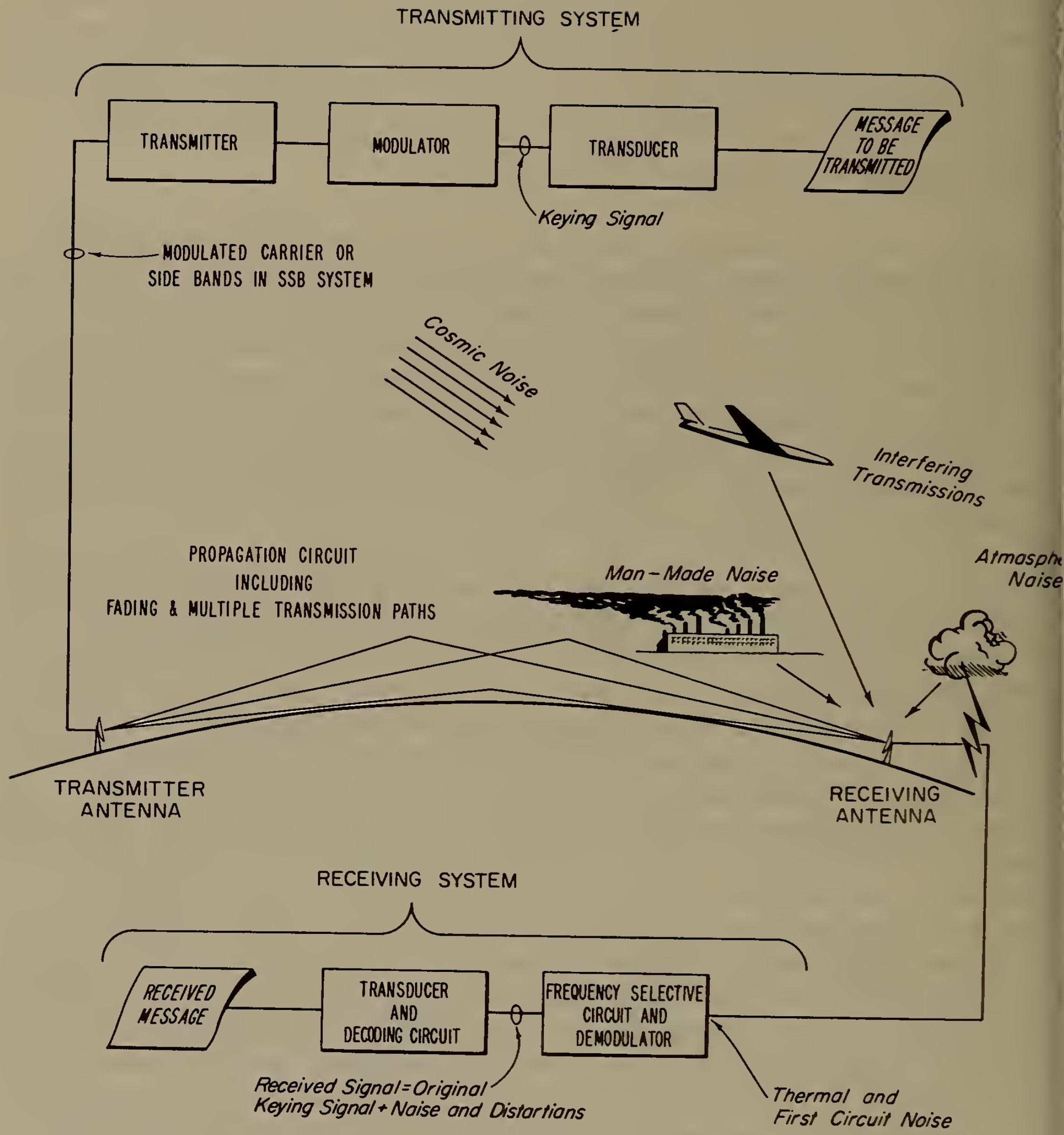

TRANSMITTING SYSTEM
TRANSMITTER
MODULATOR
TRANSDUCER
MESSAGE TO BE TRANSMITTED
Keying Signal
MODULATED CARRIER OR SIDE BANDS IN SSB SYSTEM
Cosmic Noise
Interfering Transmissions
PROPAGATION CIRCUIT INCLUDING FADING & MULTIPLE TRANSMISSION PATHS
Man-Made Noise
Noise
TRANSMITTER ANTENNA
RECEIVING ANTENNA
RECEIVING SYSTEM
RECEIVED MESSAGE
TRANSDUCER AND DECODING CIRCUIT
FREQUENCY SELECTIVE CIRCUIT AND DEMODULATOR
Received Signal = Original Keying Signal + Noise and Distortions
Thermal and First Circuit Noise

FIGURE 1

In planning and installing tropospheric communication systems the engineer is faced with exacting problems in selecting sites, choosing frequencies, and in determining what terminal equipment is needed to accomplish the communication requirement specified. It is important to realize the distinction between equipment performance and system performance. The latter includes equipment performance, but it also includes the propagation characteristics of the path. Transmission loss for nearly all tropospheric paths is a variable. Good theoretical prediction theories for transmission loss are of fundamental importance. These theories should take into account the influence of irregular terrain and of the troposphere while at the same time remaining sufficiently tractable so as to lend themselves to engineering use. Formulas based on tropospheric propagation theories have been developed which are useful for predicting tropospheric transmission loss and its variability [Air Force Technical Order, 1961]. Measurements of transmission loss can be used to improve such estimates to some extent. However, there is no way to remove all of the uncertainty concerning future levels of transmission loss that will occur on a given transmission path. Actually in most cases the cost of obtaining transmission loss measurements is seldom justified in view of the period of time over which a measurement program would have to extend in order to make a substantial improvement in the estimate over that available from good predictions.

The concept of service probability has been found extremely useful for formulating the various choices available to the engineer. Section 8 explains service probability, which is the probability of obtaining service of a given quality during a specified percentage of the hours in a year. This concept provides an objective way to balance the chances of success against the cost of installation and operation. Basically, it involves taking all of the uncertainties into account in a statistical sense and analyzing the probability of success with various assumptions concerning the equipment and frequencies to be used. For example, it is important to be able to consider how much the chances of success would be improved if a higher powered transmitter were to be used in one part of the circuit. This can be measured directly in terms of the service probability.

Propagation factors other than transmission loss must be considered. The improvement which can be realized with diversity transmission and reception depends on the degree of similarity in fading occurring simultaneously on propagation paths separated by space or frequency or with different polarizations. When wide modulation bandwidths are used, selective fading can seriously affect the quality of service.

3. FUNDAMENTAL CONSIDERATIONS

Before any useful prediction formula can be established, the fundamental mechanisms of tropospheric propagation must be thoroughly understood, and suitable propagation models must be postulated. Even though there exists a vast amount of data showing the attenuation experienced over almost any conceivable type of propagation path, any attempt to develop a strictly empirical prediction method from these data alone without regard to causes and effects of specific factors would be of little use. Quantitative predictions of scatter propagation are based largely upon theoretical models which, on the one hand, describe the mechanism and, on the other hand, lend themselves to mathematical treatment. Once the form of various factors is determined adequately the data become useful in setting empirical constants.

One of the limitations that has beset various theorists in constructing accurate models of the troposphere has been the relative difficulty of observing the atmosphere in sufficient detail at extreme heights. Instruments in aircraft, balloons, and rockets have provided some measurements, but the picture is far from complete.

The amount of transmitted energy that actually arrives at the receiver over a propagation path depends upon many factors. One of the most important factors is the mode or combination of modes of propagation which is predominant over the path. In making estimates of telecommunications system performance, it is important to know what mechanism will be useful so that reliable estimates of transmission loss and its variations can be made.

Broadly speaking, tropospheric waves are those which would not be present if there were no atmosphere, or which are substantially modified by the presence of the atmosphere. Anomalies in the refractive index of the atmosphere cause some radio frequency energy to be scattered in the forward direction. Depending upon the frequency and the path geometry, scattering can be the predominant mode at distances in excess of the line-of-sight. Ducts and layers may also aid the propagation of radio energy to great distances. These same anomalies can also cause radio "holes" and fadeouts on line-of-sight paths due to the bending of the radio ray paths.

Figure 2 shows typical relationships between long-term median basic transmission loss and distance for various frequencies. It can be seen that at the shorter distances the ground-wave mode is predominant, while at greater distances tropospheric scatter is the stronger mode. Water vapor and oxygen absorption seriously limit propagation in some bands above 10,000 Mc/s. Average variations in hourly median transmission loss, $V(p, \theta)$, about the long-term averages for tropospheric scatter are expressed in terms of time distributions as a function of angular distance, θ. Similar long-term hourly variations for line-of-sight tropospheric propagation are expressed in terms of distance and the vertical angle through which the propagation path travels from one terminal to the other. This distribution function is termed $V(p, d)$. The reader is referred to another paper for a complete description of these empirical functions and their application to prediction methods [Air Force Technical Order, 1961]. The presence of ducts and layers accounts for some of the variations observed in tropospheric scatter propagation. These are least prevalent during winter afternoons in temperate climates. Especially during these periods, propagation is in excellent agreement with forward scatter theory.

The weaker signals which are exceeded for large percentages of time are important for service consideration, whereas the strong fields which are exceeded for small percentages of time impose interference limitations between services operating on the same or adjacent frequencies. At present, predictions of service fields are somewhat more accurate than those for interference fields.

For a given antenna size, higher gain and more directivity can be realized at the higher frequencies. With parabolic antennas, for example, the free-space gain varies approximately as 20 log f_{mc}. Since the gain is realized at each end, this factor offsets the increased basic transmission loss with increasing frequency. If <u>free space</u> gains could be realized, the optimum frequency would always

MEDIAN BASIC TRANSMISSION LOSS FOR THE GROUND WAVE AND TROPOSPHERIC SCATTER MODES OF PROPAGATION OVER A SMOOTH SPHERICAL EARTH

Over Land $\sigma = 0.005$ mhos/meter $\epsilon = 15$

Polarization: Horizontal

Transmitting and Receiving Antennas Both 30 Feet Above the Surface

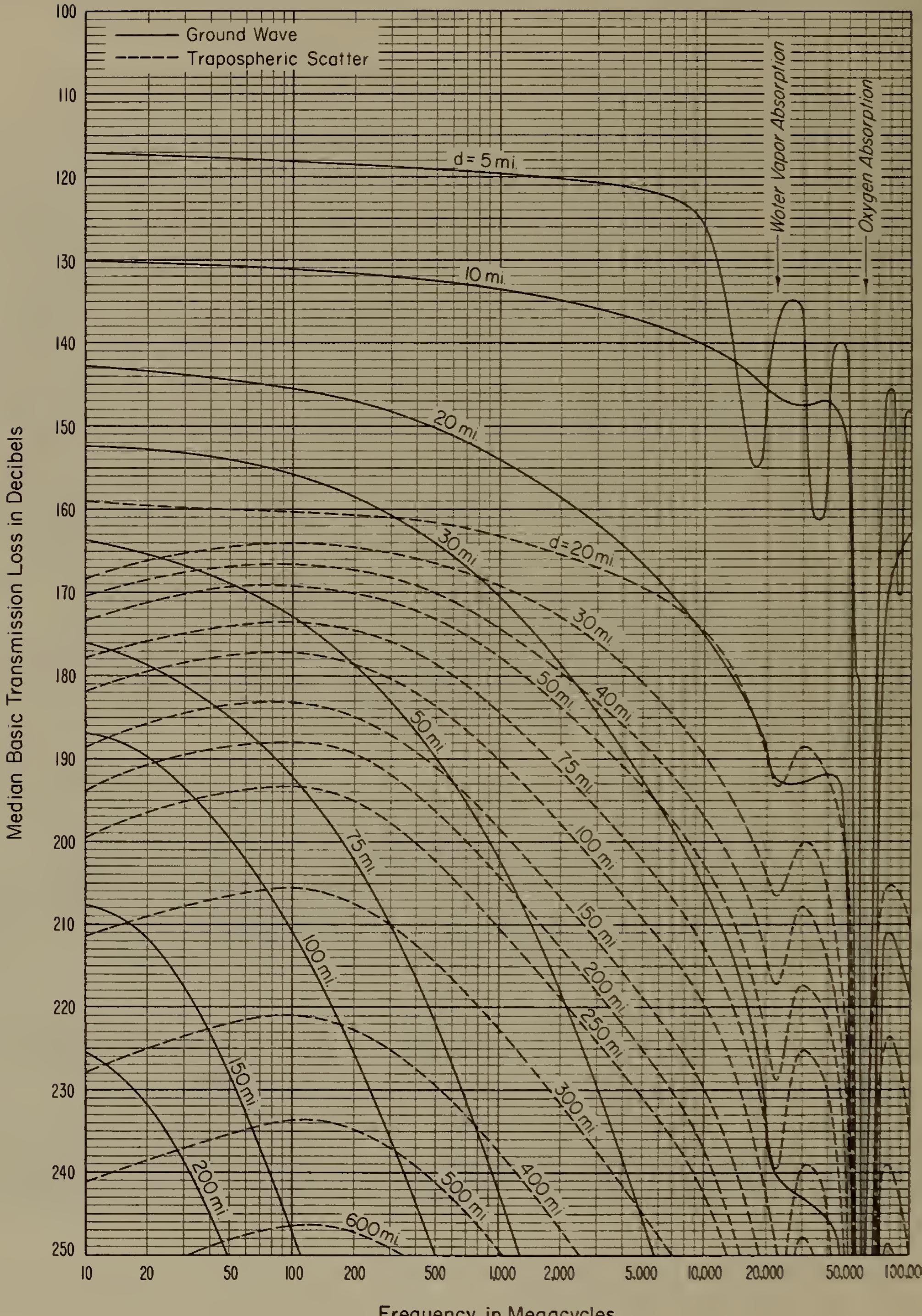


FIGURE 2

be the highest which is in keeping with the limitations of accurate positioning and for which antennas can be made.

The effective path antenna gain does not increase for a given antenna size as 40 log f_{mc} in tropospheric scatter, and optimum frequencies for most scatter paths fall somewhere in the range between 200 and 2000 Mc/s. Smaller antennas at shorter distances usually optimize at the higher frequencies. The optimum frequency is defined as that frequency at which a given grade of service can be realized with minimum transmitter power. The tendency for receiver noise figure and line losses to increase with increasing frequency must also be taken into account in determining an optimum frequency. As a general rule, a range of frequencies near the optimum will be satisfactory. Figure 3 shows typical transmitter power requirements as a function of frequency for paths over smooth earth at 150, 300, and 500 miles. In these examples the tropospheric scatter mode is assumed to be predominant, and the bandwidth and received signal levels are sufficient for 24-voice channels. Parametric amplifiers are assumed to operate at the receiver input terminals, providing low noise figures. Figure 4 shows typical ranges of telecommunications using 10 kw transmitters for various types of information.

If the first circuit of the receiver is coupled to the actual receiving antenna rather than to a lumped impedance of the same resistance and reactance as that of the antenna, then the measured value of the effective noise figure may be either larger or smaller than the receiver noise figure as measured in the laboratory due to the external noise picked up by the antenna. It should be noted that a radiation resistance is not a real resistance and thus introduces no noise into the receiver except to the extent that it absorbs noise radiation from its surroundings. The effective noise figure of the receiver antenna combination will be equal to the receiver noise figure only when there are no transmission line losses and the antenna happens to pick up the same amount of noise energy as would be available from a resistance at room temperature.

With the exception of temperature noise, which is frequency independent, all of the external noise decreases rapidly in intensity with increasing radio frequency and becomes nearly negligible above 300 Mc/s. In an aircraft flying at high altitudes the external noise energy from thunderstorms will be inversely proportional to the fourth power of the radio frequency. For antennas nearer the

TYPICAL TRANSMITTER POWER REQUIREMENTS
FOR 24 VOICE CHANNEL TROPOSPHERIC SCATTER CIRCUIT OVER SMOOTH EARTH

QUADRUPLE DIVERSITY WITH PARABOLIC ANTENNAS
FROM 28 TO 120 FT. DIAMETER RECEIVERS EQUIPPED WITH PARAMETRIC AMPLIFIERS

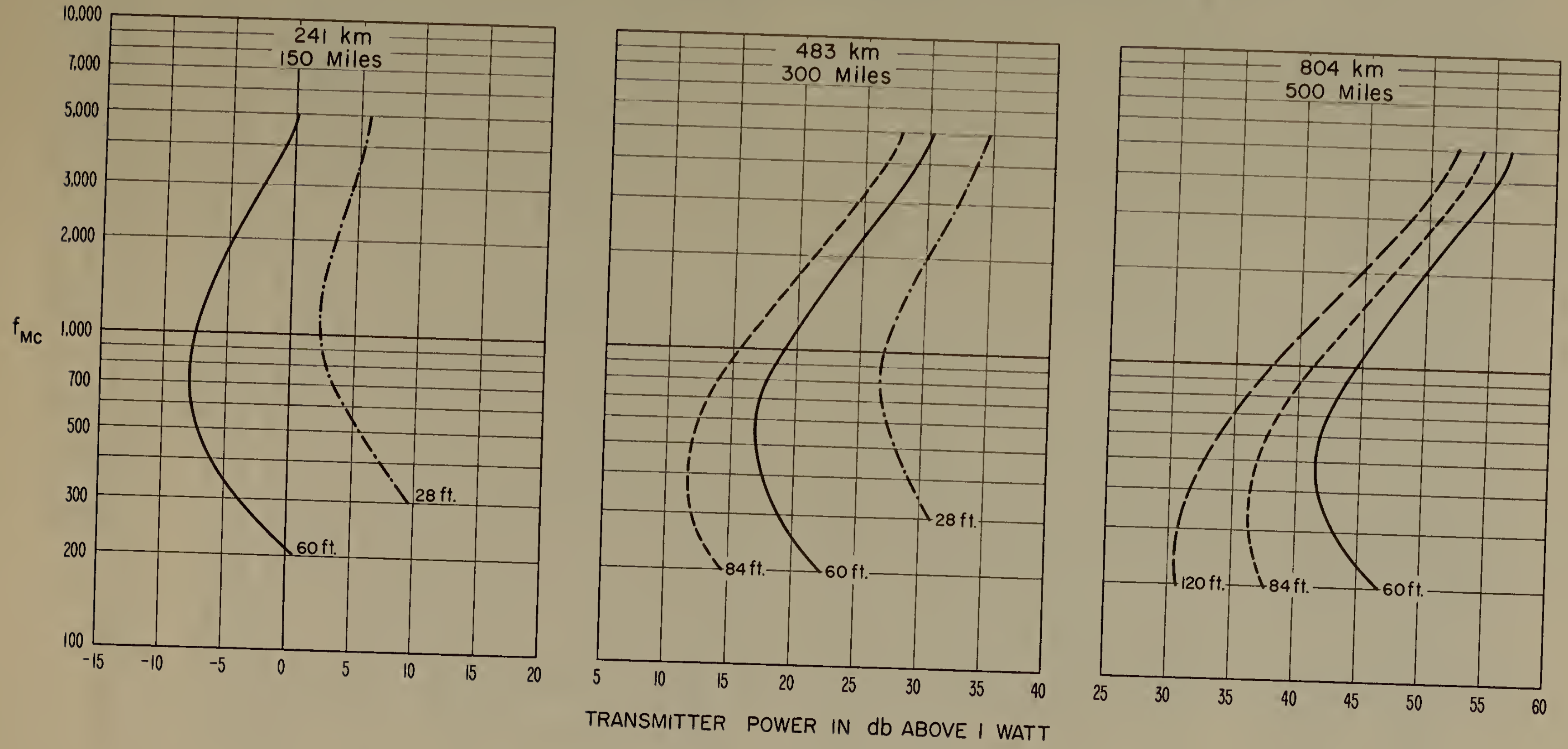


FIGURE 3

MAXIMUM DISTANCE AT WHICH SATISFACTORY SERVICE OF THE TYPES INDICATED MAY BE PROVIDED FOR 99% OF THE HOURS USING 10 KW TRANSMITTERS AND QUADRUPLE DIVERSITY

(Smooth Spherical Earth; $N_s = 301$; $h_t = h_r = 30$ feet)

Atmospheric Absorption and Rain Attenuation Typical of the Washington, D.C. Area

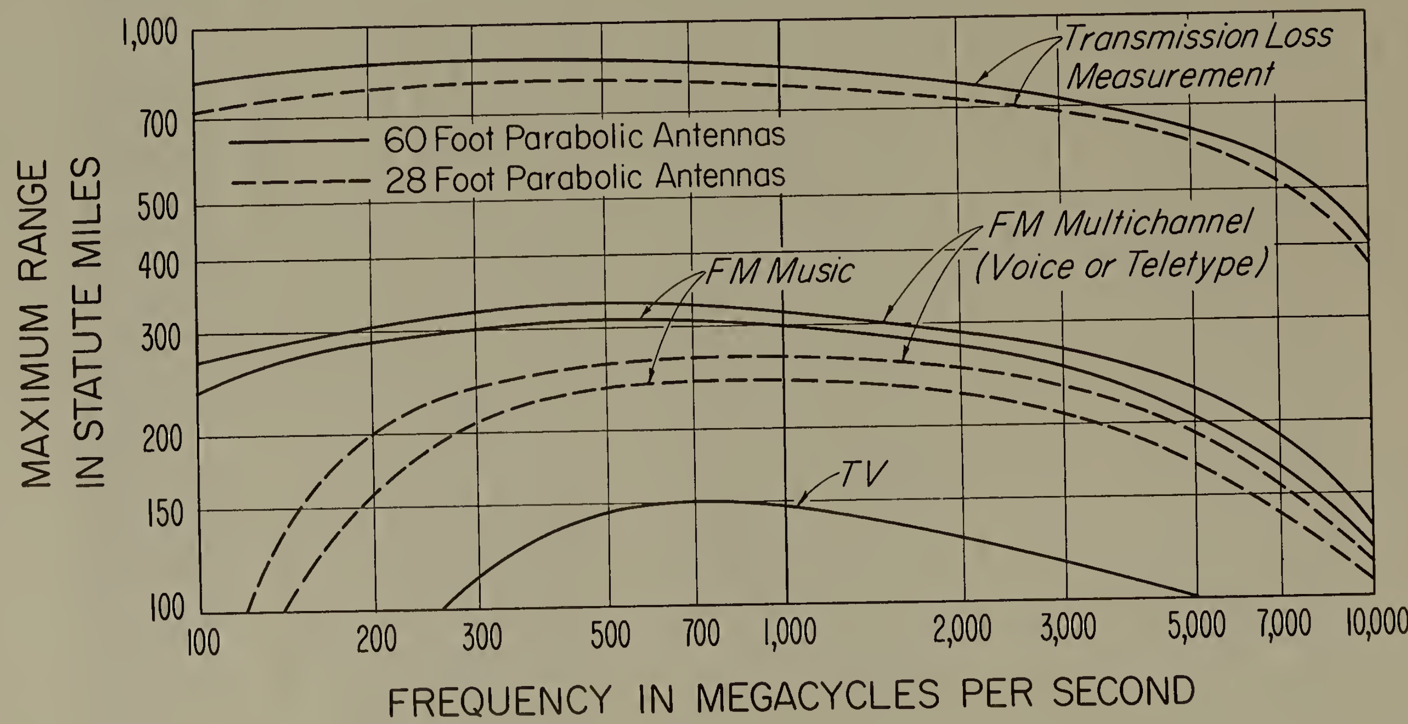


FIGURE 4

ground the noise power will follow a slightly different frequency law due to the frequency dependence of the propagation of the thunderstorm noise over the surface of the earth; this propagation factor prevents all except local thunderstorms from being heard at high frequencies and higher. Usually, cosmic noise will be of little importance above 120 Mc/s, and will form the lower limit to the sensitivity of radio reception in the lower part of the very high frequency band. The sources of this cosmic noise are not uniformly distributed over the sky but tend to be concentrated in several regions on the celestial sphere, the principal source being in the region Scorpio-Sagittarius near the center of the galaxy. At frequencies above 300 Mc/s, black-body radiation temperature noise is usually the principal source of noise external to the receiver. A directional receiving antenna will absorb different amounts of temperature noise energy as it is pointed in different directions. When receivers with very low noise figures become available in the ultra-high frequency band, it may turn out to be desirable to discriminate against ground-reflected waves in order to reduce the received noise resulting from the temperature of the ground. Discrimination against the ground-reflected wave by means of highly directional receiving antennas has already proved to be a valuable method on microwave relay circuits for reducing and in some cases practically eliminating the adverse effects of within line-of-sight fading due to the interference between direct and ground-reflected components. Man-made noise decreases rapidly with increasing frequency; the power in auto ignition noise decreases with frequency at a rate somewhere between the inverse square and the inverse cube of the frequency. By an appropriate choice of receiving location, man-made noise may often be largely avoided; thunderstorm and sun-spot noise are of importance only a small percentage of the time. Cosmic and temperature noise are therefore the most important sources of external noise because they are always present and set the ultimate limit to the sensitivity of radio reception at very high frequencies and above [Crichlow, et al, 1955].

4. THE SYSTEM LOSS AND TRANSMISSION LOSS CONCEPTS

It has been found that the concepts of system loss and transmission loss developed by Norton [1953, 1959] are convenient for the analysis of system performance at all radio frequencies. These are closely related terms differing only in that system loss includes the effect of antenna circuit losses. For many applications, particularly in the study of radio wave propagation, it is more convenient to have a definition which excludes antenna circuit losses except those associated with antenna radiation resistances. This is termed transmission loss.

The system loss of a radio circuit consisting of a transmitting antenna, receiving antenna, and the intervening propagation medium is defined as the dimensionless ratio, p_t'/p_a', where p_t' is the radio frequency power input to the terminals of the transmitting antenna and p_a' is the resultant radio frequency signal power available at the terminals of the receiving antenna. The system loss is usually expressed in decibels:

$$L_s = 10 \log_{10}(p_t'/p_a') = P_t' - P_a' \text{ db}, \tag{1}$$

This definition excludes any transmitting or receiving antenna transmission line losses since it is considered that such losses are readily measurable. It does include ground losses, dielectric losses, antenna loading coil losses, terminating resistor losses in rhombic antennas, etc. The inclusion of all of the antenna circuit losses in the definition of system loss provides a quantity which can always be accurately measured and which is directly applicable to the solution of radio system design problems.

All that is required to express (1) in terms of transmission loss is to replace p_t'/p_a' with p_r/p_a where p_r is the radio frequency power radiated from the transmitting antenna, and p_a is the resultant radio frequency signal power which would be available from the receiving antenna if there were no circuit losses other than those associated with its radiation resistance. In general, at VHF and higher frequencies antenna circuit losses are negligible with well designed antennas. When this is true, there is little difference between the values of transmission and system loss.

In order to separate the effects of the transmitting and receiving antenna gains and circuit losses from the effects of the propagation, it is convenient to define the basic transmission loss, L_b (sometimes called path loss), as the transmission loss expected between fictitious loss-free isotropic transmitting and receiving antennas at the same locations as the actual transmitting and receiving antennas. This serves also to define the path antenna gain, G_p, as the difference between L_b and the transmission loss, L, expressed in decibels:

$$G_p = L_b - L \tag{2}$$

In some cases it may be quite difficult to measure the antenna circuit losses; thus it is convenient to define the path antenna power gain, G_{pp}, as

$$G_{pp} = L_b - L_s \tag{3}$$

When antenna circuit losses are negligible the distinction between G_p and G_{pp} is not necessary, and in these cases the term is simply called path antenna gain with the symbol G_p.

5. PROPAGATION MECHANISMS

The following is a general description of various mechanisms important to the propagation of a radio signal, such as free space radiation, refraction, reflection from elevated layers, reflection of radio waves by the ground and by obstacles on the ground, absorption of energy by trees and buildings, diffraction over hills and over the bulge of the earth, omnidirectional and forward scattering of radio waves by the atmosphere, and the absorption of radio waves by the atmosphere.

Terrain irregularities, climate, weather, and atmospheric turbulence play principal roles in determining the strength and the fading properties of a tropospheric signal. The troposphere is that portion of the atmosphere responsible for the weather; properties of the atmosphere from the surface well up into the stratosphere affect the propagation of radio waves at all frequencies, but especially those frequencies above 40 Mc/s. Estimates of transmission loss and its long-term and short-term variability are essential to the design and allocation of military and commercial communication links and broadcasting and navigation facilities.

For all of the propagation mechanisms mentioned, the effects of refraction, diffraction and absorption by trees, hills, and man-made obstacles are often important, especially if a receiving installation is low or is surrounded by obstacles. Absorption of radio energy is probably the least important of these three factors except in cases where the only path for radio energy is directly through some building material or where a radio path extends for a long distance through trees. The following empirical relationship for the rate of attenuation in woods has been offered by Saxton and Lane [1955].

$$A_t = d(0.244 \log_{10} f_{mc} - 0.442) \text{ decibels}, \quad (f_{mc} > 100 \text{ Mc/s}) \qquad (4)$$

where A_t is the absorption in decibels through d meters of trees in full leaf at a frequency f_{mc} megacycles per second.

The situation with a high and a low antenna in which the low antenna is located a small distance from and at a lower height than a thick stand of trees is quite different from the situation in which both antennas may be located in the woods. Recent studies at approximately 500 megacycles show the depression of signal strengths below smooth earth values as a function of clearing depth, defined as the distance from the lower antenna to the edge of the woods [Head, 1960]. Expressing this empirical relation in terms of a formula:

$$\Delta_t = 52 - 12 \log_{10} d_c \text{ decibels}, \qquad (5)$$

where Δ_t is the depression of the field strength level below smooth earth values and d_c is the clearing depth in meters.

Studies made at 3000 Mc/s indicate that stone buildings and groups of trees so dense that the sky cannot be seen through them should be regarded as opaque objects around which diffraction takes place. Semi-transparent obstacles causing a loss of signal of 10 db or less include windows, tile or slate roofs, light wooden structures, and thin screens of tree branches [McPetrie and Ford, 1946].

Field strengths obtained when a thick belt of leafless trees is between transmitter and receiver are within about 6 db of those computed assuming Fresnel diffraction over an obstacle slightly lower than the trees. Loss through a thin screen of small trees will rarely exceed 6 db if the transmitter can be seen through their trunks. If sky can be seen through the trees, 15 db is the greatest expected loss.

At 3000 Mc/s the loss through a 23 centimeter thick dry brick wall was 12 db and increased to 46 db when the wall was thoroughly soaked with water. It follows that a brick building should be treated as an opaque obstacle. 1.5 db loss through a dry sash window, and 3 db loss through a wet one were usual values. The only objects encountered which showed a loss of less than 10 db at 3000 Mc/s were thin screens of leafless branches, the trunk of a single tree at a distance exceeding 100 feet, wood-framed windows, tile or slate roofs, and the sides of light wooden huts. Horizontal polarization provides a stronger signal than vertical polarization just outside the shadow of a diffracting obstacle; the opposite is true within the shadow. In general, for distances within optical range, it is better to assume a plane earth rather than a curved earth.

Studies at the National Bureau of Standards show that the reflecting and diffracting effects of man-made structures predominate over actual absorption of energy in the materials. The interference effects of reflections from various parts of a wall will result in large variations of field strength over short distances. Deviations on the order of 20 db at 20 Gc/s and 8 db at 5 to 10 Gc/s are not uncommon for antenna movements of a few inches and normal incidence of radio waves on a wall. Wall losses generally increase as the angle of incidence increases; for example, at 60 degrees from the normal the signal power loss may be from a few db to as much as 10 to 15 db greater than the corresponding loss through a wall at normal incidence, depending on frequency and the portion of the wall which is directly in the path of the antennas.

To make clearer the interrelationships between various propagation mechanisms and the conditions under which each is dominant, let us consider the propagation paths illustrated in Fig. 5. Figure 5a shows a great circle path terrain profile under conditions of normal refraction of radio waves in the troposphere. The height of mountains and trees and the size of man-made features are considerably exaggerated for the amount of earth curvature illustrated in the figure. The heavy dashed curves in Fig. 5a represent radio horizon rays, curving downward because the average refractive index of the troposphere normally decreases with height. The horizon ray is drawn to clear the treetops rather than the mountain top on the right-hand side of the figure, but with sparse tree coverage or frequencies lower than 100 Mc/s, the radio waves might not "see" the trees.

The legend below Fig. 5a lists the propagation mechanisms probably dominant over each of the transmission paths illustrated. Between the ship at S and the plane at P_1, almost overhead, the most important mechanism for propagation is radiation of energy from the transmitting antenna into what may be considered "free space" as if it were a vacuum containing only the transmitter and receiver. The basic transmission loss, L_{bf}, between isotropic antennas in free space can be expressed as follows:

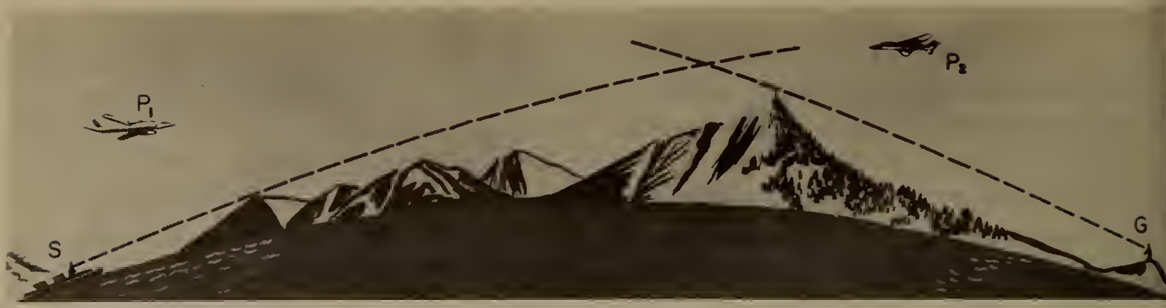
$$L_{bf} = 10 \log_{10}\left(\frac{4\pi d}{\lambda}\right)^2 = 36.581 + 20 \log_{10} f_{mc} + 20 \log_{10} d_{mi}$$

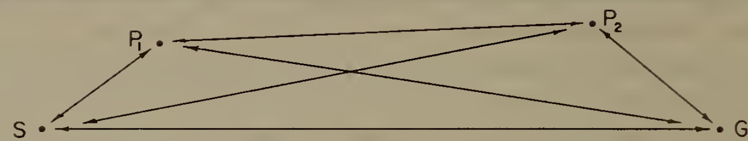
$$= 32.446 + 20 \log_{10} f_{mc} + 20 \log_{10} d_{km} \text{ decibels,} \qquad (6)$$

where d_{mi} and d_{km} denote the distance between antennas expressed in statute miles and kilometers, respectively, λ is the free space radio wavelength, and f_{mc} is the radio frequency in megacycles per second.

The attenuation with distance of the free-space fields results from the propagation of a fixed amount of energy through spheres of larger and larger radius. The frequency dependence in (6) reflects the decrease in the effective absorbing area of a receiving antenna as the frequency is increased.

PROPAGATION UNDER CONDITIONS OF NORMAL REFRACTION





Probably dominant mechanisms over each path are:

$S-P_1$;	Free-space radiation.
P_1-P_2, P_2-G	Vector addition of free-space and ground-reflected radio waves.
$S-P_2$, P_1-G	Knife-edge diffraction.
$S-G$;	Diffraction for distances less than 80 miles, forward scatter for greater distances.

PROPAGATION IN THE PRESENCE OF A GROUND-BASED DUCT AND AN ELEVATED LAYER

$S-P_1$;	Free-space radiation
$S-P_2$, P_1-P_2	Leakage through the top of the duct; weak signals further attenuated by reflection from the layer; somewhat affected by ground reflection, especially $S-P_2$
P_2-G	Vector addition of free-space and ground-reflected radio waves, slighty affected by the presence of the layer.
$S-G$, P_1-G	Strong ducting signals.

FIGURE 5

When low gain antennas are used, as on aircraft, the frequency dependence indicates that the service range for UHF equipment can be made equal to that in the VHF band only by using additional power in direct proportion to the square of the frequency. Fixed point-to-point communication links usually employ high-gain antennas at each terminal, and for a given antenna size, more gain is realized at UHF than at VHF, thus more than compensating for the additional loss at UHF indicated in (6). Where propagation is not through free space, an additional advantage may sometimes be gained for UHF by the use of diversity systems.

The effects of energy reflected from the ground sometimes modify the above conclusions. Communication between terminals located within radio line-of-sight of each other usually may be considered to depend upon the reception of a signal composed of a direct and a ground-reflected component added with the appropriate phases. From the plane at P_2 to the ground antenna at G in Fig. 5a, the vector addition of free-space and ground-reflected radio waves assumes a single ray reflected from a smooth plane or convex surface and obeying the laws of geometrical optics. The path $P_1 - P_2$, between the two airplanes, which might instead be very high ground-based terminals, involves reflection from irregular terrain. Supplements XIX and XXI of NBS Technical Note 26 [Herbstreit, 1959] discuss this problem and show results obtained by adding a Rayleigh-distributed, ground-reflected wave to the free space wave. A study of ground reflection coefficients by McGavin and Maloney [1959] is also helpful in this connection. Received signals in such a case will under most conditions vary from 5 or 6 decibels above the free-space value to 20 decibels or more below that value.

The addition of direct and ground-reflected components presupposes that the direct ray path clears obstacles between the antennas enough so that any reflected ray path is at least a half-wavelength longer than the direct ray path. Although not illustrated in Fig. 5, reflection from hillsides or obstacles off the great circle path between the antennas often contributes a significant amount to the received signal. For transmission just beyond the horizon, it may be desirable to discriminate against such off-path reflections to reduce multipath fading problems. In other cases, antenna beams may be directed away from the great circle path in order to increase the signal level by taking advantage of off-path reflection or knife-edge diffraction.

Whenever we are not in free space, the basic transmission loss L_b is the basic transmission loss in free space as given by (6) plus an attenuation, A, in decibels relative to this free space value:

$$L_b = L_{bf} + A \tag{7}$$

For instance, attenuation relative to free space for a signal composed of a direct wave component and a single ground-reflected component is

$$A = -10 \log_{10} \left[1 + (DR)^2 - 2\, DR \cos(\theta - c) \right] \tag{8}$$

where D is a coefficient allowing for the divergence of energy reflected from a convex surface, R and c are the magnitude and phase of the ground reflection coefficient, and θ is the geometric path length difference between direct and ground-reflected rays, expressed in fractions of a wavelength times 360 degrees or 2π radians. The product DR is always less than or equal to unity. Convenient formulas for θ as well as exact expressions can be found in another paper [Air Force Technical Order, 1961]. Both R and c are functions of the frequency f_{mc} and the grazing angle ψ for the reflected ray.

Equation (8) is written so that A, the attenuation relative to free space expressed in decibels, will be positive for transmission losses exceeding the free space value given by (6). When the phase of the direct and ground-reflected waves is such that $\cos(\theta - c)$ is negative, A is negative, and the expected transmission loss is less than the free space loss.

As the height gradient of refractive index changes with time, the horizon rays shown in Fig. 5a will bend less or more than normal. With a gradient increase, for instance, ray bending will increase. If a radio ray from P_1 to P_2 passes near the large mountain near G, the Fresnel-Kirchhoff knife-edge diffraction theory, either beyond line-of-sight or just within line-of-sight, may provide good estimates of the transmission loss between the airplanes or any elevated terminals. Knife-edge diffraction is expected to be dominant over the paths $S-P_2$ and P_1-G in Fig. 5a. Over a smoother terrain profile the mechanism of propagation would still be diffraction, with transmission loss increasing more rapidly with distance than is the case for diffraction over a single knife-edge.

When antennas are just within line-of-sight of each other, propagation is often troubled with a high percentage of "space-wave fadeouts" originally defined to exist whenever a signal stays at least 5 db below its monthly median value for more than a minute [Bean, 1954].

Space-wave fadeouts may result from defocusing of radio energy in some regions of space (radio holes), accompanied by a focusing effect and signal enhancement in other regions [Doherty, 1952], or phase interference phenomena associated with slowly varying refractive index profiles. In temperate continental climates, space-wave fadeouts are likely to occur primarily at night and most frequently during the summer months. These fadeouts are more frequent at UHF than at VHF, and their occurrence can be correlated with the occurrence of ground-modified refractive index profiles [Barsis and Johnson, 1961].

Prediction formulas are most useful for long surface-to-surface links such as the path S-G in Fig. 5a [Air Force Technical Order, 1961; Barsis, Norton, Rice, and Elder [1961]. Usually, diffraction or forward scatter are the dominant propagation mechanisms for more than half of any long period of time, so the associated theories are used to predict long term medians. Even where well-developed stratification of the atmosphere results in a considerable amount of energy being propagated by means of reflection from elevated layers more than half the time, a "forward scatter" theory gives good predictions. A discussion of layer theory [Friis, Crawford, and Hogg, 1957] includes one special case of great interest for any comparison of tropospheric forward scatter and reflection theories. For this case, attenuation relative to free space is

$$A = K + 10 \log \left(\frac{d\psi}{\lambda} \right) , \qquad (9)$$

where K depends upon the characteristics of the layer, d is the path distance, ψ is the grazing angle (at the layer), and λ is the free space radio wavelength. The distance dependence in (9) arises from the fact that a layer of a given size subtends small angles at the greater distances; the frequency dependence is significant as being the same as that confirmed by the work of Norton, Rice, and Vogler [1955] comparing radio transmission loss data with theories of tropospheric forward scatter.

Sometimes no distinction can be made between "forward scatter" from the turbulent atmosphere and the addition of "incoherent reflections" from patchy elevated layers. In either case, what is desired is a statistical description corresponding to average characteristics observed for a great many paths over long periods of time; methods for predicting such averages derived from either type of theory would be quite similar. It is natural to turn to a layer theory for the prediction of transmission loss if detailed information about expected layer heights and intensities is available. See Smyth and Trolese [1947] or Josephson and Eklund [1958].

Tracing radio rays through the atmosphere is essential in order to predict the transmission loss associated with most of the propagation mechanisms mentioned so far. Refraction or bending which exceeds the "normal" bending illustrated in Fig. 5a is called super-refraction and in the limit becomes ducting. Within a duct, which may be either elevated or ground-based, ray tracing is generally pointless (and improper) for angles of elevation above the horizon which are less than a certain critical value, below which the duct acts as a waveguide and traps energy associated with frequencies above a certain critical frequency. Ducts are efficient propagators at UHF and above, as commonly occurring duct heights are large compared to the shorter wavelengths. Elevated layers, on the other hand, are more efficient propagators at VHF than at higher frequencies, because the layer thickness which represents a sharp discontinuity of refractive index when wavelengths are large is a relatively gradual change of refractive index with height for propagation at the shorter wavelengths.

Ducts and elevated layers are not necessarily associated with each other, but for convenience, Fig. 5b has been drawn to illustrate propagation in the presence of a very thick ground-based duct extending all the way up to an elevated layer. Propagation from S to P_1 is still mainly free-space radiation because the wave is launched with a large angle of elevation above the horizon. Some energy will leak through the duct from S to P_2 and from P_1 to P_2 at any frequency; the path from P_1 to P_2 may in some instances correspond to the phenomenon of the "radio hole". The path P_2 to G should be slightly affected by the presence of the layer, especially at the lower tropospheric frequencies, but will probably be unaffected by the presence of the duct, again because of the high "take-off angle" of the radio energy. The paths S to G and P_1 to G illustrate the conditions for strong ducting signals at any tropospheric frequency. Since the duct is shown to extend to an unusually great height, the associated radio transmission loss will be less than that in free space for these two paths.

6. METEOROLOGICAL CONDITIONS ASSOCIATED WITH VARIOUS PROPAGATION MECHANISMS

Super-refraction sufficient to result in duct propagation is produced (a) by a pronounced decrease of moisture with height (moisture lapse), or (b) by a pronounced increase in temperature with height (temperature inversion), and (c) particularly, by a combination of both of the above conditions. Of the meteorological conditions conducive to guided propagation or trapping the most outstanding are: (1) Over sea: flow of warm dry air over colder water producing temperature inversions and evaporation into the lowest layers; (2) Over land: nocturnal cooling of ground with clear skies, calm air, or light winds (if moisture distribution is favorable); (3) Over both sea and land: low level subsidence. Conditions in the barometric high, including calm clear skies and especially low level subsidence or sinking of an air mass, favor trapping (especially during the night) but do not necessarily produce it. Conditions in the barometric low, including strong winds, intense turbulence in the lowest layers, and overcast skies are conducive to standard propagation.

As illustrated in Fig. 5b, when a transmitter is within a duct, radar range is increased for surface targets such as ships and aircraft flying in the duct. At the same time there is an increase in fixed echo strength of radar signals, and consequently in ground clutter on radar scopes. This may be accompanied by a change in the range of detection for craft flying above the duct. When the transmitter is outside the duct, the range may either be increased or decreased from its standard value. Effects of non-standard propagation are negligible when the angle of elevation of a target is over 1°. Guided propagation occurs almost exclusively in the lowest 2,000 feet above the ground and usually is confined to the lowest few hundred feet, except in warm climates.

Standard propagation as illustrated in Fig. 5a results in a slight downward bending of radio rays throughout the atmosphere, so that the radio horizon is slightly farther than the geometrical horizon. This is taken into account operationally by using coverage diagrams with an earth's radius slightly greater than the true value; on a diagram modified in this way radio rays appear as straight lines. One of the objects of presenting this same terrain profile in two different atmospheres in Fig. 5 was to show that the same propagation path can at different times represent line-of-sight, just beyond the horizon, and far beyond the horizon propagation conditions, and that the mechanisms important in these cases are different.

Interference between direct rays and rays reflected from the ground gives rise to a lobe structure in the vertical cross section of coverage, the position of which depends on the wavelength, the height of antennas above the ground, and the refraction of the radio waves. When a duct is present, the upper part of a diagram corresponding to reflection at high angles is unaffected by super-refraction. Fig. 6 illustrates this phenomenon. It should be noted that space-wave fadeouts [Bean, 1954] weaken the signal normally corresponding to low angles of reflection by the ground but strengthen the signal just beyond the radio horizon of an antenna.

Turbulence of the air has a distinct normalizing effect, tending to smooth out the temperature and moisture variations which are conducive to super-refraction and the formation of layers. Moderate to strong winds produce a turbulent layer extending normally to a height of about 4,000 feet. The air is well mixed within this layer and consequently the standard type of refraction prevails. Regions of a barometric low are characterized by strong to moderate winds and pronounced turbulence in the lower layers. In addition, low pressure areas usually have overcast skies; hence, a barometric

INTERFERENCE PATTERN IN A NON-STANDARD ATMOSPHERE

At high angles, the vector addition of free space and ground-reflected waves forms a lobe pattern. Unusually strong signals near the surface are due to the presence of a duct.

Figure 6

low will as a rule lead to propagation of the standard type illustrated in Fig. 5a. It should be mentioned in passing that clouds and rain storms will scatter and reflect radio energy in a different way than the ordinary turbulence of the atmosphere scatters the radio energy.

Dutton [1961] discusses the synoptic climatology of duct formations and shows how to trace rays through the atmosphere under all sorts of super-refractive conditions which occur in practice as well as under standard conditions. It appears that elevated ducts would rarely trap energy from ground-based antennas but that ground based ducts are of greatest importance to a study of long distance tropospheric propagation.

The geometrical ray-optics theory is usually used to estimate coverage by ray tracing techniques. This theory usually assumes a relatively simple model for the decay of the radio refractive index with height above the earth, or possibly an airless earth, and proceeds to the general solution of Maxwell's equations. Just beyond the radio horizon of a transmitting antenna, the observed radio fields result from diffraction over ridges, hills, or the bulge of the earth. At one extreme is the case of diffraction over obstacles so high and so isolated that a knife-edge diffraction theory gives theoretical results which agree well with observations. At the other extreme is diffraction over a smooth spherical earth. This condition results in low field strengths which are soon exceeded, as one progresses beyond the horizon of an antenna, by radio fields produced by reflection from elevated layers or by forward scatter radio waves.

Tropospheric forward scatter becomes a useful propagation mechanism for distances between roughly 100 and 1,000 miles and for frequencies between 40 and 10,000 megacycles per second when advantage is taken of recent developments of high power transmitters and high gain antennas suitable for use at these frequencies.

Our atmosphere even in its quietest state is turbulent, and the refractive index of any small volume of air will fluctuate measurably with time from its average value. If variations in time are strongly correlated at points widely separated in space, the "scale of turbulence" of the atmosphere is large, and "blobs" of the medium behave as large obstacles in the path of the radio wave, scattering energy primarily forward.

A small obstacle in the path of a radio wave scatters radio energy equally in all directions. This is called Rayleigh scattering, after Lord Rayleigh, who deduced that the amount of such scattered energy is proportional to the fourth power of the frequency; with this kind of scattering, blue light is scattered about 10 times as efficiently as red light. Rayleigh scattering of radio waves results from very small inhomogeneities in the refractive index structure of the atmosphere as well as from such obstacles as raindrops.

7. LONG-TERM AND SHORT-TERM FADING

In temperate latitudes the seasonal variation of forward scatter signals shows a minimum during the winter and the diurnal trend has its minimum in the afternoon. These minima are on the order of 10 decibels below the annual median value, except that diurnal trends are less pronounced at great distances. Since the signal level depends to some extent on atmospheric refraction, the median signal level in low latitudes is usually higher. Long-term variations are caused by slow variations in the propagation medium, such as changes in the intensity of turbulence in the troposphere or stratosphere, varying stratification of the atmosphere, and changes in average refraction conditions.

Short-term variability of radio signals is generally attributed to phase interference among simultaneously occurring modes of propagation; that is, to multipath effects. Recent work has indicated that fading rates within radio line-of-sight are largely independent of frequency but depend upon the number of atmospheric inhomogeneities or "blobs" that cross the propagation path each minute. Beyond radio line-of-sight, fading rate tends to increase with frequency and depends, in a complex manner, on the relative importance of various propagation mechanisms and on the state of the atmosphere.

Sometimes it is convenient to consider received VHF and UHF fields as consisting essentially of two components; one has a slowly varying amplitude and results from some mechanism such as ground wave propagation within the horizon, or diffraction accompanied by ducting, or reflection from elevated layers in propagation beyond the horizon. Another component has a rapidly fluctuating amplitude and results from atmospheric scattering.

Typical observed long-term and short-term fading characteristics can be seen from the results of a 17-day recording over an 803-km (509-mile) propagation path in the Pacific. Continuous propagation measurements were made using 409.9 Mc/s and 8.6-meter (28-foot) parabolic dishes during the period April 2-18, 1959. Fig. 7 shows a profile of this propagation path. The primary characteristics of this profile are the high elevation of one terminal and the mountain obstruction at the horizon of the other terminal. Fig. 8 shows a two and one-half minute sample of the recorded transmission loss on a slow-speed graphic recorder, together with a 9-second sample on a high-speed recorder. The fine detail in the latter sample does not appear in the other recording because of its one-second time constant. The time constant for the high-speed recorder is on the order of 0.01 seconds.

This example demonstrates the large range of values of transmission loss which occur during short periods of time on tropospheric scatter paths. Diversity reception is useful in overcoming much of this fading because the short-term fading at each of the diversity antennas is relatively independent of the others, and the received intelligence benefits from the receiver's ability to select the highest signal.

In order to evaluate long-term time variations it is convenient to consider the hourly median transmission loss. This level of transmission loss is exceeded for a total of one half of a given hour, and the instantaneous values of transmission loss are less than the hourly median for one half of the hour. A distribution of the hourly medians gives a measure of the long-term time variations. In Fig. 9 the hourly medians are shown by time of day for all 17 days of measurement. Also shown are hourly variations in atmospheric refractivity observed near the surface at the receiver site. It has been found that long-term variations in transmission loss expressed in terms of monthly or even weekly medians are well correlated with similar medians of surface refractivity. Medians for periods less than a week do not correlate well.

In predicting the performance of a tropospheric-scatter communication circuit, we are primarily concerned with determining the maximum hourly median values of basic transmission loss that are likely to occur during a year or more of operation. The minimum values of transmission loss are not particularly important for

PROFILE OF A TROPICAL MARITIME PATH FOR WHICH ESTIMATES AND MEASUREMENTS HAVE BEEN MADE

FREQUENCY 409.9 Mc/s; ANTENNAS 8.6 METER PARABOLAS (28 FEET)

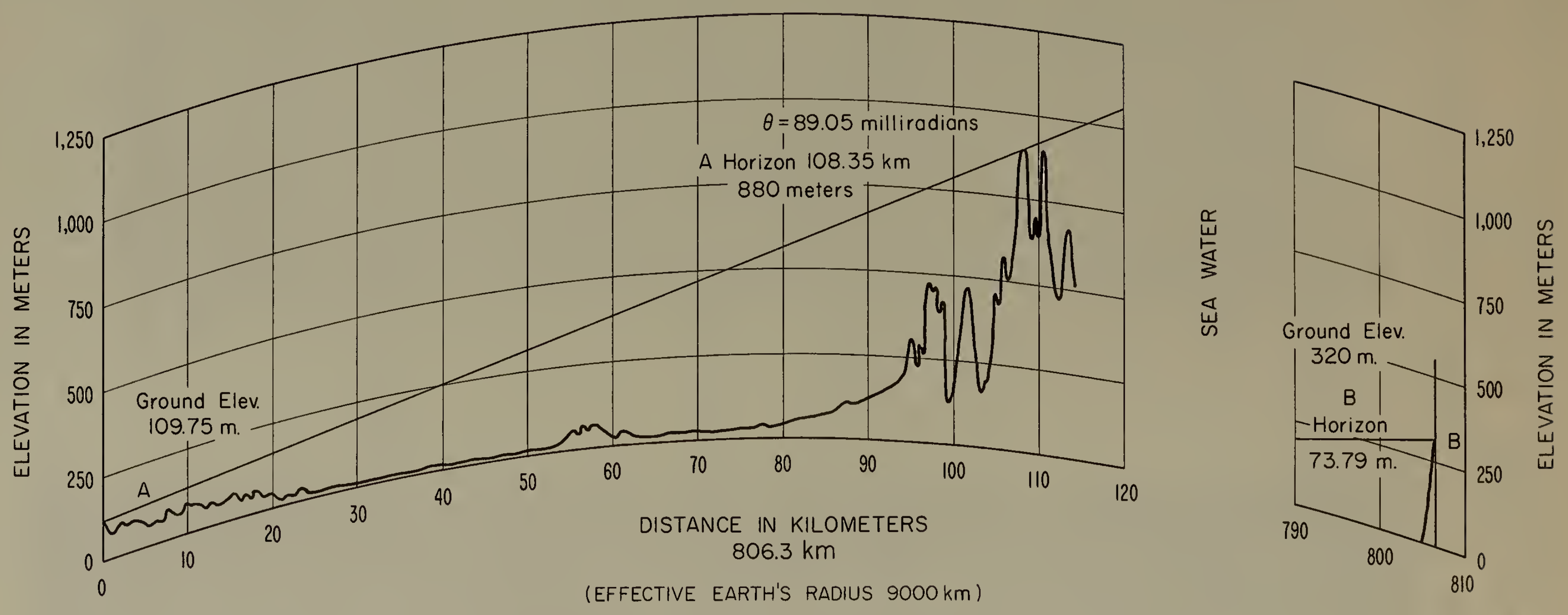


FIGURE 7

RECORDED TRANSMISSION LOSS VARIATIONS
806.3 km PATH; 409.9 Mc
APRIL 10, 1959; 12:47pm LOCAL TIME

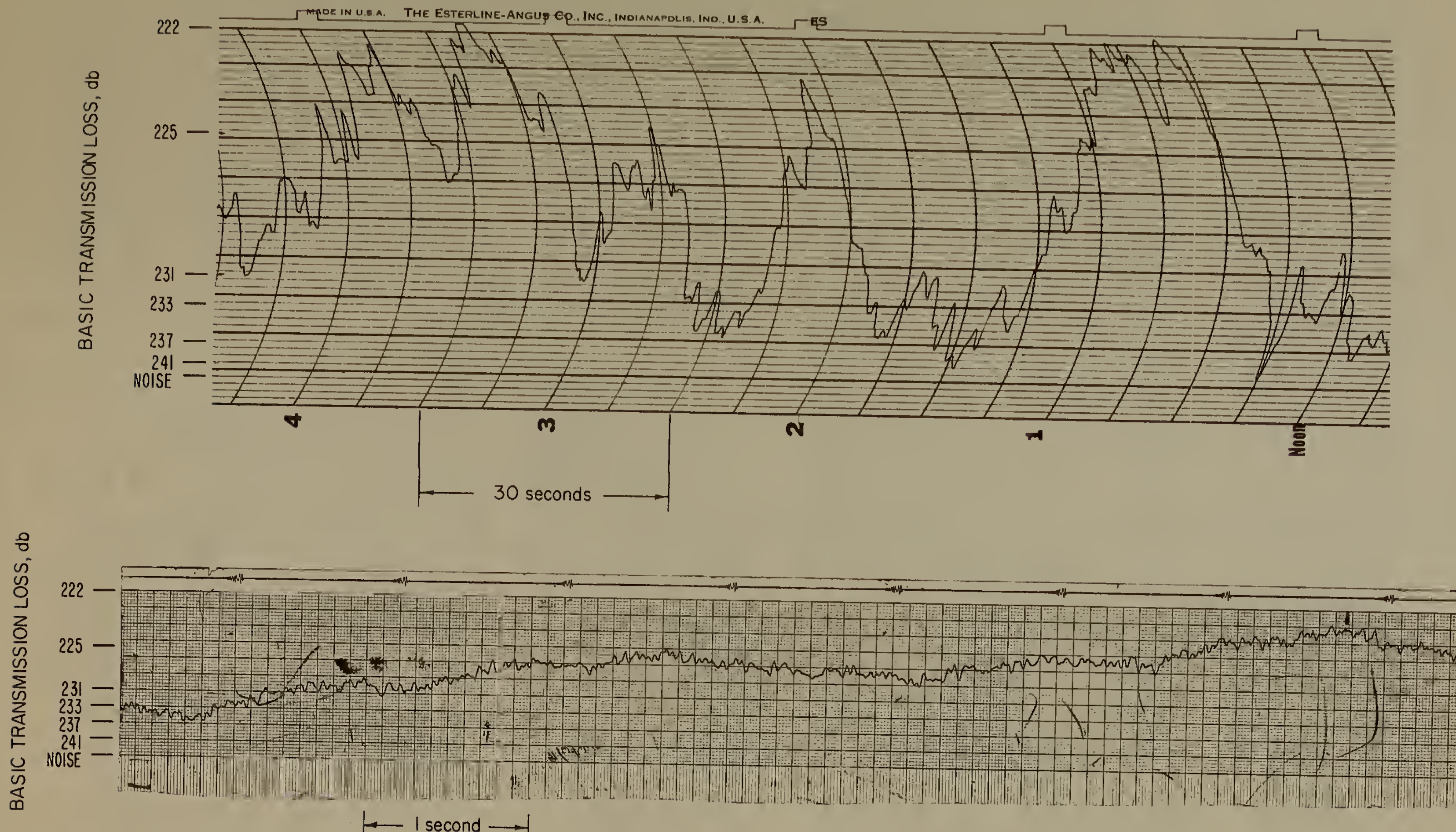


FIGURE 8

DIURNAL VARIATIONS OF MEASURED DATA
APRIL 2–18, 1959
366 HOURS

d = 806.3 km; θ = 89 mr; 8.6 m PARABOLIC ANTENNAS

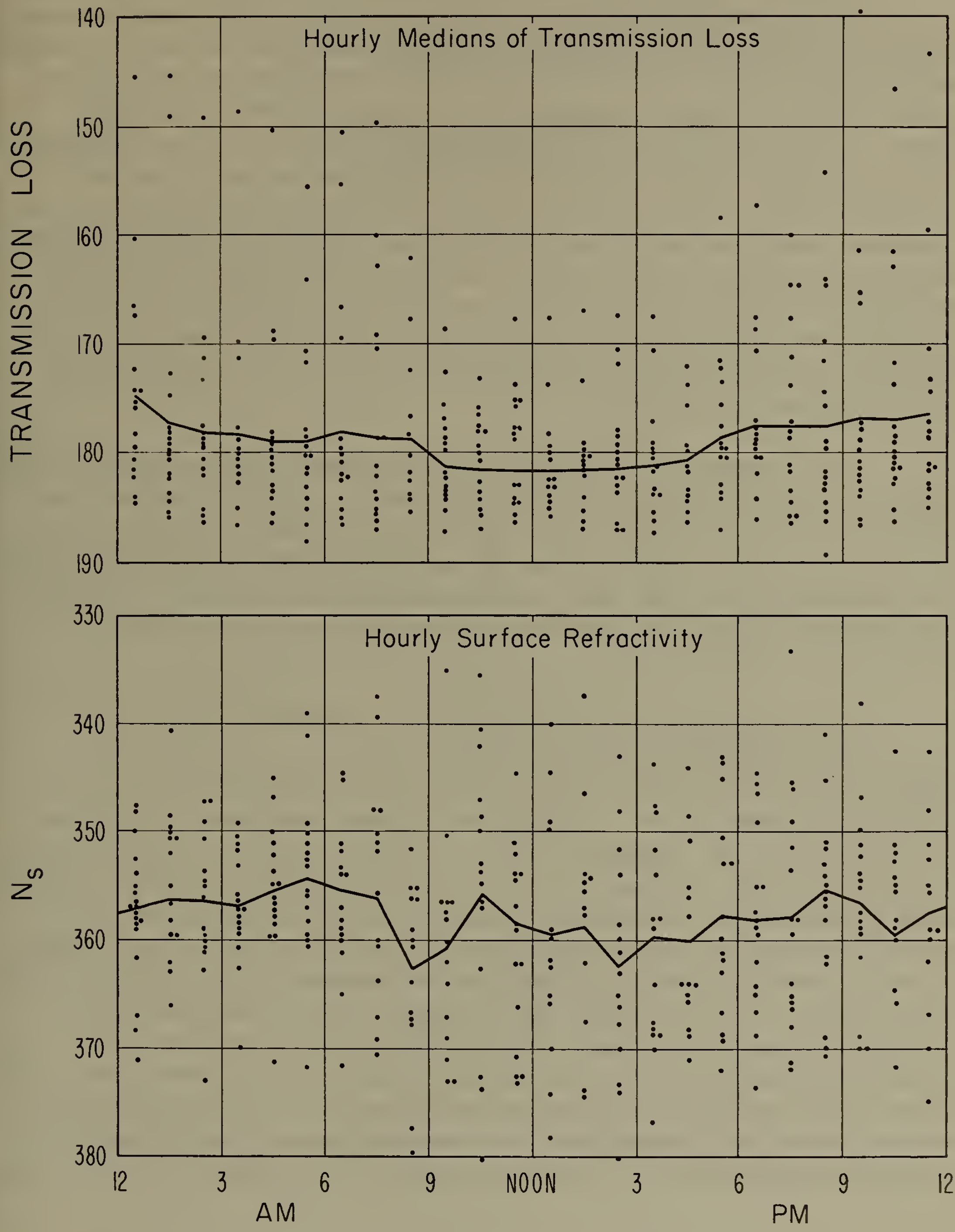


FIGURE 9

service considerations, but they are important in evaluating interference characteristics.

Prior to making the measurements shown in Figs. 8 and 9, an estimate of the distribution of hourly median basic transmission loss was made using a prediction method developed by Rice, Longley, and Norton, [1959]. Fig. 10 shows this predicted distribution together with the limits of probable error and the 90% confidence bands. These bands can be interpreted in terms of the probability that for a given number of similar predictions the indicated percentage of observed distributions will fall within these limits. For example, only one out of ten observations would be expected to fall outside of the 90% range between the 5% and 95% bands. Approximately 50% would fall within the probable error bands. It can be seen that the measurements during the 17-day period were in excellent agreement with the prediction at levels of transmission loss exceeding the median.

It is quite probable that the low values of transmission loss associated with high fields are influenced by modes of propagation other than scatter. Even though the path is extremely long, ducts of this extent occur in the tropical maritime areas quite frequently. The example chosen for Fig. 10 illustrates the fact that at present it is possible to predict service fields with greater accuracy than interference fields.

Over line-of-sight and knife-edge diffraction paths an entirely different fading characteristic has been found to occur. During periods of layering and ducting in the atmosphere these propagation paths show a tendency to go into relatively deep fades with long durations extending from periods of less than a minute to an hour or more. During periods of uniform refractive-index lapse rates these fades are much less intense or do not exist, or sometimes those that do exist are caused by multipath reflections which arrive in such a phase and amplitude relationship that a slight change in the lapse rate will cause a large change in the resultant field. The latter type can be overcome in most instances by either relocating the terminal antennas or by the use of space diversity. The fading characteristics associated with atmospheric discontinuities such as ducts and layers have been termed space-wave fadeouts. Ordinary space diversity does not appear to be helpful in overcoming

MEASURED AND EXPECTED DISTRIBUTION
OF HOURLY MEDIAN TRANSMISSION LOSS
All Hourly Medians

d = 806.3 km; θ = 89 milliradians
8.6m parabolic antennas

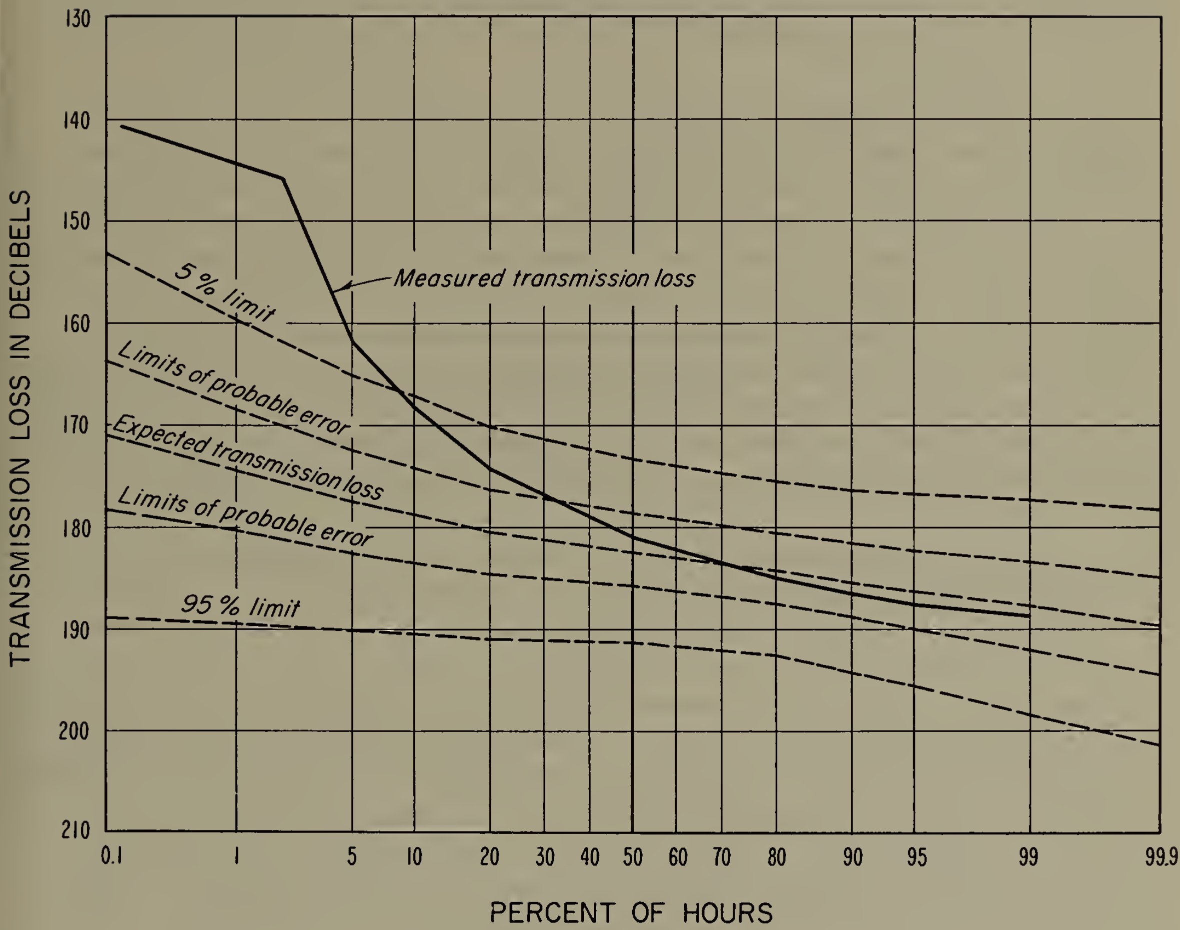


FIGURE 10

this type of fading, although there are indications that extremely wide spacing, particularly with different heights, may be effective. For convenience in analysis procedures a space-wave fadeout is defined for line-of-sight and knife-edge diffraction paths to be any fade in which the signal level drops more than 5 db below the monthly median for a period in excess of one minute.

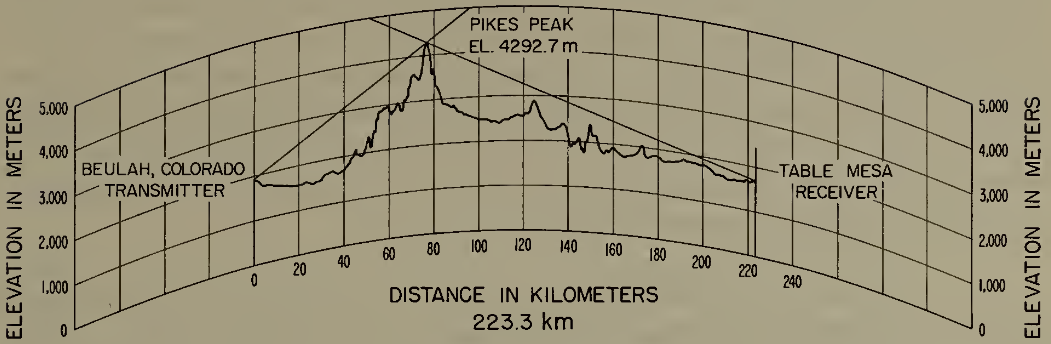
Space-wave fadeouts are more predominant in the UHF band than in the VHF band. They are also much more predominant in geographic areas where layers and ducts occur frequently. The atmosphere along the southwest coast of the United States exhibits persistent layering, and line-of-sight paths in this area are characterized by a large incidence of fadeouts even in the 100 Mc/s range.

One example of the frequency dependence of space-wave fadeouts over knife-edge diffraction paths can be seen in a comparison of the results of two different circuits in Alaska. Dickson, et al [1953] analyzed a 30-day period of measurements from Yakutat to Gustavus, Alaska, over Mt. Fairweather and found that the transmission loss during this entire period varied from its mean value by less than ± 2 db. These measurements were made at 38 Mc/s. Later one of the White Alice tropospheric circuits was installed over almost the identical path. This circuit used 900 Mc/s. Recordings of transmission loss obtained at this frequency show a high incidence of deep fading, many fades exceeding 20 db below the median level.

An example of this type of fading on a 223-km path over a knife-edge type obstacle in Colorado is shown in Fig. 11. In this test a 751 Mc/s signal was transmitted directly over Pike's Peak, which was visible from either terminal. Insofar as the peak acts as a knife edge, Fresnel-Kirchhoff diffraction formulas can be used to estimate the transmission loss. An estimate of basic transmission loss based on a simple, one-ray solution gives a value of $L_b = 179$ db. Actually, there are probably some ground-reflected rays involved which modify the single-ray analysis. The ground is extremely rough, making a rigorous analysis of its effect very difficult. The median value of basic transmission loss for the period of the example was found to be 189.4 db for an antenna at an elevation of 17.4 meters (57 feet) above ground and 198.7 db for an antenna at 8.2 meters (27 feet) above ground. Some of the additional loss may be attributed to the fact that the top of the peak is not a true knife

PROPAGATION BY KNIFE EDGE DIFFRACTION AT 751 Mc/s

TRANSMITTER POWER	500 WATTS	
TRANSMITTING ANTENNA	4.3 m. DISH	G_t = 26.7 db, H_t = 7 m.
RECEIVING ANTENNAS (1)	CORNER REFLECTOR	G_r = 13.9 db, H_r = 17.4 m.
(2)	3.3 m. DISH	G_r = 23.6 db, H_r = 8.2 m.



RECORDINGS MADE 0000-0200 JUNE 23, 1960

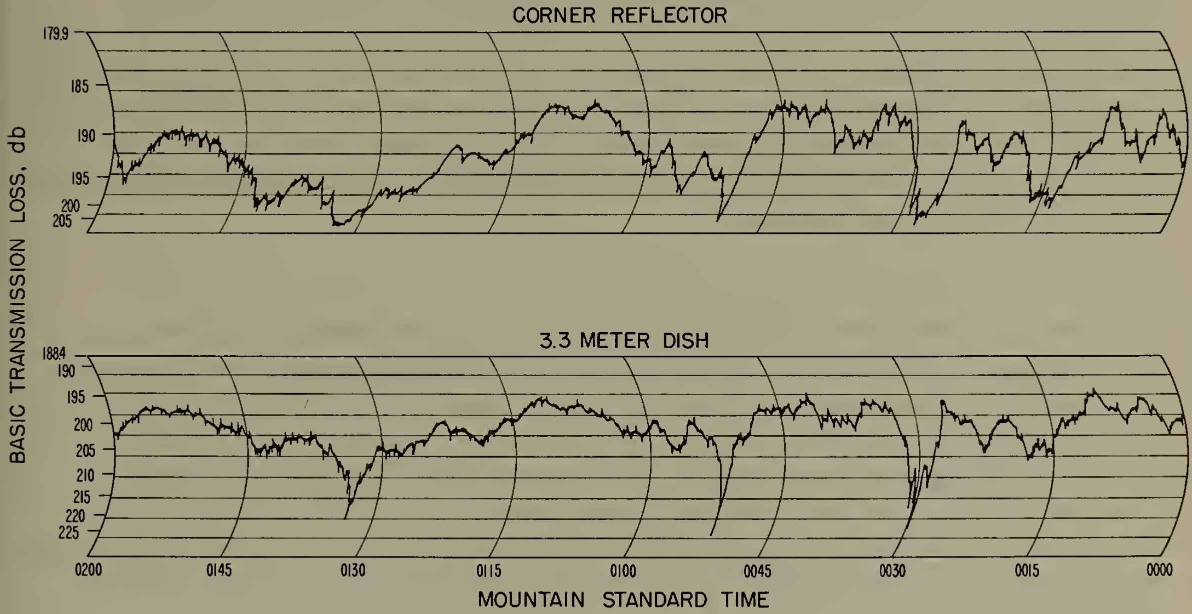


Figure 11

edge, but is actually curved both along and normal to the path of propagation.

A point of interest in the data shown on Fig. 11 is the relatively frequent occurrence of deep and prolonged fadeouts. These are believed to be similar to the space-wave fadeouts on line-of-sight paths which are associated with the occurrence of non-linear refractive index profiles in the atmosphere [Bean, 1954; Barsis and Johnson, 1961]. A radiosonde observation, Fig. 12, obtained from Stapleton Field in Denver, Colorado, during the period 0430 - 0500 MST on 23 June shows the presence of a weak layer. This sounding was obtained considerably off the propagation path and there may have been more pronounced layering nearer the mountains. The data obtained from this sounding are plotted in refractivity units versus altitude in Fig. 12.

Figure 13 illustrates an analysis of six hours of recording for the 223-kilometer path which passes over Pike's Peak. The figure shows distributions of fade duration for various depths of fading, as well as distributions of signal duration for various levels above the median. It should be emphasized that this period is characterized by moderately severe fading. Other periods of recording show little or no fading and there are some periods during which the fading was even more severe. It can be seen from Fig. 13 that fades of fairly long duration occur frequently. The deeper fades occur less frequently and with shorter durations than the shallow fades. For a small percentage of the time the signal faded in excess of 20 db below the median.

Periods of high signal level are analyzed in the same manner as the fades. The duration and the percentage of the recording period that signal levels exceeded the median are shown on the right hand side of Fig. 13. The range of levels for high fields goes only on the order of 6 db above the median compared to 21 db below for the fades. The experiment from which these data were obtained is currently underway. It is hoped to obtain a complete year of recordings at frequencies ranging from 100 Mc/s to 10 Gc/s over this path using sample recording runs of one week per month.

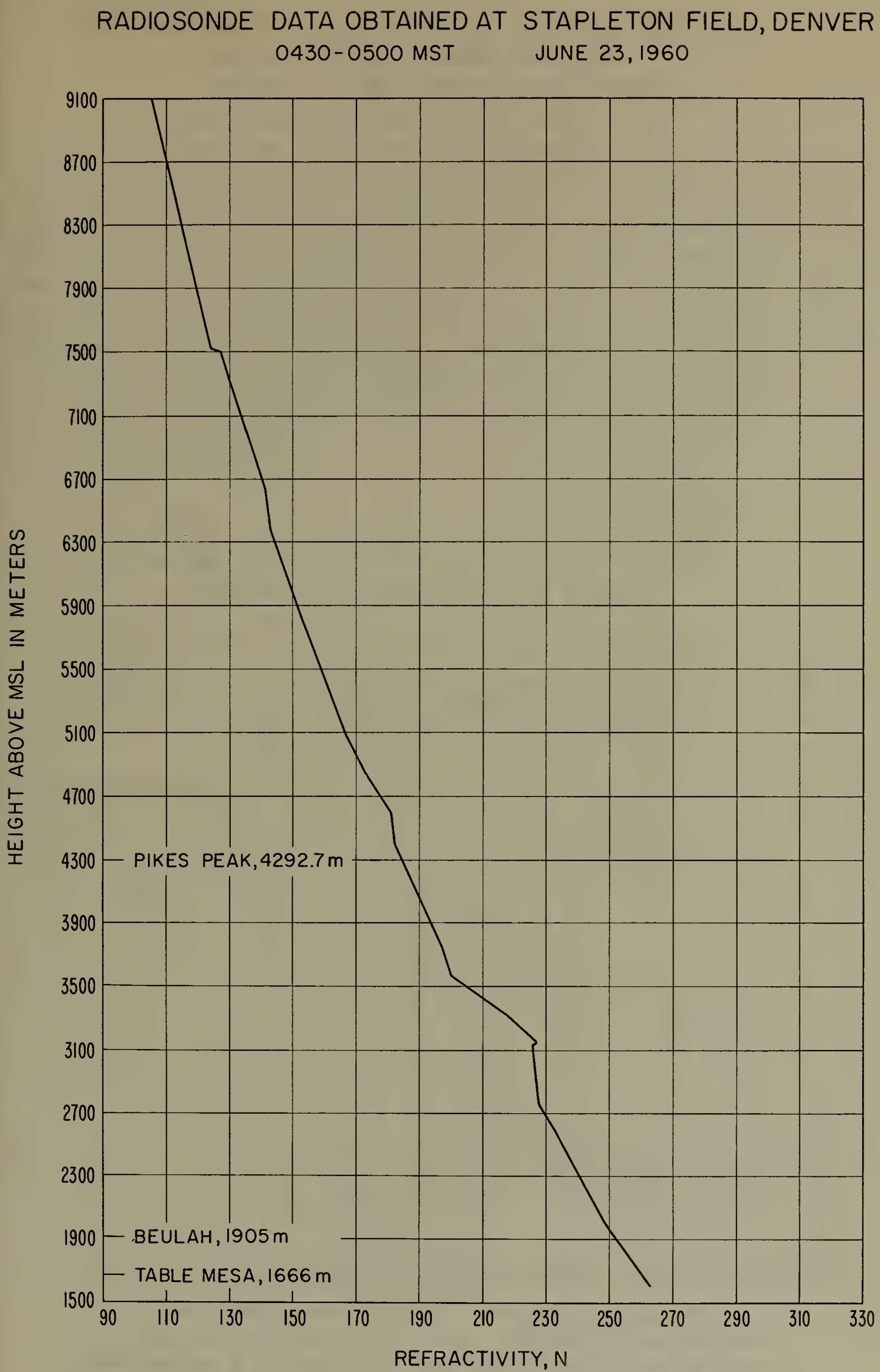
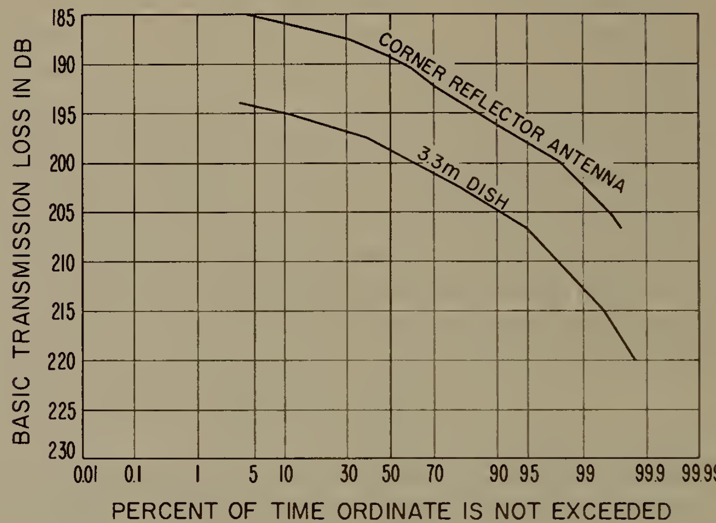

RADIOSONDE DATA OBTAINED AT STAPLETON FIELD, DENVER
0430-0500 MST JUNE 23, 1960
9100
8700
8300
7900
7500
7100
6700
6300
5900
5500
5100
4700
4300
3900
3500
3100
2700
2300
1900
1500
HEIGHT ABOVE MSL IN METERS
PIKES PEAK, 4292.7 m
BEULAH, 1905 m
TABLE MESA, 1666 m
90
110
130
150
170
190
210
230
250
270
290
310
330
REFRACTIVITY, N

FIGURE 12

CUMULATIVE DISTRIBUTIONS OF BASIC TRANSMISSION LOSS
FADE AND SIGNAL DURATIONS FOR
KNIFE EDGE DIFFRACTION AT 751 Mc/s

DATA OBTAINED 0000 - 0600 MST JUNE 23, 1960
DURING MODERATELY SEVERE FADING CONDITIONS



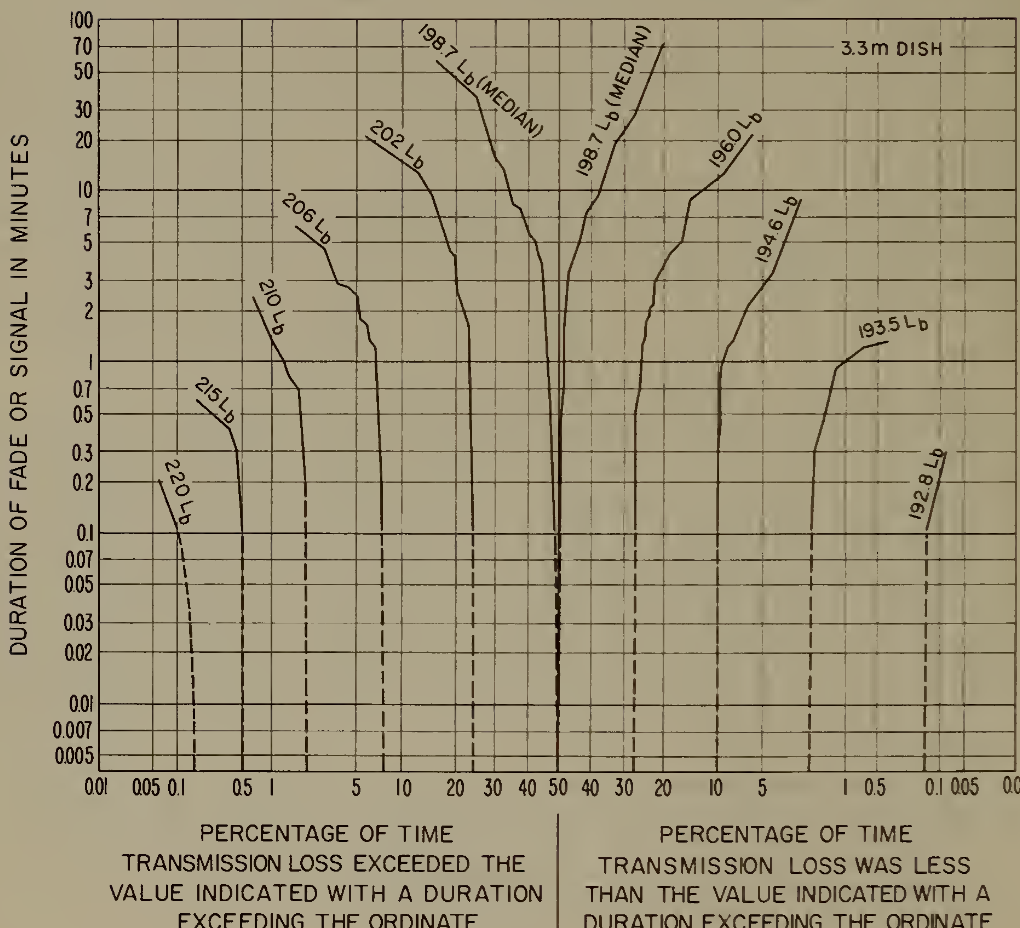


FIGURE 13

8. EVALUATING SYSTEM PERFORMANCE

In order to specify what equipment is needed to carry out the communication function and how well it is likely to perform over a given communication circuit, (or, in the case of a system in operation, to measure its performance) it is necessary to make an analysis including all of the pertinent factors involved. We are interested in the effects of coding, modulation, transmitter and antenna performance, propagation and noise, and receiver and terminal equipment performance. The following equation relates the power required at the output terminals of a transmitter with the propagation and equipment performance factors associated with a communication circuit [Norton, 1956]:

$$P_t = L_b - G_p + L_t + F + B + R - 204 \text{ dbw} \qquad (10a)$$

or

$$R = P_t - L_b + G_p - L_t - F - B + 204 \text{ db} \qquad (10b)$$

In equation (10):

P_t is the transmitter power in decibels above one watt.

L_b is the basic transmission loss.

G_p is the effective path antenna gain.

L_t includes transmitting antenna, transmission line and associated losses.

F is the effective noise figure of the receiver including transmission line and matching network losses, L_r, as well as the effects of receiver, cosmic, and man-made noise.

B is $10 \log_{10} b$, where b is the total RF or IF bandwidth in cycles per second (including the effect of drift between transmitter and receiver oscillators).

R is the pre-detection RMS-carrier-to-RMS-noise ratio for the bandwidth, type of modulation, and order of diversity used, and is usually expressed as an hourly median value.

204 is a constant equal to $-10 \log_{10} kT$, where k is Boltzmann's constant and the reference temperature, T, is taken to be 288° Kelvin or 60° Fahrenheit. It is the noise power in a one-cycle bandwidth expressed in db below one watt.

The capability of a communication circuit is usually specified in terms of the errors that occur during a given time period. Errors can be defined in terms of the percentage of words that are missed and teletype errors in terms of character or bit errors. Because of their digital character, teletype errors are easier to analyze quantitatively than analog information such as voice or facsimile. It has been found that the ratio of voice errors to teletype character errors on a typical multiplex circuit operating by the tropospheric scatter mode is on the order of 100:1, in some cases.

One of the most difficult parameters to predict or even to measure is the transmission loss. This includes both terms L_b and G_p. The Air Force Technical Order [1961] presents methods for estimating transmission loss for all modes of propagation involved in transmitting signals through the troposphere. Over most paths the transmission loss varies with time, and it is necessary to estimate the maximum values that are likely to occur. This is usually expressed in terms of hourly median values of transmission loss likely to be exceeded for various percentages of the hours of the year. The primary difficulty with measuring transmission loss in order to predict performance lies in the fact that measurements are usually made over short periods of time, and little information can be resolved from such measurements regarding the long-term variability. In most cases predicted rather than measured values provide the more reliable estimates of long-term median transmission loss. Line-of-sight and knife-edge diffraction measurements can be misleading when the measurements are made under stable atmospheric conditions. Even in areas where ducts and layers are rare, it is important to consider the possibility of radio holes [Doherty, 1952] and space-wave fadeouts in estimating mex-imum values of transmission loss if the circuit is to be highly reli-able. Estimates of the reliability of the prediction methods outlined in the Air Force Technical Order [1961] are given by Barsis, Norton, Rice, and Elder [1961].

Probably the easiest factor to determine in (10) is the line loss, L_t. It can be seen, however, that it is important, particularly in high-power transmitter installations, to use transmission line with low loss and to carefully match impedances.

No simple tabulation of values of R, F, and B can be made; Florman and Tary [1961] deal with this subject in great detail. Typical values are given for these factors by Barsis, et al [1961], but these should be considered as only state-of-the-art guide lines and subject to change and improvement. B, F, and kT together determine the noise power against which the signal must compete. The pre-detection signal-to-noise ratio, R, is related to the receiver output signal-to-noise ratio which in turn is related to the error rate. For any telecommunication system there is a relationship between the error rate and R which depends on many factors, in-cluding the type and manner of modulation, the characteristics of fading, the order of diversity, and the method of combining diversity signals.

Because there are uncertainties in the prediction of all the values on the right hand side of (10a), particularly in predicting $L_b - G_p$, performance estimates are made in terms of statistical probability. For this purpose the service probability concept is defined. It is important to understand the service probability con-cept thoroughly. Service probability, designated F(t), is a number between zero and unity which expresses the probability of obtaining service of a given quality; i.e., a certain percentage of errors or less, during a specified percentage of the hour in a year. For example, a service probability, F(t) = 0.95 would be interpreted to mean that on the average 95 paths out of 100 randomly chosen paths with the same nominal parameters would be expected to pro-vide the specified quality of service for at least the percentage of hours in the year indicated by p.

In order to illustrate the application of service probability and also to demonstrate the use of a simple, approximate formula for use in estimating transmission loss with tropospheric scatter, the following example is used.

Let us assume that it is desired to use the Haswell to Table Mesa, Colorado, path for a tropospheric scatter communication link. An approximate estimate of the transmission loss expected is obtained using the prediction methods described in a recent Air Force Technical Order [1961]. Basic transmission loss, L_b, equal to the winter afternoon tropospheric scatter component, L_{bms}, can be expressed approximately as a free space loss, L_{bf}, plus a scatter loss, A, such that $L_{bms} = L_{bf} + A$, where

$$A = 48 + d_{km}/16 = 48 + d_{miles}/10 \tag{11}$$

at 100 Mc/s with L_{bf} given by (6). Additional loss at higher frequencies should be allowed for by adding 1 db at 600 Mc/s, 8 db at 1000 Mc/s, and 17 db at 5000 Mc/s.

The use of this empirical approximation neglects effects of terrain, meteorology, antenna height, and many other factors that are taken into account in the refined prediction methods of Rice, Longley, and Norton [1959], and of the Air Force Technical Order [1961]. Fig. 21 (discussed later) shows a gross terrain effect presented as a function of the sum of horizon elevation angles (take-off angles, θ_{ct}, θ_{cr}) expressed in degrees, or as a function of the angular distance $\theta_{mr} = 2\pi(\theta_{ct} + \theta_{cr})/0.360 + d/a$ expressed in milliradians, where a is an effective earth's radius. An analysis of the relative accuracy of the empirical estimates and the refined estimates has been made using data from propagation paths for which a large number of measurements are available. The variance of observed values relative to the estimates using (11) was found to be on the order of $\sigma^2_{rc} = 47$ db^2 whereas for the precise predictions the variance was more on the order of $\sigma^2_{rc} = 17$ db^2. The effect of the variance of observed relative to predicted values is taken care of in the process of determining the service probability, as will be shown in this example.

It is necessary to determine first the optimum frequency range for this path. This can be determined on the basis of antenna performance and equipment factors, such as line loss and noise figure, all of which are frequency-sensitive parameters. For the purpose of illustration we can assume an FM system with 120-voice channels, 60-foot parabolic antennas operating with dual diversity, and receivers with conventional RF amplifiers. Table 1 gives values used in this analysis for application in (10a) together with an indication of the source of the values.

Fig. 14 shows the results of this analysis plotted to show the frequency dependence of the required power expected to provide an acceptable grade of service for fifty per cent of the winter afternoon hours. The purpose in plotting this curve is to determine an optimum frequency range and to estimate additional losses resulting from the use of frequencies which may not be optimum. The optimum frequency range using the empirical estimate of transmission loss can be taken as 275 to 550 Mc/s. For comparison a similar curve is shown which is based on refined estimates of transmission loss. The empirical estimate is somewhat more optimistic than the refined estimate in terms of transmitter power requirements. Also, the optimum frequency range using the empirical estimates comes out somewhat higher. A limited number of measurements over this path at 409.9 Mc/s and at 1040.1 Mc/s indicates that both estimates may be too optimistic.

In order to allow for prediction uncertainty it is convenient to determine the probable error range for the estimates. This error range has been determined from a large number of measurements made over tropospheric scatter paths. Differences between measured and predicted values of transmission loss expressed in decibels are approximately normally distributed with a mean of zero. The total dispersion for this type of distribution can be expressed in terms of a variance, σ^2, which is the mean of squared deviations between estimated and observed values. This analysis shows that the variances depend on the particular part of the distribution of hourly median values of transmission loss for which the estimate applies. Values of transmission loss near the median or somewhat greater can be predicted more successfully than values at the extremes. Since we are interested in high reliability, we are most concerned with the variance associated with transmission loss not

Table 1

Application of Equation (10a) to the Table Mesa-Haswell path using the less accurate, empirical estimate of basic transmission loss.

	Parameter		Equation and Source	Frequency Mc/s 200	500	700	1000	1500
1.	L_{bf}	db	(6)	127.0	134.9	137.8	140.9	144.5
2.	A	db	(11)	64.5	64.5	64.5	64.5	64.5
3.	Freq. Corr.	db	(11)	0	0	3	8	12
4.	Take-off Angle Corr.	db	Figure 21	2.7	2.7	2.7	2.7	2.7
5.	L_{bms} (expected for winter afternoons)	db	Sum of 1 through 4	194.2	202.1	208.0	216.1	223.7
* 6.	G_t, G_r	db	(Free space gains)	29.2	37.2	40.1	43.2	46.7
* 7.	θ_{mr}		(Angular distance)	34.0	34.0	34.0	34.0	34.0
* 8.	θ/Ω		(Ratio of Angular distance to half-power beamwidth)	0.336	0.750	1.19	1.68	2.49
* 9.	G_L	db	Loss in path antenna gain, G_p.	0.7	2.5	4.2	6.3	9.5
10.	G_p	db	$= G_t + G_r - G_L$	57.7	71.9	76.0	80.1	83.9
† 11.	L_t	db		1.0	1.6	1.9	2.5	3.0
† 12.	F	db		5.5	8.4	9.9	12.0	13.0
† 13.	B	db		66.9	66.9	66.9	66.9	66.9
† 14.	R	db	(10b) Dual diversity and 0.01% errors.	18.6	18.6	18.6	18.6	18.6
15.	P_t	dbw	(10a)	24.5	21.7	25.3	32.0	37.3

* Air Force Technical Order [1961]

† Barsis, Norton, Rice, and Dougherty [1961]

DETERMINATION OF OPTIMUM FREQUENCY RANGE FOR TROPOSPHERIC SCATTER COMMUNICATIONS BETWEEN HASWELL AND TABLE MESA, COLORADO

FOR 120 VOICE CHANNELS USING DUAL DIVERSITY 60 FT. DISHES AND CONVENTIONAL RF AMPLIFIERS

TRANSMITTER POWER IS VALUE EXPECTED TO PROVIDE SERVICE FOR 50% OF THE WINTER AFTERNOON HOURS, F(t) = 0.5

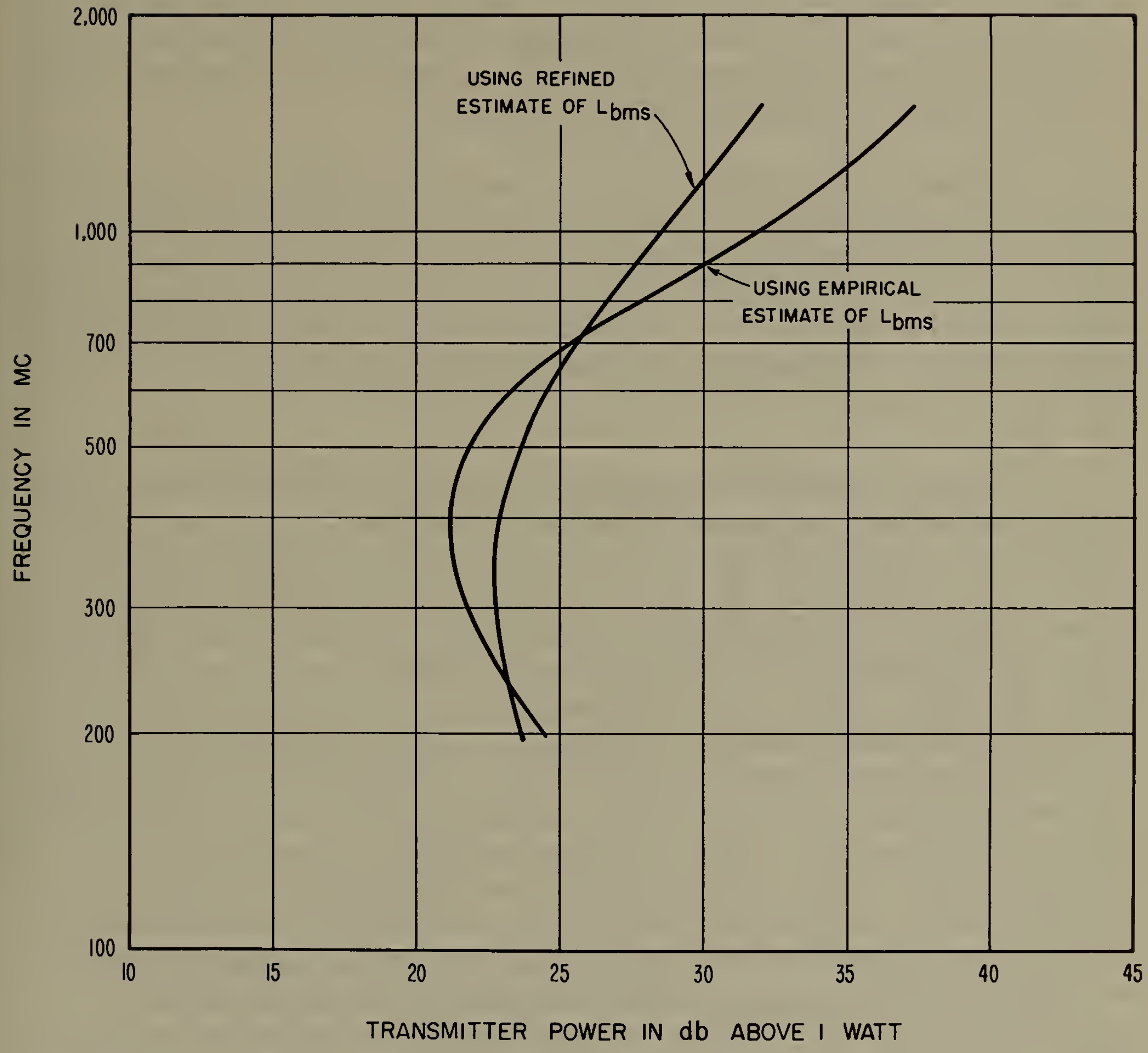


FIGURE 14

exceeded for 99% or 99.9% of the hours of the year. Barsis, Norton, Rice, and Elder [1961] give the values of a standard deviation σ_{rc} appropriate when the refined estimating procedure is used. When the empirical estimates of transmission loss are used, the variance σ_{rc}^2 can be expected to be higher.

An analysis was made to determine how much higher the variance should be when the empirical estimate is used. In this analysis, a number of scatter paths for which long series of measurements were available were studied. Estimates of the distribution of transmission loss were made using both methods. The variance for the empirical estimates was found to be on the order of 30 db^2 higher than the variance using the refined estimates.

Figure 15 is a plot of the standard deviations, σ'_{rc}, associated with the percentage of hours in a year for which the estimate applies. The values on this chart are appropriate only for estimates made using the empirical formula and are consequently considerably larger than the values of σ_{rc} given by Barsis, Norton, Rice, and Elder [1961]. The graph was constructed by assuming

$$\sigma'^2_{rc} = \sigma^2_{rc} + 30.$$

Having selected an optimum frequency range and determined the amount of required power expected to provide a specified grade of service for fifty percent of the winter afternoon hours, it is now necessary to determine the power required to provide this same grade of service as a function of the number of hours in the entire year. Since these will be expected power levels, the service probability remains $F(t) = 0.5$. In order to do this it is necessary to know how the hourly median transmission loss is expected to vary throughout the year relative to the winter afternoon hourly median. This relationship has been established empirically and is expressed in terms of a function $V(p, \theta)$, presented by Rice, Longley, and Norton [1959], and in the Air Force Technical Order [1961]. The expected hourly median level of basic transmission loss exceeded for (100 - p) percent of the hours of the year is next obtained from the $V(p, \theta)$ values appropriate for all hours in the year for the angular distance, $\theta = 34$ milliradians, applicable to the Haswell-Table Mesa path. See Table 2. The values from Table 2 are plotted in Fig. 16.

ESTIMATED PREDICTION UNCERTANTY FOR ALL HOURS OF THE YEAR
FOR USE WITH EMPIRICAL ESTIMATES OF TRANSMISSION LOSS

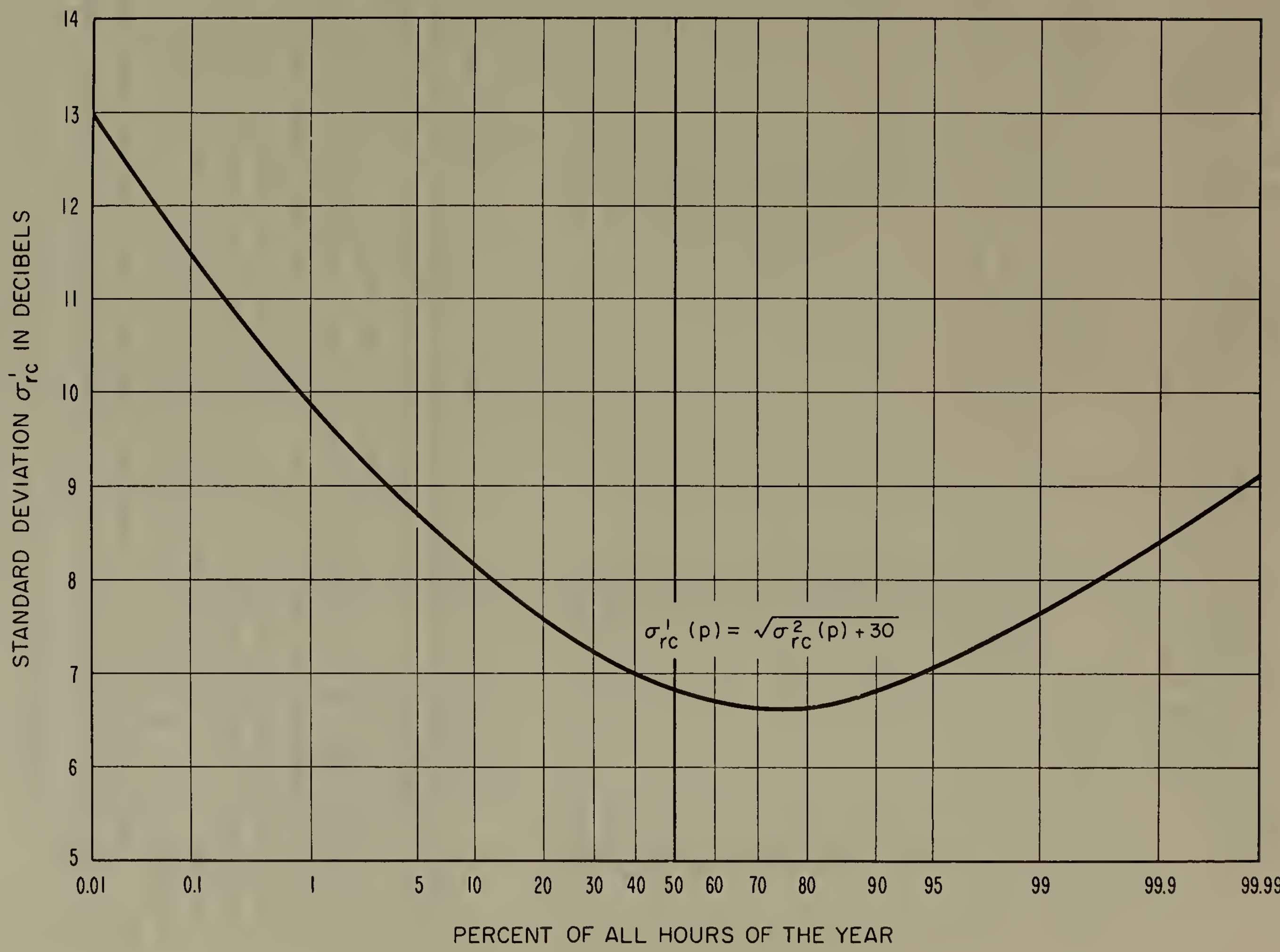


FIGURE 15

TABLE 2

Expected Long-Term Variation, $V(p, \theta)$, and Transmitter Power Expected to Provide the Desired Grade of Service for the Indicated Percentage of Hours Per Year at 500 Mc/s over the Table Mesa-Haswell Path.

Percent of Hours During the Year p	$V(p,\theta)$ db	Expected Power, $P(0.5, p) = 21.7 - V(p, \theta)$ dbw from (10a) with $P_t \equiv P(0.5,p)$, $L_b \equiv L_b(p)$
0.1	24.2	-2.5
1.0	18.7	3.0
5.0	13.9	7.8
10.0	11.6	10.1
20.0	8.7	13.0
50.0	3.4	18.3
80.0	-0.7	22.4
90.0	-2.8	24.5
95.0	-4.5	26.2
99.0	-7.3	29.0
99.9	-10.5	32.2

The final step in the procedure is to determine the probability of service for specific terminal equipment. Up to this point, all the equipment characteristics except actual transmitter power have been specified. We may wish to determine, for example, the probability that a one-kilowatt transmitter will provide the specified grade of service, or alternatively what the probabilities are of obtaining other grades of service. It is now necessary to determine a standard normal deviate, t, such that the probability of exceeding a value, t, in a normal distribution of mean zero and standard deviation $\sigma = 1$ will be the service probability, F(t). The values of t associated with the time availability, p, can be found using the following relationship for any fixed value of transmitter power, $P_t = P_o$:

$$t = \frac{P_o - P(0.5, p)}{\sigma'_{rc}(p)} \qquad (12)$$

TRANSMITTER POWER EXPECTED TO PROVIDE
THE SPECIFIED GRADE OF SERVICE FOR INDICATED PERCENTAGE OF HOURS

HASWELL TO TABLE MESA, COLORADO

FOR 120 VOICE CHANNELS USING DUAL DIVERSITY
60 FT. DISHES AND CONVENTIONAL RF AMPLIFIERS

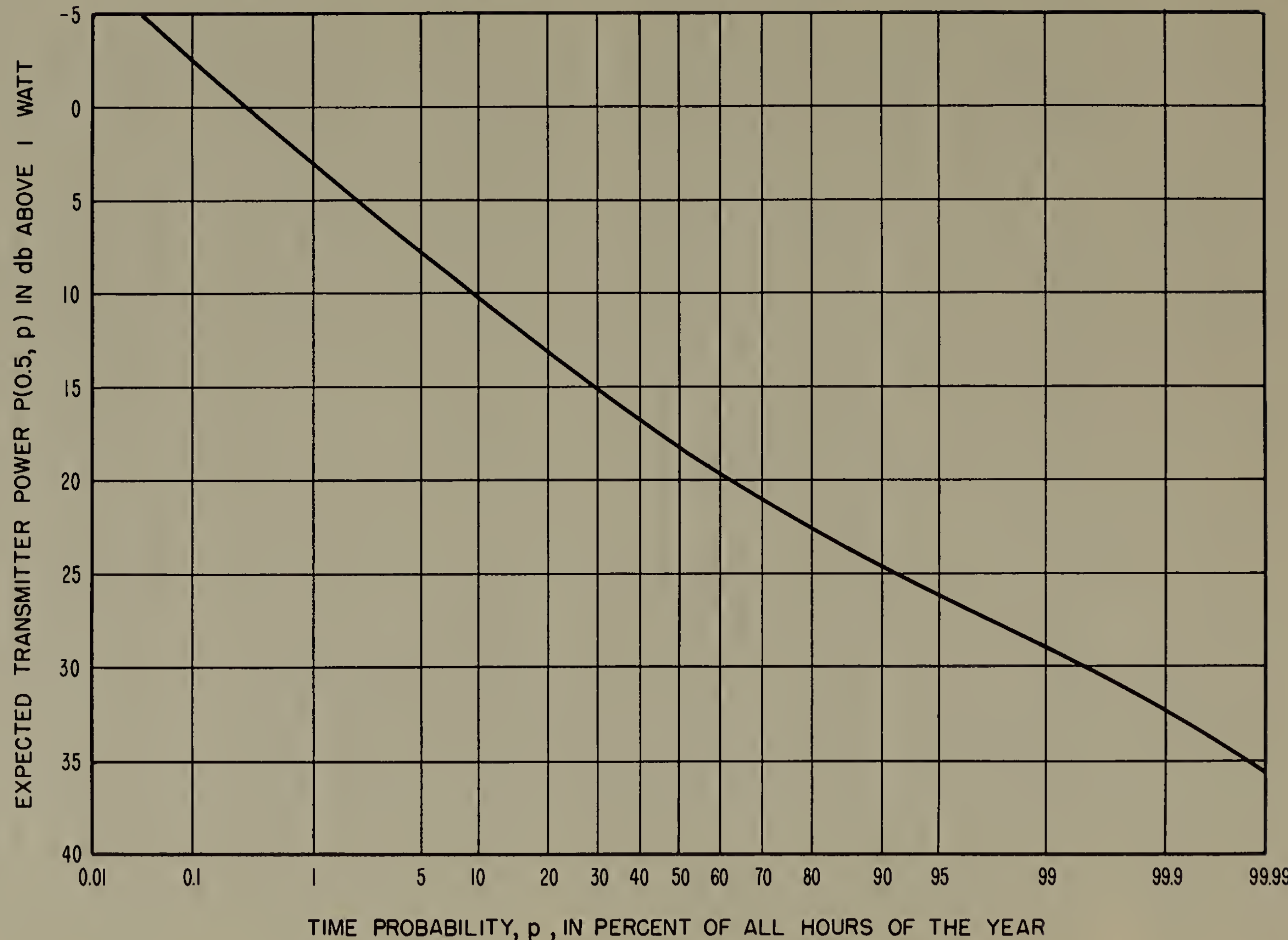


FIGURE 16

It is important to note that the only difference between this estimate of t and the estimate of t for the refined estimates of L_{bm} is in the use of σ'_{rc} rather than σ_{rc} which allows for the additional error range introduced in the empirical estimate of transmission loss. In this example, setting P_o = 30 dbw (1 kw), the values of F(t) are determined from Fig. 17 as a function of t, as given by (12) and listed in Table 3.

A similar computation showing the service probability for 10 kw of transmitter power instead of 1 kw can be simply made by adding 10 db to the values in column (3). The new set of values of F(t) is determined in the same manner. Fig. 18 shows the final relationship between service probability and percentage of the hours of the year the specified grade of service or better is expected to be available. The service probability should be interpreted to mean that if a large number of paths of similar configuration were considered, the percentage of hours during the year, p, for which the specified grade of service is available will vary from path to path. The percentage of paths for which p will be greater than the value on the ordinate of Fig. 18 is on the average 100 F(t). Another way of stating this is that when F(t) = 0.95 then 95 percent of the paths are expected to provide the specified grade of service more than p percent of the hours.

Figure 18 shows different methods for estimating the transmission loss expected over the path. The solid lines are based on empirical estimates and the dashed lines are based on refined estimates of transmission loss. The solid lines are steeper because the prediction uncertainty is greater. For significantly large values of service probability such as F(t) = 0.95, the refined estimate indicates greater time availability than the empirical estimate. On the average, refined estimates for predicting service probability will provide more certainty of service than the empirical estimates and the result will normally be a reduction of transmitter power requirements in the terminal equipment. Therefore, it is recommended that when it is important to specify equipment requirements as accurately as possible, the refined estimating procedure should always be used. Empirical formulas such as (11) are most useful in making preliminary estimates of the feasibility of propagation paths. To insure a high probability of service from a given transmitter, F(t) may be arbitrarily chosen as 0.9 or 0.95, and sufficiently high values of P_o

THE PROBABILITY $F(t)$ OF A STANDARD NORMAL DEVIATE, t, BEING LESS THAN THE ORDINATE

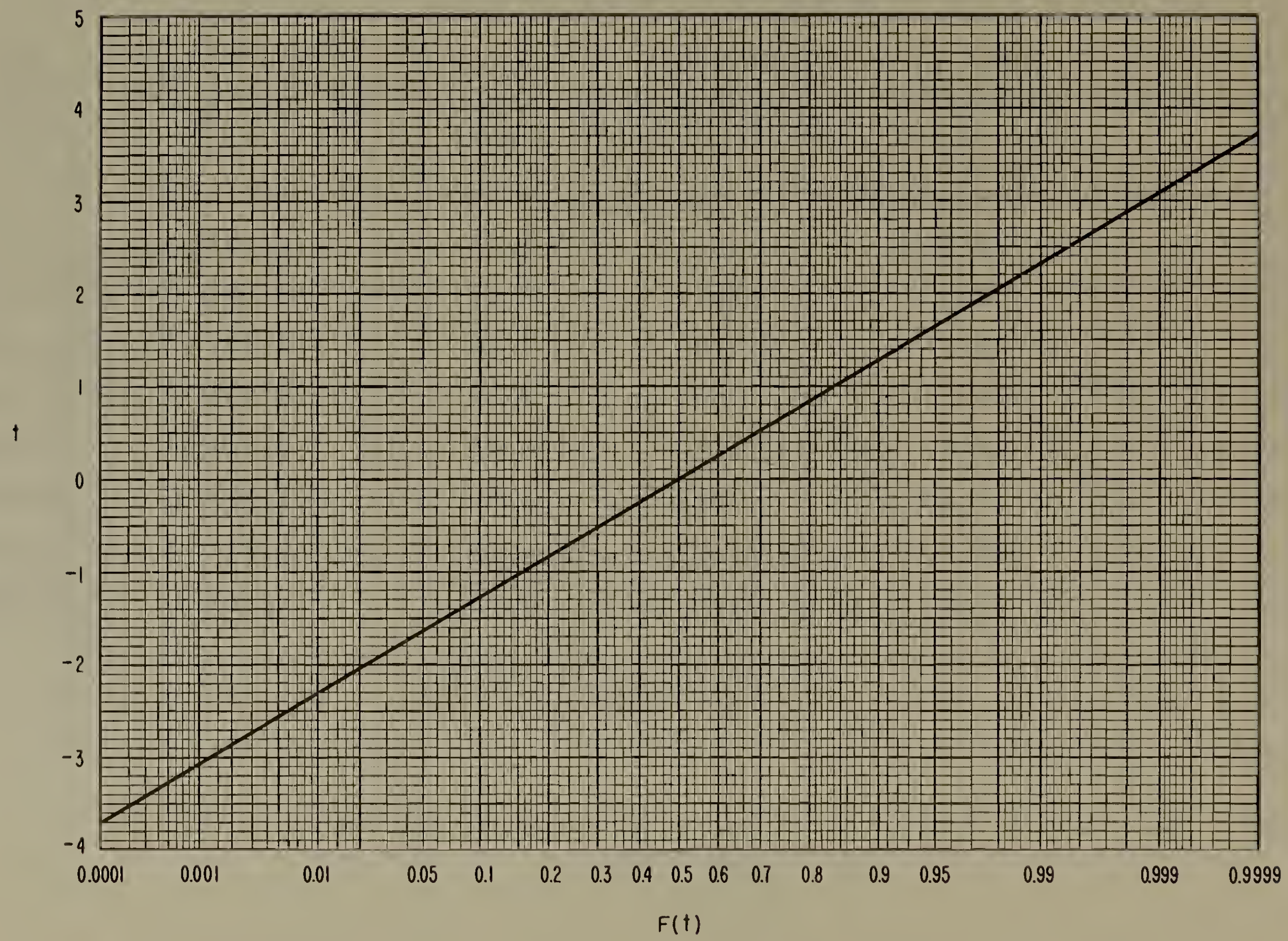


FIGURE 17

TABLE 3

Service Probability Calculations

Time Availability, p in percent of all hours	P(0.5, p) in db from Fig. 16 and Table 2	$P_0 - P(0.5,p)$ in db for $P_0 = 30$ dbw	$\sigma'_{rc}(p)$ from Fig. 14	$t = \frac{P_0 - P(0.5,p)}{\sigma'_{rc}(p)}$	F(t) from Fig. 17
99.99	35.5	-5.5	9.12	-0.6031	0.273
99.9	32.2	-2.2	8.41	-0.262	0.397
99	29.0	1.0	7.66	0.131	0.551
95	26.2	3.8	7.09	0.535	0.703
90	24.5	5.5	6.82	0.821	0.794
80	22.4	7.6	6.65	1.113	0.867
50	18.3	11.7	6.81	1.716	0.957
20	13.0	17.0	7.56	2.243	0.9875

SERVICE PROBABILITY VS. PERCENTAGE OF HOURS DURING THE YEAR TELETYPE ERROR RATIOS ARE EXPECTED TO BE LESS THAN 1:10,000 (R ≥ 18.1 db)

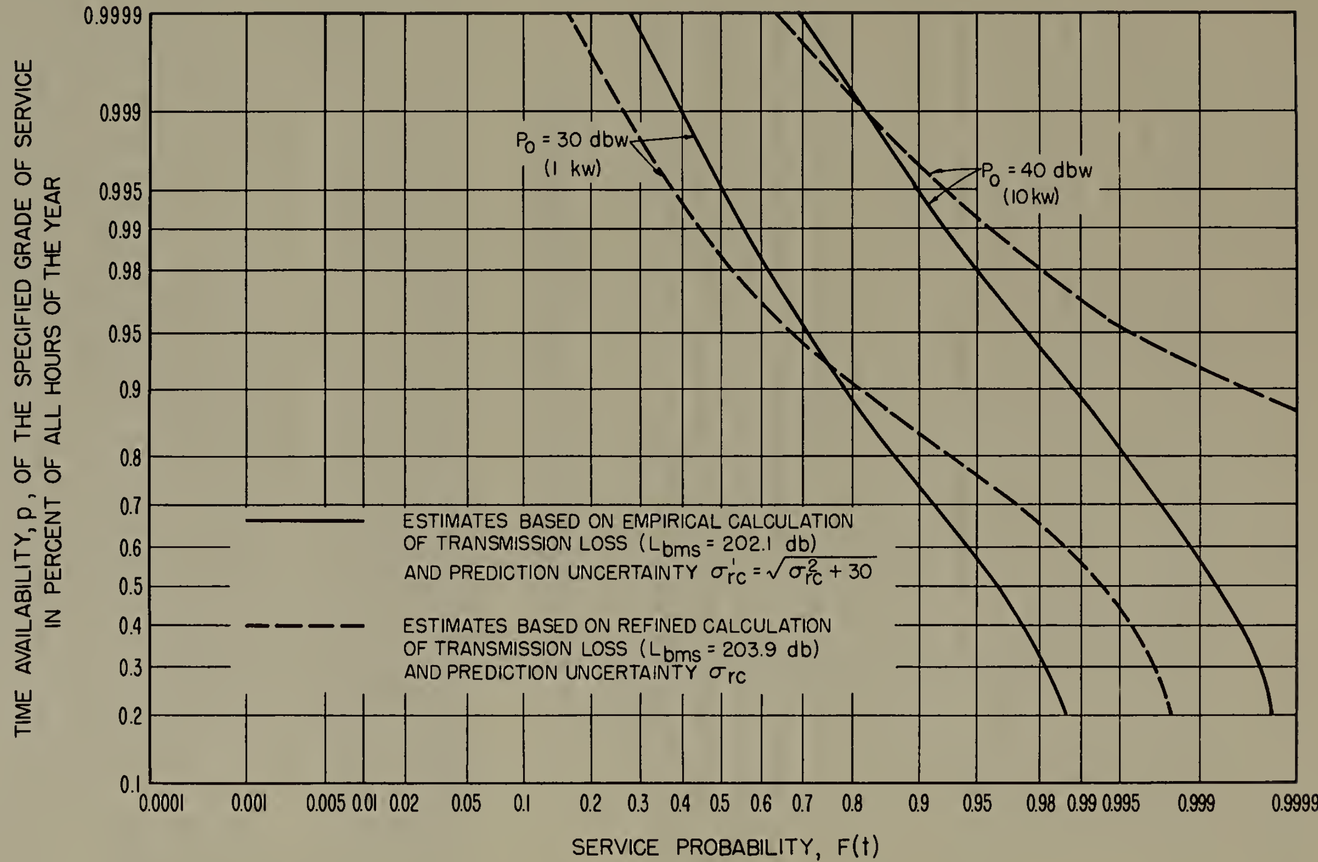


FIGURE 18

required to insure that the time availability, p, exceeds some high value such as 99 or 99.9 percent.

Figure 18 shows only one method of displaying the service probability concept. This method is most useful in comparing the effectiveness of various proposed types of terminal equipment. For example, the use of different transmitter power levels, antenna sizes, diversity configurations, receiver r-f amplifiers, etc., can be readily compared. This type of display does not specifically require the use of the relation between grade of service (error rate) and input RMS-carrier-to-RMS-noise ratio, R. This relation may just as well be defined by the user. Other useful displays can be shown, some of which require defining the above relation and some of which do not. For example, a slight variation in the formulation of the solution would make it possible to show the service probability and corresponding percentage of hours in the year for various values of R. The estimated relationship between R and error rate given by Barsis, Norton, Rice, and Elder [1961] can be used to show the distribution of the expected error rate for all hours of the year as a function of service probability. This would provide much more detailed information regarding the performance of a single, specific terminal configuration than would the Fig. 18 type display.

9. BASIC SITING REQUIREMENTS

Proper consideration of siting is perhaps one of the most important factors in determining the ultimate success of the communication circuit as well as its cost. Tropospheric propagation involves many types of mechanisms, but in this section we are primarily concerned with three basic types. These are tropospheric scatter, line-of-sight, and obstacle gain. The latter two are similar in that both involve relatively short paths for which the terminals, or each terminal and obstacle, are visible to each other. This condition is described as being intervisible. The terminals for tropospheric scatter propagation paths are not intervisible. Site selection requires a proper balance between choosing good sites which fulfill technical requirements (taking advantage of natural terrain features, avoiding sources of interference) and other considerations such as accessibility and availability of sites and logistic support.

In most instances the concept of a tropospheric scatter communication system begins with a requirement for multichannel voice, teleprinters, and other types of transmission between several specific locations. Usually the first attempt at selecting sites for the terminal facilities is to consider as potential sites those locations which can be seen by microwave relay or can be reached by short runs of cable from the communication relay centers. This approach almost invariably limits the selection of sites so severly that little or no advantage can be taken of natural terrain features, and many high-powered terminal and relay facilities are required. When intersiting is accomplished by short scatter circuits or, in some instances, by obstacle diffraction paths, this siting restriction is largely removed. The problems of site hardening and vulnerability are also considerably alleviated in those locations where such considerations are important.

There are many disadvantages to selecting sites in remote locations. These result almost entirely from consideration of logistics and site development, including access. High mountain tops make the most ideal sites for tropospheric scatter terminals when they are available, insofar as efficient propagation is concerned. They are usually sufficiently remote so that man-made noise and radiation hazards to nearby facilities need not be considered. However, the cost of site development in such locations is often prohibitive. Local thunderstorms are frequently associated with mountain tops and can be somewhat troublesome.

Quite often other military activities, such as aircraft communication and warning facilities, require mountain top locations. In many cases collocation can be tolerated by both facilities, resulting in a considerable reduction in the cost of site development and logistical support.

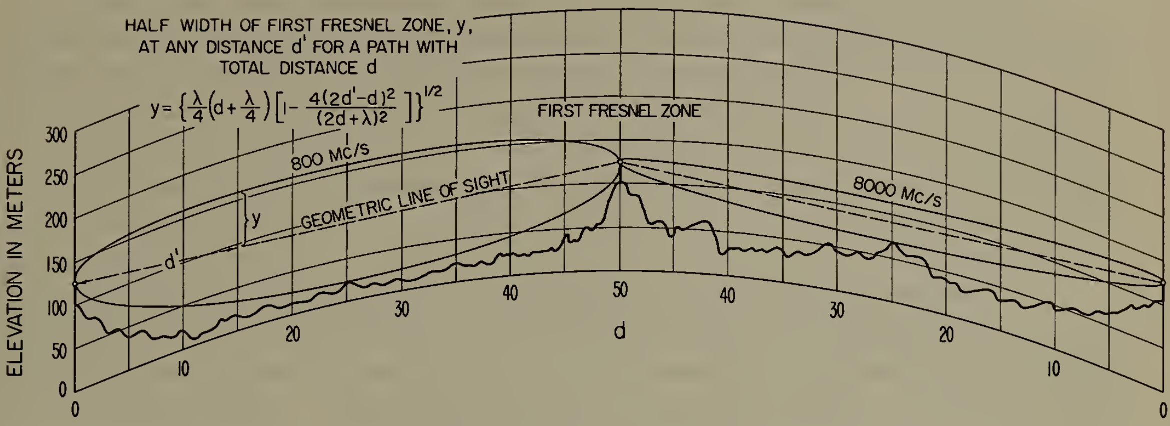
It is important for those engaged in the selection of sites to keep open minds about various possibilities for setting up communication paths. Advantage can often be taken of factors which are not apparent in planning the circuits until the site survey work is underway. For example, it may not occur to a site selector who is attempting to select terminal locations for a line-of-sight relay that a somewhat beyond line-of-sight path will accomplish the communication requirement just as well and will quite likely eliminate some of the requirements for remote relay facilities. The site selection team will rarely have all the factors at hand in order to make a completely objective, final selection of sites. In almost every case a number of possibilities should be evaluated by the site selectors leaving the final selection until all of the factors, technical and otherwise, can be assembled and weighed.

The primary use for line-of-sight paths in the Air Force is in intersiting between communication relay centers and long-distance communication terminal facilities and in some cases where short-haul communication is required, such as between nearby military facilities. In mountainous terrain, predominant peaks or ranges are frequently located on or near the great circle path between proposed sites, and in such cases advantage can be taken of obstacle-gain propagation for reasonably long distances. When such a path is feasible, tremendous economies are effected, and the possibility of using an obstacle-gain path should not be overlooked.

Because of the difficulty with maintenance and operation of a large number of line-of-sight relays the use of multi-hop paths for long distance communication has not been emphasized greatly. In the future it is possible that few frequency bands in the UHF and lower SHF regions of the spectrum will be available, and more reliance will necessarily have to be placed on higher frequencies, perhaps as high as 40 Gc/s. Fixed point-to-point allocations of certain bands up to this frequency have already been made internationally at the Administrative Radio Conference - Geneva, 1959, and have been incorporated into the U. S. national table of frequency allocations. Frequencies of this order will be useful primarily in line-of-sight applications.

The primary consideration in selecting sites for line-of-sight paths is not only to insure that the terminals selected are line-of-sight, but also to insure that the entire first Fresnel zone is clear of obstructions. Obstructions within the first Fresnel zone may usually cause increased fading and a decrease in reliability; however, in some cases it may be desirable to tolerate this to some extent by increasing the power rather than using two systems in tandem. A profile showing the concept of first Fresnel zone clearance and the effect of obstructions within the first Fresnel zone is shown in Fig. 19. Height is shown in meters and distance in kilometers. Often

ILLUSTRATION OF FIRST FRESNEL ZONE
CLEARANCE FOR LINE OF SIGHT PATHS



EXAMPLE OF TRANSMISSION LOSS VARIATIONS
AT 800 Mc/s WHEN LESS THAN FIRST
FRESNEL ZONE CLEARANCE EXISTS

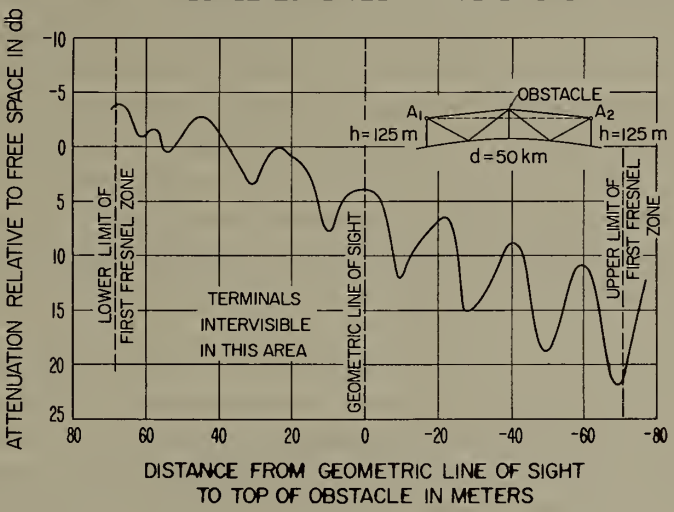


FIGURE 19

a map study will indicate that such clearance exists when in fact vegetation or other obstructions are present which interfere with the clearance. The first Fresnel zone consists of the locus of all points in space which are associated with paths exactly one-half wavelength longer than the straight-line distance between the two terminals. It is an ellipsoid of revolution with its foci at each of the two antennas.

Having more than first Fresnel zone clearance will not necessarily be helpful. This is because reflections from surfaces located anywhere on the first Fresnel zone will arrive in phase with the direct wave. If path length differences are integral multiples of wavelengths, the energy will arrive out of phase and degrade the signal to an extent dependent upon the smoothness of the reflecting surface.

Sometimes terrain clearance is considerably in excess of first Fresnel zone clearance. If the terrain in the area of reflection is relatively uniform, in particular if it is over water, a large number of lobes are likely to occur with deep minima. Variations in refractive index will cause fading associated with vertical motion of these lobes at the receiving location. Vertical diversity and antenna tilting can be used to overcome this type of fading. Normally the vertical diversity antennas are separated in height by half the vertical distance between lobes. This distance will depend upon the geometry and the radio frequency contemplated for the path. In cases where lobing is a possibility, the site selector should compute the expected vertical separation using the geometric ray optics so that an estimate of the height of tower required for vertical diversity antennas can be made. The Air Force Technical Order [1961] describes this procedure in detail.

In many cases the requirements for communication involve paths which are short but are not intervisible. In these cases the decision will have to be made whether to meet the requirement with a multihop line-of-sight circuit using relays or by a short not-line-of-sight circuit. Technically there is nothing wrong with the multihop circuit, but the practical problems of operating remote relays limit their effectiveness considerably. When the site survey party is confronted with the problem on non-intervisible terminals, they will not have all the facts at hand to make an intelligent decision as to which type of path to settle on. In this case it is usually best to make the survey with both possibilities in mind.

10. PRELIMINARY PLANNING AND MAP STUDIES

Good topographic maps are essential for planning propagation paths for tropospheric propagation. Scales of 1:250,000 or 1:500,000 can be used for overall planning and for preliminary selection of sites, but these usually do not have enough detail for extensive studies of the terminal areas and important parts of the propagation path. They do indicate where these areas are and in what locations more detailed maps are essential.

Maps of the continental areas of the United States may be obtained from the U. S. Geological Survey and from the U. S. Coast and Geodetic Survey. Other areas of the world are covered by the Army Map Service series. Very excellent maps can also be purchased locally in many foreign countries. U. S. Embassies and the U. S. Army Corps of Engineers can frequently be of great assistance in obtaining them.

The first step in planning tropospheric propagation paths is to obtain the small-scale coverage, say 1:250,000, of the entire area under consideration. Index maps of all the areas likely to come under more intensive scrutiny can be obtained from appropriate sources at the same time. From these maps a tentative selection of terminal locations is made bearing in mind that the satisfaction of the technical requirements is only part of all of the considerations that must eventually be taken into account. After a number of possible paths have been tentatively selected, path profiles are plotted from large scale maps. These profiles will not show important obstructions and vegetation. These can only be determined by visiting the proposed sites.

The primary technical considerations required for choosing a site can be listed in the following categories, some of which apply to tropospheric scatter and line-of-sight paths, while others are more important for one or the other type of path. Those which are common to scatter, line-of-sight, and obstacle-gain paths are:

1. Path length

2. Antenna height
3. Vegetation and obstructions
4. Mutual interference and radiation hazard
5. Site area

Those factors primarily of concern for tropospheric scatter paths are:

6. Signal takeoff angle (horizon angle)
7. Distance to radio horizon

Those factors primarily of concern to line-of-sight and obstacle-gain paths are:

8. Terrain clearance
9. Effect of layers and ducts

All of these technical factors, together with site availability and support, affect the choice of the site in varying degrees for different conditions. Consequently, several sites should be investigated and evaluated.

10. 1 Evaluation of the Parameters Affecting Site Choice

a. Path Length

The effect of such slight variations in path length as may be encountered in selecting a site will be negligible. For a given tropospheric scatter path a change of one mile in path length introduces a change in transmission loss of approximately 0. 1 db; consequently, decreasing the total path length by 10 miles decreases the transmission loss by only 1 db on the average.

For line-of-sight and obstacle gain applications, the transmission loss is frequently estimated in terms of the loss below free space. The free-space loss is proportional to the square of the total distance. Doubling the distance, for example, will cause the free-space transmission loss to increase by 6 db. The remaining part of the total transmission loss will depend on many factors, but it is usually greater for long paths than for short ones. In addition, time variations are dependent upon distance. Long-term variations are estimated empirically in a recent Air Force Technical Order [1961].

b. Antenna Height

In tropospheric scatter propagation the main effect of increasing antenna height is to decrease the takeoff angle. Raising the antenna above the surrounding terrain may reduce the transmission loss caused by interference between direct and ground-reflected waves.

In line-of-sight and obstacle-gain applications the effect of antenna height is best evaluated in terms of terrain clearance which is discussed in subsection h.

c. Vegetation and Obstructions

Merely plotting a profile of terrain heights does not give an accurate display of the actual propagation path in every case. Obstacles, particularly vegetation, are frequently present. The degree to which vegetation affects propagation is relatively uncertain; sparse growth is more penetrable than heavy growth, and lower frequencies penetrate more than higher frequencies. The safest procedure is to consider that vegetation such as trees, vines, and high grass or weeds is impenetrable to radio frequency energy. The top of the vegetation is thus used in determining the terrain clearance and the takeoff angle.

d. Mutual Interference and Radiation Hazards

Collocation of terminal facilities with other activities is often desirable for economical installation and operation. Often, terminals are collocated with aircraft communication and warning services. In such cases particular consideration will have to be given to the possibility of mutual interference. All frequencies generated by the equipment, including those from frequency multipliers and local oscillators must be considered as possible sources of interference to sensitive receivers. High-energy RF fields can overload receiver input circuits at frequencies other than those to which the receivers are tuned.

The problems associated with collocation cannot be treated adequately in a general manner. Each installation presents its own set of problems which must be studied separately. For example, collocation with major air bases is sometimes necessary, but there is a danger that high levels of man-made noise may occur during some periods of time due to the many and varied activities that may be carried out on these bases. High-speed electronic computers often cause trouble. Radiation of strong RF fields in areas where aircraft operate, particularly in approach zones, should be avoided.

The radiation hazard to personnel and equipment within the immediate vicinity and within the beam of a high-power transmitter should be considered in siting. It is known that very high-power radio frequency energy can be injurious to humans and animals, can burn out crystals in electronic equipment, and can cause detonation of some types of explosives. While the radiation hazard is not alarming in most cases, the site selector should avoid a site necessitating transmission directly across an airfield runway, highway or a residential or otherwise populated area within approximately one-half mile. Further information on the radiation hazards can be found in Section 11.4.

e. Site Area

The type of terminal that is planned for line-of-sight communications will largely dictate the requirements for the site. Some of the important considerations are: accessibility, security, availability of power, and the relative difficulty of developing the area. In most cases there will be a requirement for a building and a tower; however, in some microwave installations, all of the operating and maintenance facilities are completely contained in the tower. Additional area may have to be provided for large antennas, such as two 120-foot paraboloids with a 200-wavelength separation.

f. Signal Takeoff Angle (Horizon Angle)

The takeoff angle is one of the controllable technical factors in tropospheric scatter propagation. The takeoff angle as defined in Fig. 20 is the angle between the horizontal at the radiation center of the antenna and a ray extending from the radiation center of the antenna to the radio horizon. It is recommended that the takeoff angle be computed from accurate topographic maps because of the difficulty of positioning a transit at the intended center of radiation, which may be at a considerable height above ground. Transit observations cannot be corrected for this height effect in most cases,

SITE CHOICE CONSIDERING TAKE-OFF ANGLE

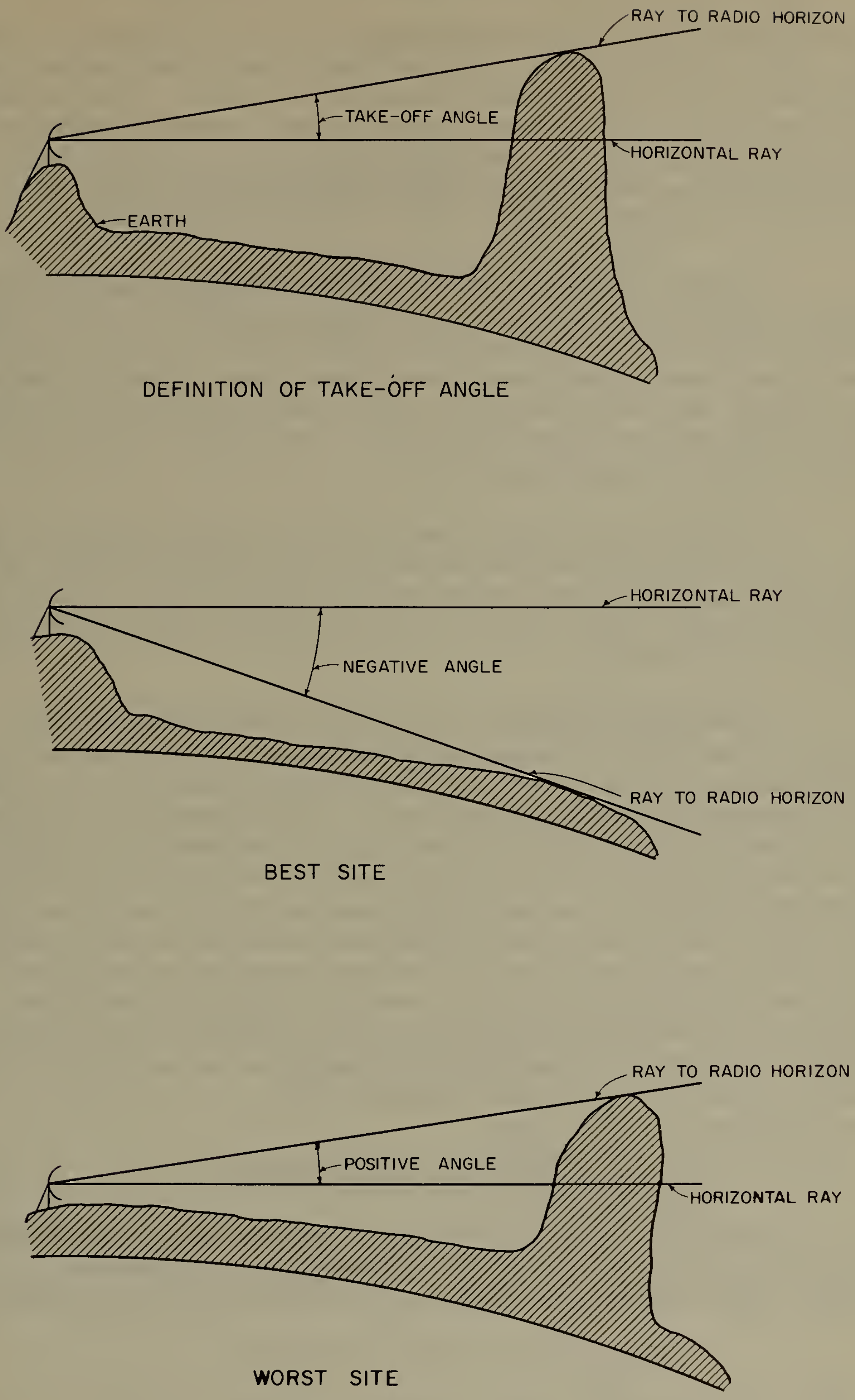


FIGURE 20

because horizons are often different for the different heights. When the antenna is to be sited at a height where transit observations cannot be made and no satisfactory maps are available, it will be necessary to obtain the profile information by other methods. Stereo aerial photographs can be used effectively for this. Sometimes arrangements can be made for special photographic flights, if photographs are not available.

Accurate altimeters are sometimes used to measure relative heights along the path azimuth. The leapfrog method uses two altimeters. In this method progressive height differences are measured along a line, and the profile is plotted from these. Profile information may be obtained relatively rapidly in this manner and is sufficiently accurate for this purpose. For a description of the leapfrog method see Breed and Hosmer [1953].

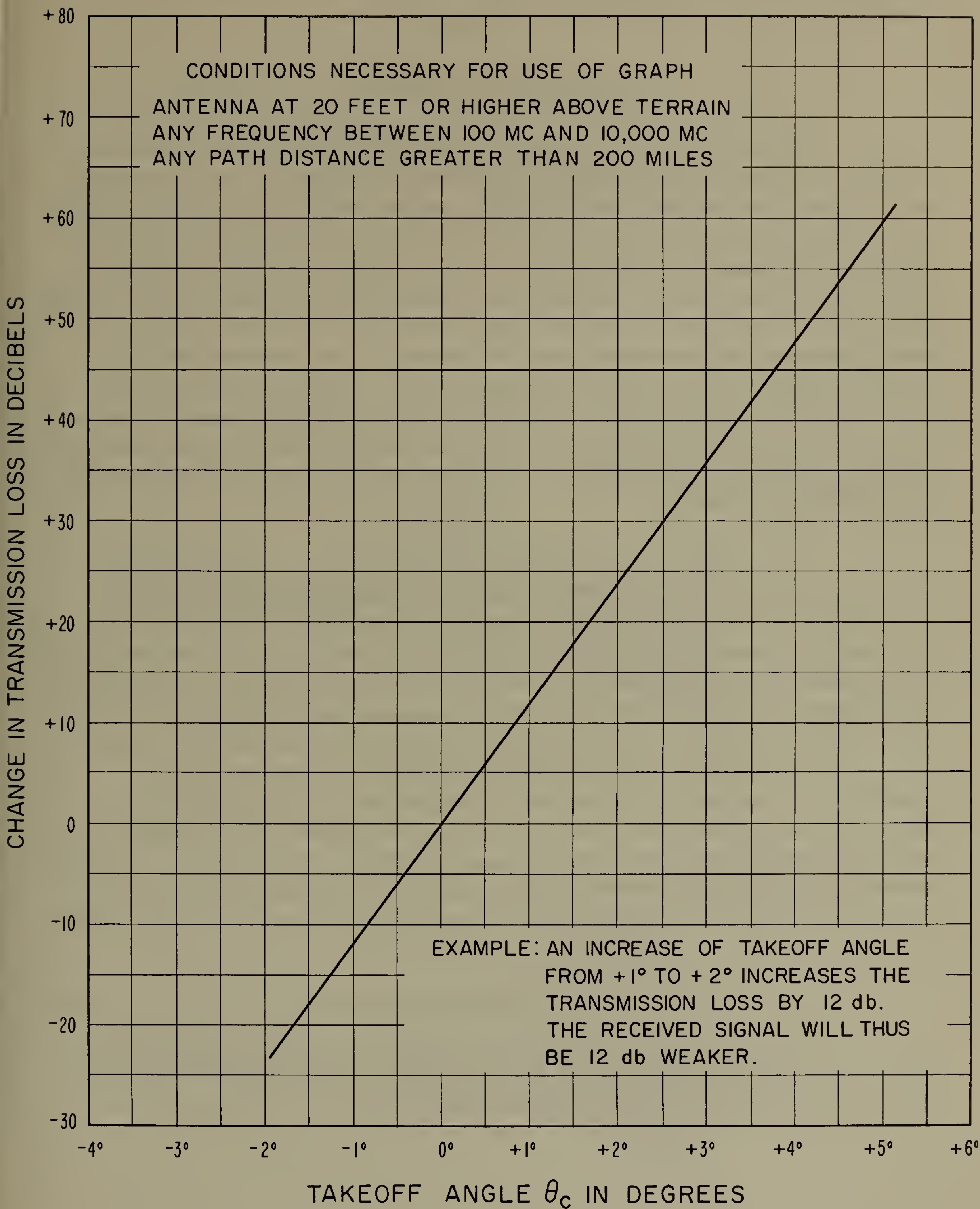
Except in those rare cases where the consideration of one or more of the other geometrical parameters outweighs the effect of the takeoff angle, the site with the most negative angle should be the first choice with a zero angle the second, and the smallest positive angle the last choice.

As the takeoff angle is increased, transmission loss increases, resulting in a weaker received signal. The effect of the takeoff angle on the transmission loss is very significant; this added loss is approximately 12 db per degree. Consequently, in choosing a site, every effort should be made to take advantage of the effect of the takeoff angle of transmission loss. A rough approximation of the effect will have to be made on the spot by the site selection team before more elaborate transmission loss calculations can be undertaken. For this purpose Fig. 21 has been prepared showing this relationship. Figure 21, together with the empirical method for prediction of transmission loss discussed in Section 8, will enable the site survey team to make quick comparisons of the relative merits of various paths under consideration.

g. Distance to Radio Horizon

The major effect of distance to the horizon is to change the takeoff angle in beyond the horizon propagation. Maintaining a constant takeoff angle, the distance to the horizon can vary widely

EFFECT OF TAKEOFF ANGLE AT ONE SITE ON TRANSMISSION LOSS FOR COMMUNICATIONS USING TROPOSPHERIC SCATTER PROPAGATION



SUM OF TAKE OFF ANGLES $= 0.7(\theta_{mr} - \frac{d_{mi}}{5.28})$ OR $0.7(\theta_{mr} - \frac{d_{km}}{9})$

FIGURE 21

with a relatively minor effect on the transmission loss. In general, for a constant takeoff angle, the greater the distance to the horizon the smaller the transmission loss. Fig. 22 is an illustration of varying distances to the radio horizon with the same takeoff angle.

h. Terrain Clearance

Although the maintenance of first Fresnel zone clearance in line-of-sight propagation is a somewhat arbitrary requirement, it is a good one since it will usually assure minimum transmission loss. The same concept can be applied to obstacle-gain paths by considering these to be made up of two paths, as if the obstruction were a relay terminal. Sometimes paths will be chosen which have much more than first Fresnel zone clearances. In such cases a large number of fine lobes may be formed, due to interference between direct and ground reflected rays. Changes in the height gradient of refractive index will shift the position of these lobes and cause fading, particularly when the reflection point is over water. In many cases, vertical space diversity may be used to compensate for this type of fading.

The reflection coefficient of the ground is expressed in terms of the ratio of the reflected to the incident field strength. Vertically polarized waves are reflected with less efficiency than horizontally polarized waves. Both the dielectric constant and the conductivity are important in determining the reflection coefficient, but at VHF and above the dielectric constant plays the predominant role. If the terrain is rough and covered with vegetation, a large part of the incident energy will be scattered and some will be absorbed. Rayleigh's criterion of roughness can be applied as a guide in determining whether or not the reflected wave will be specular or will be scattered to some extent. Sometimes, the first Fresnel zone associated with the reflected ray path intersects the reflecting surface. If the terrain roughness is small enough so that

$$\Delta h < \lambda/(16 \sin \psi), \tag{13}$$

then the reflected energy will be specular. In (13) Δh represents the standard deviation of terrain heights and ψ is the angle the

ILLUSTRATION OF VARYING DISTANCES TO RADIO HORIZON WITH SAME TAKE-OFF ANGLE

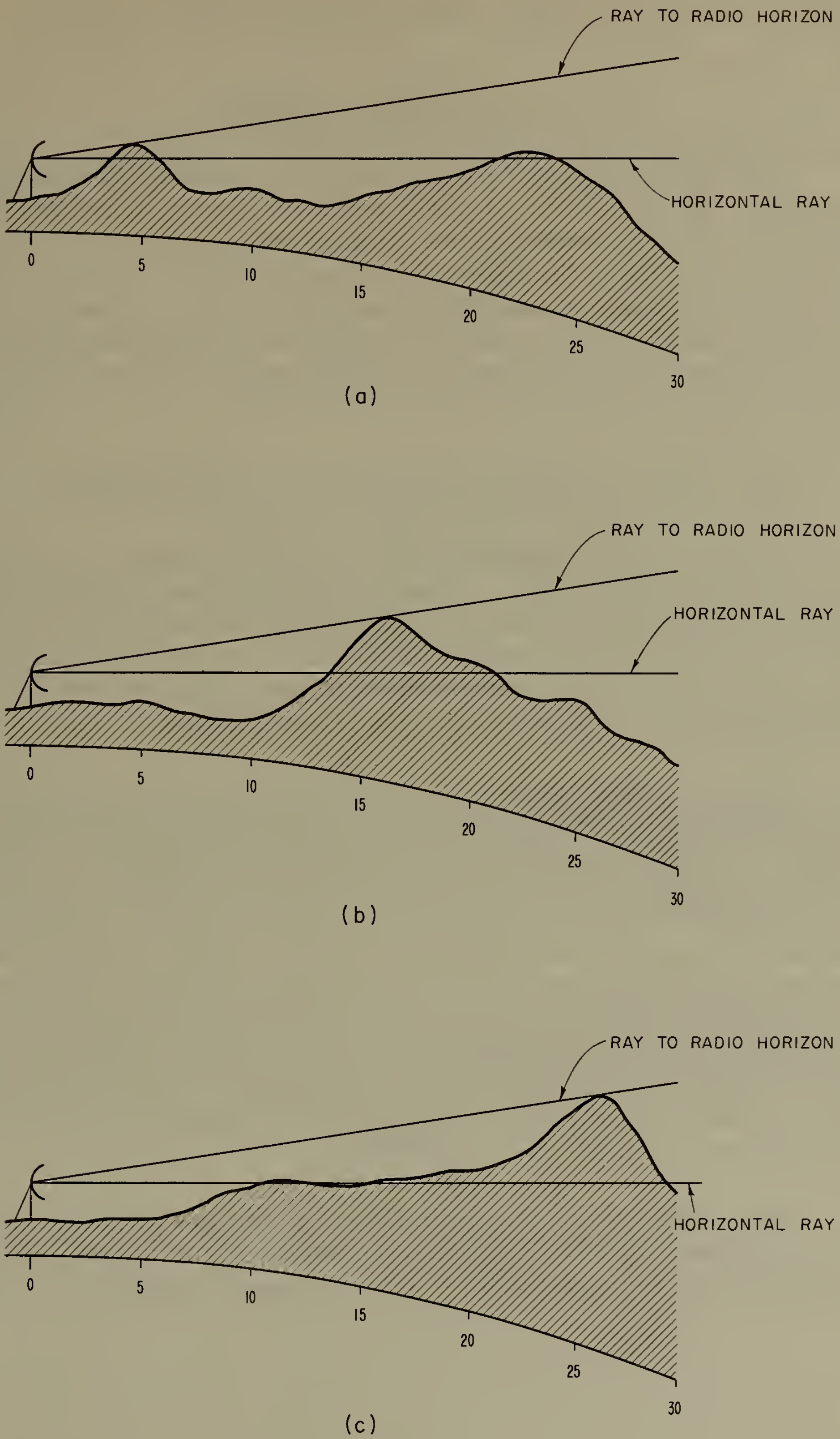


FIGURE 22

incident and reflected rays make with the reflecting surface. Formulas for computing the extent of the Fresnel zone are given in Appendix 1.

i. Effect of Layers and Ducts

The major effect of layers and ducts is to bend and deflect radio waves. In some line-of-sight cases, when transmitting through a discontinuity in refractive index, the transmission loss is increased by as much as 30 db. The effect is more pronounced on long paths and when the ray path is nearly tangent to the duct. Obstacle-gain paths using relatively steep takeoff angles are not as likely to be affected. Overwater paths are most likely to be affected because of the persistence of low-level ducts and layers.

10.2 Great-Circle and Rhumb-Line Computations

Before a final selection of sites can be made it is necessary to plot accurate path profiles. These should whenever practicable be plotted during the site survey so that any discrepancies can be checked and vegetation or other obstructions can be included on the profile. Geographic coordinates of the two ends of the path are normally expressed in units of longitude and latitude.

In most cases line-of-sight paths are not long, and it is not always necessary to make great-circle computations in order to determine the location of the path with sufficient accuracy. Either the line can be drawn directly on the map, or a rhumb line (which is much easier to compute than a great circle) can be used. It is recommended that this procedure be limited to those cases in which the difference in longitude is not much more than one-half degree. The rhumb line will more nearly approximate a great circle near the equator than at greater latitudes. A rhumb line is defined as a line which intersects all meridians at the same angle. Except in special cases, it is not a great circle and is therefore not the shortest distance between two points on a sphere.

The computation of rhumb lines, given the terminal coordinates, involves only very simple trigonometric formulas. We can designate the two terminals as A and B, their latitudes Φ_A and

Φ_B, and their longitudes Λ_A and Λ_B. Since the rhumb line intersects meridians at the same angle, the bearing angles X and Y are supplements of each other. Figure 23 is an example of a rhumb-line path between two points. To minimize the distortion resulting from the mercator projection in which the meridians are shown parallel to each other, it is convenient first to determine the middle latitude, Φ_M.

$$\Phi_M = (\Phi_A + \Phi_B)/2 \tag{14}$$

Then:

$$\tan X = \frac{(\Lambda_A - \Lambda_B)\cos\Phi_M}{(\Phi_A - \Phi_B)} \tag{15}$$

$$Y = 180^\circ + X \tag{16}$$

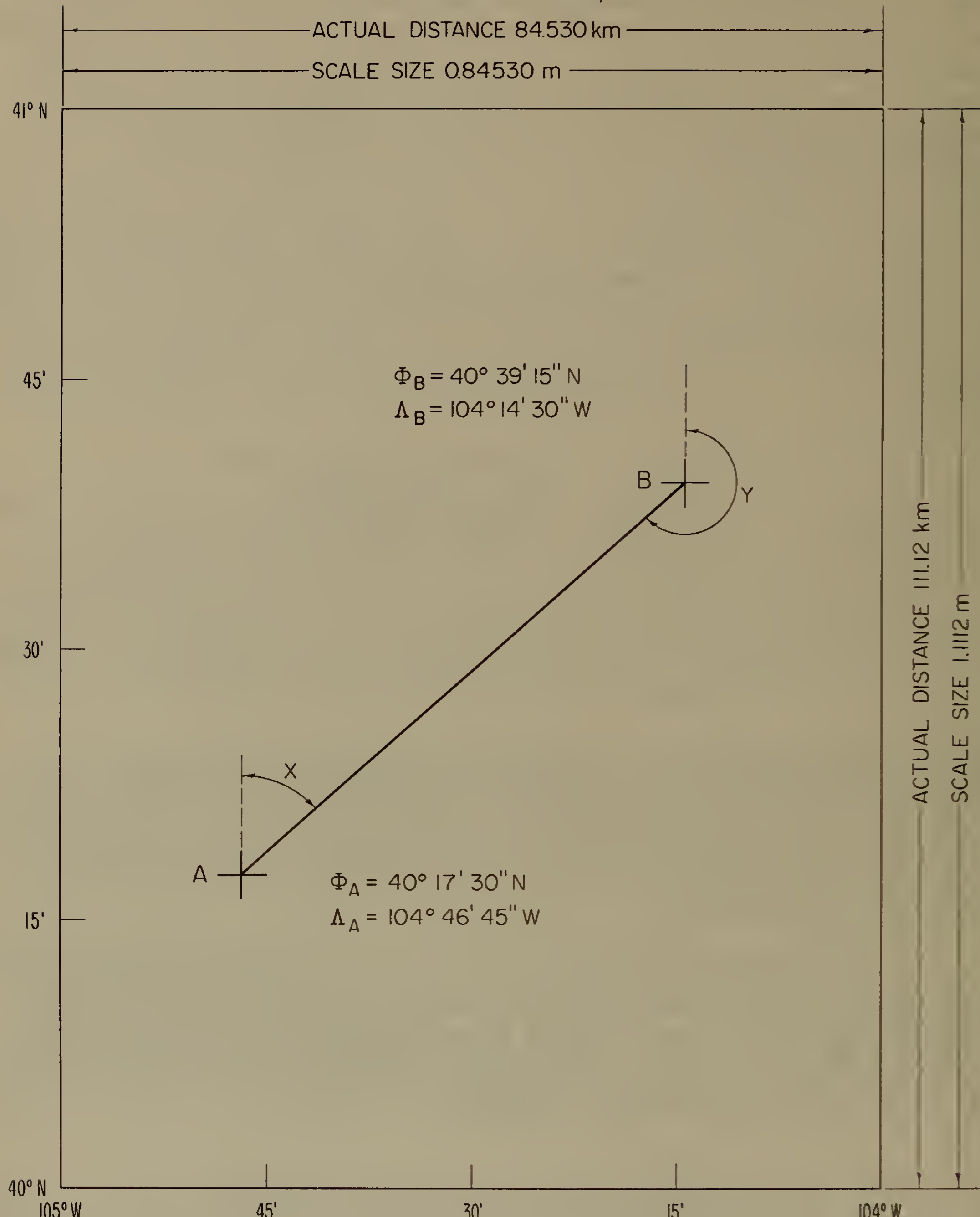
In the above equations it is usually more convenient to subtract the smaller from the larger number in each case and adjust the angles into the proper quadrants to obtain azimuth later. Some obvious adjustments must necessarily be made when the terminals are in different hemispheres.

To compute the distance A to B it is convenient to convert the differences in latitude and longitude into minutes with decimals for the fractional parts, since a minute of latitude is equal to one nautical mile. Then the approximate rhumb-line distance d, from A to B can be expressed as follows:

$$d = (\Phi_A - \Phi_B)\ /\ \cos X \text{ nautical miles}\ . \tag{17}$$

EXAMPLE OF A MERCATOR PROJECTION WITH
A RHUMB LINE APPROXIMATION TO THE
GREAT CIRCLE PATH FROM A TO B

(SCALE ON ORIGINAL 1:100,000)



$\Phi_m = 40° 28' 22.5''$, $\cos \Phi_m = 0.76071$

(NOTE: 111.12 km × 0.76071 = 84.530 km)

X = 48° 26' 28", Y = 228° 26' 28"

DISTANCE FROM A TO B = 60.720 km

FIGURE 23

To convert from nautical miles to other units use the following:

d(nautical miles) × 1.8520 = kilometers

d(nautical miles) × 1.508 = statute miles

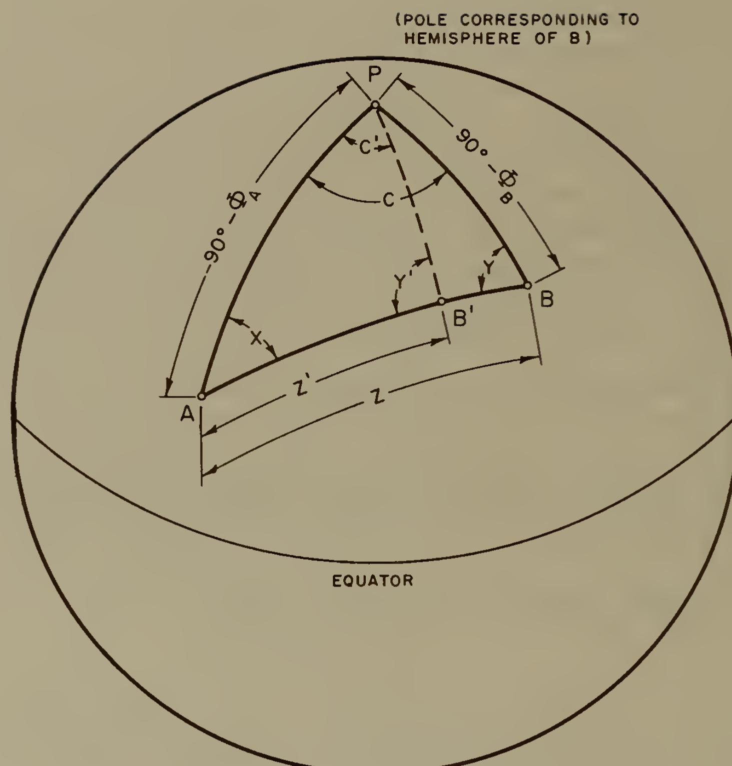
More accurate conversion factors are listed in Appendix 3.

In those cases in which it is necessary to compute the actual great circle path, the initial bearings and the distance and the location of intermediate points can be computed by reference to the spherical triangle shown in Fig. 24. A good table of trigonometric functions is necessary, and should be included among the items the survey team carries with it. In Fig. 24 the spherical triangle is shown as PAB, where A and B are the terminals, (B having the higher latitude) and P is the pole in the same hemisphere as B (north or south). B' is any point along the great circle path from A to B and is solved by reference to the spherical triangle PAB'. Φ_A, Φ_B and $\Phi_{B'}$ are the latitudes of A, B, and B', respectively; C and C' are the differences in longitude between A and B and between A and B'; while Z and Z' are path lengths from A to B and from A to B', respectively. The following are convenient for the solution of this triangle, both by manual means and by automatic digital computation using trigonometric subroutines.

To compute initial bearings X and Y:

$$\tan \frac{Y - X}{2} = \cot \frac{C}{2} \left[\left(\sin \frac{\Phi_B - \Phi_A}{2} \right) \Big/ \left(\cos \frac{\Phi_B + \Phi_A}{2} \right) \right] \qquad (18)$$

$$\tan \frac{Y + X}{2} = \cot \frac{C}{2} \left[\left(\cos \frac{\Phi_B - \Phi_A}{2} \right) \Big/ \left(\sin \frac{\Phi_B + \Phi_A}{2} \right) \right] \qquad (19)$$



SPHERICAL TRIANGLE FOR
GREAT CIRCLE PATH COMPUTATIONS

FIGURE 24

$$\frac{Y + X}{2} + \frac{Y - X}{2} = Y \text{ and } \frac{Y + X}{2} - \frac{Y - X}{2} = X \qquad (20)$$

To compute great circle distance, first compute the angle Z, expressed in degrees:

$$\tan \frac{Z}{2} = \tan \left[\frac{\Phi_B - \Phi_A}{2}\right] \left[\left(\sin \frac{Y + X}{2}\right) \Big/ \left(\sin \frac{Y - X}{2}\right)\right] \qquad (21)$$

To compute latitude, $\Phi_{B'}$, given the longitude difference, C':

$$\cos Y' = \sin X \sin C' \sin \Phi_A - \cos X \cos C' \qquad (22)$$

$$\cos \Phi_{B'} = \sin X \cos \Phi_A / \sin Y' \qquad (23)$$

To compute longitude difference, C', given latitude, $\Phi_{B'}$:

$$\sin Y' = \sin X \cos \Phi_A / \cos \Phi_{B'}$$

$$\cot \frac{C'}{2} = \tan \frac{Y' - X}{2} \left[\left(\cos \frac{\Phi_{B'} + \Phi_A}{2}\right) \Big/ \right. \qquad (24)$$

$$\left. \left(\sin \frac{\Phi_B - \Phi_A}{2}\right)\right] \qquad (25)$$

Equations (18) through (21) have been published by the International Telephone and Telegraph Corporation [1956]. To convert Z in degrees to other useful units of length use the following constants:

$$Z \times 111.120 = \text{kilometers}$$

$$Z \times 69.047 = \text{statute miles}$$

$$Z \times 60.000 = \text{nautical miles.}$$

Since the radius of the earth varies somewhat from place to place, the precise conversion of the arc, Z, in angular units to distance will require different constants. The above constants strictly apply for an earth radius of 6366.7 km; however, the error introduced by this approximation is extremely small and can be ignored in this application. With this radius one minute of great-circle arc is exactly equal to one nautical mile.

10.3 Plotting Profiles

In most cases the great-circle path will traverse more than one of the large-scale topographic maps from which the profile will be constructed. A very convenient and accurate way to draw the great-circle path on these maps is as follows:

(1) Construct a mercator grid chart large enough so that both terminals can be plotted on the grid. A mercator grid is a projection of the spherical meridians and parallels of latitude upon a cylinder tangent to the earth at the equator. It is not useful at latitudes near the poles, and the scale is not constant. However, at most latitudes encountered and for distances of a few hundred miles, the distortion can be tolerated.

(2) On this grid all of the available topographic maps can be overlaid to scale in their relative positions as in Fig. 25. A straight line drawn between the two terminals on this grid is a rhumb line, and indicates approximately where the great circle will cross the individual maps.

(3) Latitudes or longitudes where the line crosses the edge of each map are next selected, and the corresponding longitude or latitude which lie on the great-circle as well as the great-circle distance from either terminal are computed using (18) - (25). Additional points showing the position of the great-circle path within the maps may be added to the maps and joined together with lines to show the position of the great-circle path. An example of this type of procedure for Fig. 25 is shown in the following tabulation:

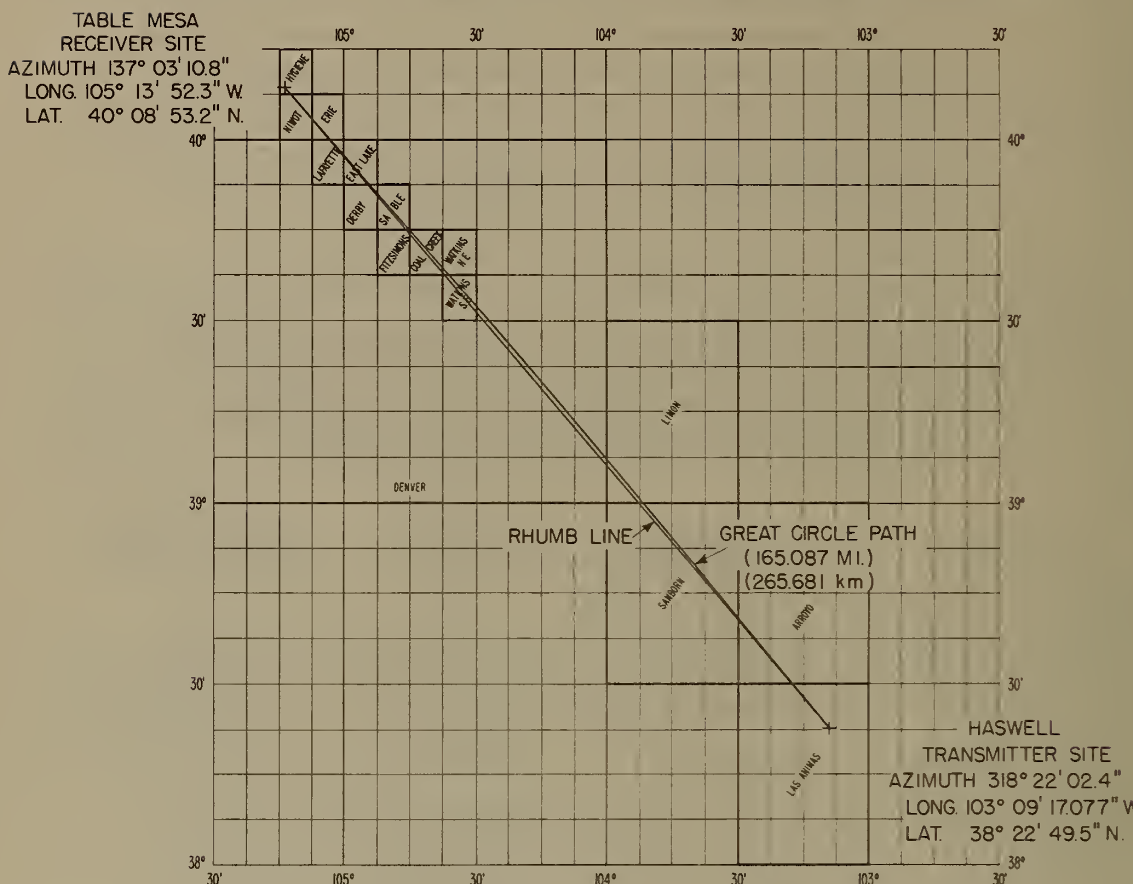
TABLE 4

Coordinates for Locations Along the Great-Circle Path from Haswell to Table Mesa, Colorado, Shown in Fig. 25. Underlined Coordinates were Given and the Other Coordinates were Computed.

Longitude	Latitude	Distance in km	Distance in Statute Miles
*103° 09' 17.077"W	38° 22' 49.5"N	0	0
103° 17' 26.340"	38° 30' 00"	17.803	11.062
103° 30' 00"	38° 40' 59.304"	45.112	28.032
103° 51' 56.952"	39° 00' 00"	92.496	57.474
104° 00' 00"	39° 06' 54.864"	109.773	68.210
104° 30' 00"	39° 32' 23.964"	173.651	107.902
104° 37' 30"	39° 38' 42.180"	189.501	117.750
104° 45' 01.584"	39° 45' 00"	205.355	127.602
104° 45' 00"	39° 44' 58.704"	205.301	127.568
104° 52' 30"	39° 51' 13.644"	221.054	137.357
104° 54' 01.908"	39° 52' 30"	224.265	139.352
105° 03' 05.076"	40° 00' 00"	243.203	151.120
105° 07' 30"	40° 03' 38.700"	252.418	156.845
105° 12' 11.052"	40° 07' 30"	262.172	162.906
**105° 13' 52.3"	40° 08' 53.2"	265.681	165.087

*Haswell
**Table Mesa

LAYOUT OF PROPAGATION PATH BETWEEN
HASWELL AND TABLE MESA COLORADO SHOWING
TOPOGRAPHIC COVERAGE AVAILABLE FOR DETERMINING PROFILE



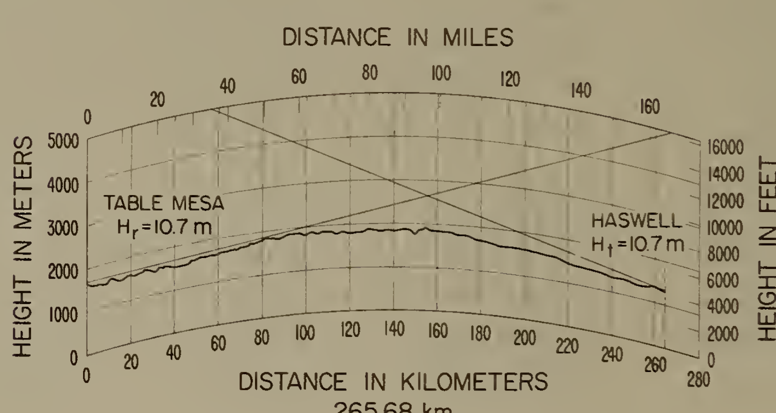


FIGURE 25

It is inevitable that in some cases adequate topographic maps do not exist or those that do exist will be of doubtful accuracy. This makes the process of constructing accurate profiles exceedingly difficult. Celestial observations and other surveying techniques may be needed in order to establish the great circle path terrain profile between the antenna terminals. Often it is possible to determine radio horizon elevation angles or take-off angles, θ_{et} and θ_{er}, in the field. The angular distance is

$$\theta = \theta_{et} + \theta_{er} + d/a \text{ radians,} \qquad (26)$$

where d is the path distance and a is an effective earth's radius factor which allows for average radio ray bending in the atmosphere. Commonly used values for a are 5280 miles or 9000 kilometers.

The best celestial method for determining true azimuths in northern latitudes is that of Polaris observation. Polaris rotates in a small circle (radius 55') about the axis of the earth in the celestial sphere. Its altitude is approximately equal to the latitude of the observer. For azimuth determination Polaris is best observed at elongation, either east or west. Observations at other times require accurate timing of the sighting. At high northern latitudes and in all southern latitudes azimuth determinations can be made by forenoon and afternoon sun observations or by sights on circumpolar stars. Latitudes and longitudes can be observed by similar methods. The determination of longitude requires the access of very accurate time. Instruments with high precision and equipment with filters and reticle illumination for sun and star observations, such as theodolites, are recommended for this work. Non-illuminated instruments can be used for star observations by deflecting a small amount of light from a flashlight through the objective lens of the instrument. The reader is referred to standard surveying textbooks such as Breed and Hosmer [1953] for a detailed description of the procedures for celestial observations.

Frequently in site survey work it is necessary to obtain a reasonably accurate azimuth quickly without resorting to night-time Polaris observations. In many cases a magnetic azimuth corrected to true azimuth by applying magnetic declination is sufficient, but is not particularly reliable. A method which is quite reliable, but which does not appear in standard textbooks, is to observe the sun to transit the meridian at local apparent noon when it is at its highest altitude and is true north or south from the observer. For this observation the sun can be observed for ten or twenty minutes before and after transiting. Two or three pairs of observations at the same altitude before and after transiting can be averaged to obtain an azimuth accurate to about ten to twenty minutes of arc. Parallax and semi-diameter corrections can be automatically compensated for by taking altitude observations on the lower or upper limb and setting the left limb of the sun on the vertical cross hair before transit and the right limb after transit. This method will not work when the sun transits near the zenith. At other times of the day a graph of the sun's azimuth versus time can be plotted in advance for the period of planned observations. In this case correction will have to be made for the sun's semi-diameter. Parallax errors will be within two seconds of arc and can be ignored. The Nautical Almanac [yearly] and Ageton's "Deal Reckoning Altitude and Azimuth Table," [1943], are recommended publications for the site survey party if celestial observations are contemplated.

11. SPECIAL CONSIDERATIONS

Many special considerations in addition to the technical requirements enter into the selection of transmitting and receiving sites. Some of these considerations can be anticipated; others will be peculiar to each survey.

11.1 Site Availability

In populated areas the acquisition of valuable land is not only expensive, but may lead to misunderstanding and hard feelings, particularly in foreign countries. Fortunately, by virtue of the tendency for hill-tops to be less valuable land in most areas, this problem is not too serious for tropospheric communication terminals and relays. The acquisition of cultivated land should be avoided whenever possible. Many foreign countries are also sensitive about the erection of structures in their park lands and scenic areas.

11.2 Site Development and Logistic Support

Many otherwise ideal sites will inevitably be eliminated from serious consideration because of the lack of access and the difficulties associated with logistic support. This is perhaps one of the most difficult factors to evaluate in choosing terminal locations, and requires the utmost consideration. In some cases such difficulties may be partially overcome by collocating with other facilities which also require this kind of site. This is difficult to accomplish in many cases because of the high radiated power levels of the tropospheric transmitters. However, many examples of collocation have been accomplished, particularly with aircraft warning installations.

11.3 Vulnerability

Adequate security is difficult to achieve over a large number of remote line-of-sight relays and terminals. This is one reason that line-of-sight propagation is not considered favorably for long-distance, military communication. There are two aspects to vulnerability. One involves actual damage or destruction of facilities, and the other involves jamming. To some extent protection from damage can be accomplished by site hardening. Intentional jamming is less of a threat with line-of-sight communication because jammers must be relatively close to the receivers, because of the highly directive antennas used and the poor long-distance propagation of the frequencies normally used on line-of-sight paths.

In the event of hostilities the prospect of incidental destruction or large communication complexes resulting from attacks on military facilities makes the isolation of strategic communication trunk-line terminals from other military activities desirable. Long intersite paths connecting military bases with these trunk-line facilities will materially assist in accomplishing a desirable degree of isolation.

11.4 Electromagnetic Wave Radiation Hazards

In the siting of communication terminals, careful consideration should be given to the possible effects of electromagnetic energy on the human body and on physical objects such as radio equipment, electrically detonated explosives, volatile gases, etc.

a. Biological Hazards

Since the early days of World War II, thought has been given to the possible biological effects of electromagnetic radiation on the human body. At that time a study was made of U. S. personnel engaged in the operation and testing of relatively low-powered radars. This study revealed no evidence of radar-induced injury to human beings.

During the past ten years, with the development of more powerful equipment, interest in this problem has increased and a number of experimental programs have been initiated. An air frame manufacturer engaged in the installation, testing, and servicing of powerful airborne transmitters instituted a comprehensive medical program for its several hundred employees working with radar and those who might be exposed to microwave energy. This program, which has been operating since 1954, constitutes one of the longest continuous surveys of radar-exposed personnel in the United States. No acute transient or cumulative physiological or pathological changes attributable to microwaves have been revealed by this study.

However, in view of the trend toward ever increasing power, it is possible that a serious biological hazard may be created. Research on this problem is being coordinated by the Air Research and Development Command. Damage may conceivably occur to those body systems not equipped with adequate means of heat regulation. In this category are included the lens of the eye, the testes, and internally the liver, gall bladder, and gastrointestinal tract. The vulnerability of the body is further affected by the ambient temperature, humidity, the heat loss factor of the particular organs and their temperature sensitivity. The sensitivity of the lens and the testes is due to a poor ability to dissipate heat and to their physical locations relative to the body surface.

The undesirable effects of excessive temperature in the whole body, the lens of the eye, and the testes are heat disablement, lenticular opacities, and tubular injury, respectively. Although cataract production has not been experimentally established as an electromagnetic radiation effect in man, the formation of lens opacities in animals subjected to such radiation suggests the need for precautions in situations where the human eye is exposed.

Experimental investigations of the biological hazard of electromagnetic radiation have been carried out, primarily on animals, but to a very limited extent on humans in the frequency range of 100 to 35,000 Mc/s. Based on these data, a hazardous electromagnetic radiation level of 10 milliwatts per square centimeter, or greater, has been established by the Armed Forces and most of the industrial laboratories in the country. It is believed at the present time that the continuous exposure to power density levels not exceeding 10 milliwatts per square centimeter of average power does not constitute a hazard. Due to the lack of data on the effects of chronic exposure, no time factor has been included.

It is highly probable that in the not too distant future, with the anticipated increase of system power levels, it will be necessary to provide personnel working in the vicinity of the transmitting facilities with protective clothing and to provide shielded passageways through the potentially hazardous areas.

There are several sub-divisions within the transmitting system where significantly different electromagnetic power levels exist. First, we have a high power density in the transmission line, which normally is closed and therefore not readily accessible. Next, the power is conveyed by the transmission line to an antenna feed which in turn feeds the energy to the antenna. The energy in transit from the feed to the antenna is no longer enclosed and is therefore more accessible than the inside of the transmission line. This area normally has a larger cross-sectional area than the transmission line and therefore a lower power density. Finally, the energy is radiated into free space by the antenna. Here, when we radiate the energy to the outside world, we face the biggest problem in the control of electromagnetic radiation hazards. The dependence upon distance of the energy is indicated in Fig. 26. At distances close to the antenna, in what is known as the near field, or Fresnel region, the power is contained within a beam of about the same size as the antenna aperture. This beam, however, is not uniform, but tapered across the aperture in order to keep the power in the side lobes to a minimum. The power density in the beam decreases smoothly from a maximum at the center of the aperture to a minimum at the aperture edge, which is about 10 db below the maximum.

GEOMETRY FOR THE DETERMINATION OF POWER DENSITY FROM A PARABOLIC ANTENNA

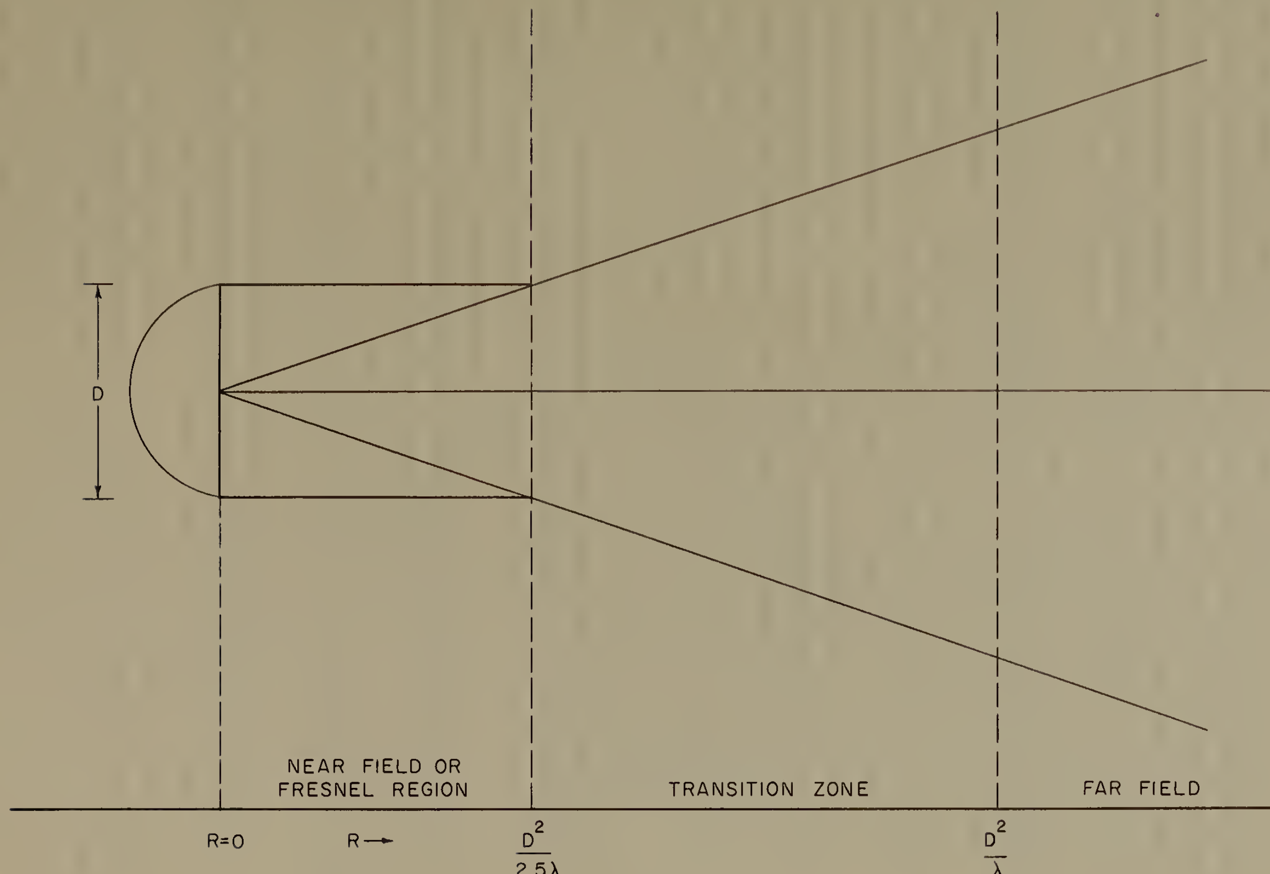


FIGURE 26

The near field may be described approximately by:

$$d_{Fresnel} < \frac{D^2}{2.5\lambda} \tag{27}$$

where

d is the distance from the antenna
D is the largest aperture dimension
λ is the wavelength

The power density in the field along the parabolic antenna axis can be obtained as follows:

$$W_d = 8.48\,\bar{w}\left[.433\sin^2\left(\frac{m}{4}\right) + .468\left\{\left(\frac{2}{m}\right)\sin\left(\frac{m}{4}\right) - \frac{1}{2}\cos\left(\frac{m}{4}\right)\right\}^2\right] \tag{28}$$

W_d is the power density, w/cm^2 at distance d
$\bar{w}$ is the mean power density across the aperture, w/cm_2, obtained by dividing the total power by the area in cm^2 of the dish.

$$m = \frac{\pi D^2}{2\lambda d}$$

If we designate the limit of the near field, $D^2/(2.5\lambda)$, as d_o, (28) can be written as

$$\frac{W_d}{\bar{w}} = 3.664\left[\sin^2\left(\frac{\pi d_o}{3.2d}\right) + .270\left\{\frac{3.2d}{\pi d_o}\sin\left(\frac{\pi d_o}{3.2d}\right) - \cos\left(\frac{\pi d_o}{3.2d}\right)\right\}^2\right] \tag{29}$$

This equation is plotted as a function of distance in terms of d_o in Fig. 27. From the curve, d_{max} or the distance at which the maximum power density occurs is seen to be about 0.58 d_o. Similarly, the maximum power density is seen to be equal to about 4.11 times the mean power density across the antenna aperture.

As the distance from the antenna exceeds the value given in (27), the beam begins to diverge until finally the power density is decreasing in accordance with the inverse square law. This region is known as the far field, or Fraunhofer region, and is described approximately by (17).

$$d_{Fraunhofer} > \frac{D^2}{\lambda} \tag{30}$$

The power density at the center of the beam in the Fraunhofer region is given as follows:

$$W = \frac{P_t g_t}{4\pi d^2} \quad w/m^2 \tag{31}$$

Ranges for the 10 mw/cm^2 power density value are shown in Table 5 for various frequencies, antenna gains, and transmitter powers.

TABLE 5

Typical Ranges for Which the Power Density Exceeds 10 mw/cm^2

P_t (kw)	D (ft)	Freq. (Mc)	$P_{d\,max}$ mw/cm^2	d_{max} (ft)	d_{10} (ft)
75	120	400	29.34	1359	3280
75	60	400	117.35	340	1447
50	60	1000	78.23	849	2949
50	28	1000	359.23	185	870
10	60	8000	15.65	6793	11712

RATIO OF POWER DENSITY ALONG THE AXIS OF A PARABOLIC ANTENNA TO AVERAGE POWER ACROSS THE FACE OF THE ANTENNA

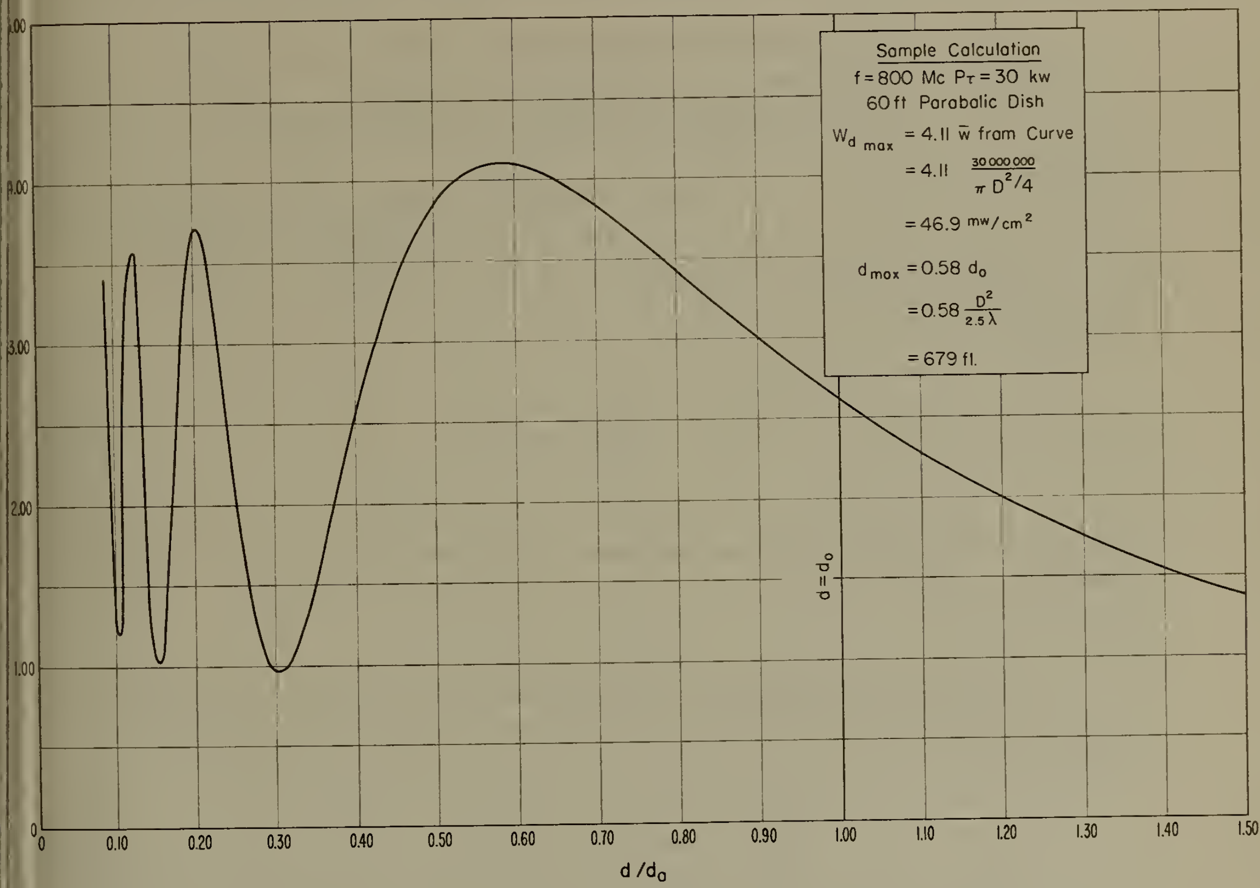


FIGURE 27

P_t	is the transmitter power
D	is the diameter of the parabolic reflector
Freq	is the frequency of operation
$P_d max$	is the maximum power density
d_{max}	is the distance from the antenna at which the maximum power density occurs
d_{10}	is the distance from the antenna within which the power density can be expected to exceed 10 mw/cm²

where

p_t	is the antenna input power, watts
g_t	is the antenna power gain
d	is the distance from the antenna, meters

Equation (31) may be used to calculate the approximate distance within which a given system will produce a radiation field with a power density equal to or greater than 10 milliwatts per square centimeter.

$$d = \frac{p_t g_t}{4\pi W} \text{ meters,} \qquad (32)$$

with W in watts per square meter. This equation again is valid only for $d > \frac{D^2}{\lambda}$.

Where calculations based on the above equations (or the possible existence of reflections) indicate a hazardous area, final conclusions and decisions should be based on field measurements.

b. Physical Effects

Photo flashbulbs may be ignited if brought in the direct beam of some equipment at distances less than 300 to 350 feet. Under certain circumstances dry steel wool may be ignited. Neon gas tubes will light in the presence of low intensity microwave fields.

Care should be taken to avoid handling of volatile liquids in a high level RF field. Sparks are known to occur at various points on metal structures when touched by portions of the body or by metallic objects held in the hand. The possibility of igniting volatile liquids, such as aviation gasoline, by these RF-induced sparks is a matter of concern. In order for gasoline to be ignited by a spark, the following conditions must exist: (a) inflammable gasoline vapor-air mixture must exist; (b) the spark must contain a sufficient amount of energy; (c) the gap across which the spark occurs must be a certain minimum distance, which is termed the "quenching" distance.

Investigation has shown that inflammable mixtures are not found at distances greater than six inches in any direction from exposed puddles of gasoline. The DC voltage required to break down an air gap of the minimum quenching distance for propane is approximately 2500 volts. The RF voltage required is believed to be about the same as that required for DC.

During recent years several accidents have occurred involving electrically initiated explosive devices. These accidents have been attributed to currents induced by radio frequency fields. The devices known as electro-explosive devices are designed to function by the passage of an electric current through them. Among such devices are primers, detonators, squibs, blasting caps, rocket ignitors, etc. Unfortunately, the problem of vulnerability of electro-explosive devices to RF radiation fields has only been superficially examined. Because of this and of the serious nature of an accidental explosion, they are presumed to present a dangerous hazard in the presence of high level RF fields. It is recommended that they should not be used or stored within 7000 feet of a transmitting antenna.

With the rapid increase in power levels used at radio frequencies, it is possible for previously unknown properties to be demonstrated by certain materials at these higher power levels. An example of this was a situation in which an inert gaseous fluorine compound, selected on the basis of published data, was used in a pressurized wave guide. Arcing in the wave guide was found to liberate large amounts of fluorine. Except for action by alert personnel, the planned use of this gas might well have resulted in injury and possible death.

The increase in transmitting power levels introduces the question of possible interference with other communication systems. Although this question has not been thoroughly explored, the potentially serious consequences of such interference makes mandatory the consideration of such possibilities.

c. Ionizing Radiation

In addition to the biological hazard created by electromagnetic energy at microwave frequencies, there is also a potential hazard from ionizing radiation produced by modern radio frequency power tubes. These tubes include magnetrons, klystrons, thyratrons and other types. Levels up to 200 roentgens per hour have been measured from certain klystrons. This is quite disturbing in view of the fact that the present maximum allowable exposure level has recently been reduced from 300 to 100 milli-roentgens per week.

The large number of radioactive electron tubes which have come into common use constitutes another potentially harmful source of ionizing radiation. The Air Force inventories over 500 types of these tubes containing such radioactive materials as carbon 14, cobalt 60, and radium 226. While disposal of this type of tube presents a problem, the high level of radiation resulting from storage of such items is more important to personnel. Continuous monitoring of radiation levels should be maintained. It should be realized that radio frequency electromagnetic fields have a degrading effect upon the measuring capabilities of many of the common types of dosimeters. The film type dosimeter, however, accurately records high levels of ionization even in strong radio frequency fields.

12. THE SITE SELECTION TEAM

Upon the thoroughness of the work of the Site Selection Team will depend the ultimate success of the entire circuit. The intelligent selection of sites for line-of-sight facilities is important. At the conclusion of an assignment the team will prepare a report which will describe all the tentative sites and serve as the basis for the ultimate selection of sites. The development of information to make up this report is the concern of the team throughout all of its work.

12.1 Makeup of the Team

Depending on the extent of the survey two to five individuals are recommended for this work. At least two of these should be competent in survey techniques. It is not recommended that a single individual be sent on such a mission alone, because no matter how competent he may be, there are so many details to be looked into that he will be overwhelmed. There is also a psychological advantage in having more than one individual because the many decisions that must be made can be talked over, and decisions are likely to be made more rationally as a result. The Site Selection Team must always bear in mind that it is not necessarily making the final site selection. More often than not it is selecting a number of possible locations and developing as much information as possible so that an intelligent selection can be made later when all of the facts are assembled.

Lack of a proper understanding of this principle is responsible for the reluctance on the part of some local commands, particularly those in populated foreign countries, to permit the team to investigate sites which may cause some difficulties in their own areas of administration. The sites that are left frequently leave much to be desired and may fail in some cases even to meet the minimum technical requirements. When doubts like these arise, it is always better for the team to investigate additional sites even though tact must be exercised.

12.2 Equipment

The equipment that the team carries will consist primarily of surveying instruments and drafting instruments. The amount of equipment will depend upon the type and extent of the survey and the mode of transportation. Transportation is one of the most difficult problems. In populated areas where roads are relatively abundant, a car exclusively assigned to the team is of inestimable assistance. In any case, because of transportation problems, it will always be necessary to limit the equipment to bare essentials. The following list divides items of equipment into the essential items and the desirable items:

a. Essential Items

Theodolite or transit with tripod
Altimeters (2)
Tables of Trigonometric Functions, logarithms, and celestial ephemeris
Tape (100' minimum, 300' invar preferred)
Camera and film
Protractor
Straight edge
Slide rule
Notebook and pencils
Maps
Map scale or variable scale
Parallel ruler
Red bunting
Binoculars
Flashlight
Hatchet
Plumb-bob
Water purifying pills

b. Desirable But Less Essential Items

Small computer (hand operated)
Range poles
Stadia rod
Portable dark room

Many other items will be found useful in special circumstances. A great deal of thought will necessarily be devoted to the special problems of particular areas. Items for personnel safety and comfort head this list. In some cases it may even be desirable to send an individual to the area in advance of the survey to determine the needs more thoroughly.

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APPENDIX 1

Formulas for Fresnel Zone Calculations

In ray tracing the reflection of a ray is usually shown for simplicity to occur at a point. Actually the entire surface is illuminated and reradiates, but the resulting field at the receiver arrives with such a phase and amplitude relationship that the contributions very nearly cancel each other except for a small elliptical zone in the center. This is called a Fresnel Zone, since it is closely related to the Fresnel Zones of diffraction theory. The length of the ray path at the edge of the first Fresnel Zone is one-half wavelength longer than the geometrical ray path. More generally the length of the reflected ray path at the outer edge of the $\underline{n}^{th}$ Fresnel Zone is $\underline{n}$ half-wavelengths greater than the geometrical path. Norton and Omberg [1947] have derived formulas for the intersection of the Fresnel Zone with a plane surface which are useful in evaluating terrain roughness and other factors involving reflections. Figure 28 shows the geometry of Fresnel Zones on a plane earth. With one terminal (usually the lower one) at the origin the position of the center of the ellipse, the semi-major and the semi-minor axes can be computed by means of the following formulas:

$$x_o = d_1 \left[1 + \frac{(h_2 - h_1)}{2h_1[1 + (h_1 + h_2)^2/n\lambda(R + n\lambda/4)]} \right] \qquad (1\text{-}1)$$

GEOMETRY OF FRESNEL ZONES ON A PLANE EARTH

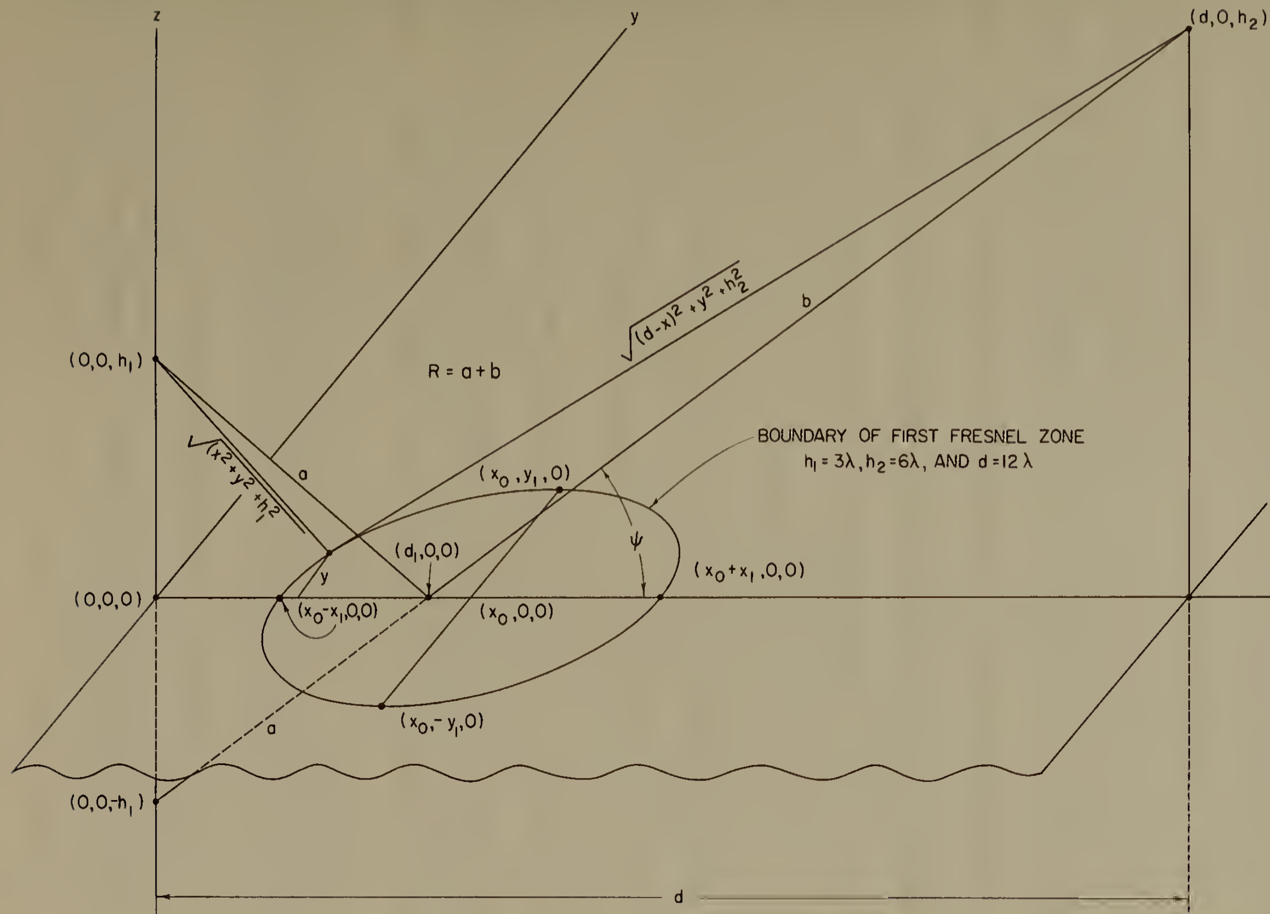

FIGURE 28

$$x_1 = \frac{\left(1 + \frac{n\lambda}{2R}\right)\left(1 + \frac{n\lambda}{4R}\right)}{\sin\theta \left[1 + \frac{n\lambda\left(R + \frac{n\lambda}{4}\right)}{(h_1 + h_2)^2}\right]} \sqrt{\frac{abn\lambda}{a + b + \frac{n\lambda}{4}} \left[1 + \frac{n\lambda\left(R + \frac{n\lambda}{4}\right)}{4h_1 h_2}\right]} \tag{1-2}$$

and

$$y_1 = \left(1 + \frac{n\lambda}{4R}\right) \sqrt{\frac{abn\lambda}{a + b + \frac{n\lambda}{4}} \left[1 + \frac{n\lambda\left(R + \frac{n\lambda}{4}\right)}{4h_1 h_2}\right] \Big/ \left[1 + \frac{n\lambda\left(R + \frac{n\lambda}{4}\right)}{(h_1 + h_2)^2}\right]} \tag{1-3}$$

Under the conditions that one terminal is much higher than the other and also is many wavelengths high, these formulas may be replaced by approximate formulas with very good results:

$$x_o \cong d_1 \left[1 + \frac{\lambda}{2h_1 \sin\psi}\right] \tag{1-4}$$

$$x_1 \cong \sqrt{\frac{h_1 \lambda}{\sin^3 \psi} \left[1 + \frac{\lambda}{4h_1 \sin\psi}\right]} \tag{1-5}$$

$$y_1 \cong x_1 \sin\psi \tag{1-6}$$

In (1-4) through (1-6), $h_2 >> \lambda$, $h_2 >> h_1$.

APPENDIX 2

Earth Profiles

In plotting profiles of propagation paths it is convenient to use a standard profile paper with an exaggerated vertical scale. This type of grid allows for ray bending to a first approximation by increasing the actual earth's radius, a_o, to an effective value, a. When the distance involved on the profile is much smaller than the effective earth's radius the spherical surface can be approximated by a parabolic surface by the following simple formula:

$$\Delta h = \frac{d^2}{2a} \tag{2-1}$$

where Δh is the height of a plane at distance d from its point of tangency on a sphere of radius a.

The actual radius of the earth is 3960 miles or 6370 km. It has been common practice in the past to assume $a/a_o = 4/3$ which gives an effective earth's radius of 5280 miles. A better value and one which more nearly approximates the CRPL reference atmosphere with $N_s \sim 316$ is $a/a_o = 1.41$. The effective earth's radius then is 9000 km. This gives a convenient relationship which can easily be remembered. If Δh is expressed in meters and d in km, (2-1) becomes $\Delta h = d^2/18$ (or conversely $d = 3\sqrt{2\Delta h}$).

It is relatively easy to construct a profile grid using any convenient scale for distance and for height. Referring to Figure 29, convenient height and distance scales are first arbitrarily selected. To construct the grid it is best to start in the center and let d increase in both directions. Later the distance scale can be shifted so as to start from either end or any other location. The same grid can be used for a number of height and distance scales. If the distance scale is changed by a constant, C, the height scale is changed by the square of this constant, C^2. For example, to increase the distance scale by a factor of 2, it is necessary to use a height scale increased by a factor of 4.

CONSTRUCTION OF PROFILE GRIDS USING
ARBITRARY EARTH RADIUS, a
ACTUAL EARTH RADIUS, a_0=6,370 km, 3,960 MILES

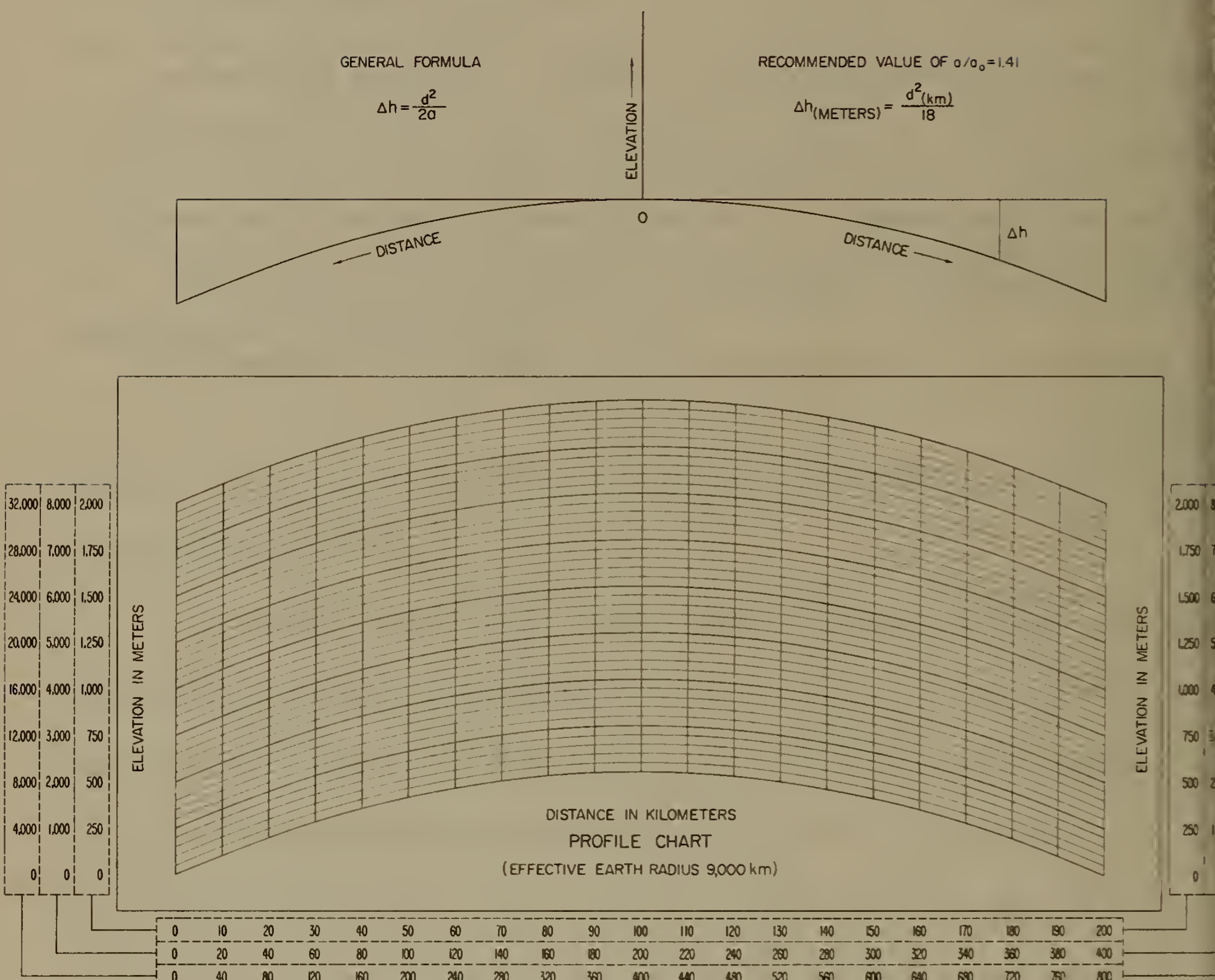

FIGURE 29

APPENDIX 3

Conversion Factors and Constants

The international meter is the universal standard of length throughout the world. Its actual length is known with an accuracy of about one part in ten million. Under the guidance of the International Committee of Weights and Measures work is in progress toward the establishment of an atomic standard for length measurement. The inch, originally the width of a man's thumb, has been different in length as has been the foot, the yard, the mile, etc., in different countries owing to the use of different conversion constants from the meter.

In October 1958 the International Committee adopted the international yard as exactly 0.9144 meters. Listed below are many of the constants to be used to convert various units of length into other units in keeping with the new definition.

$c = 2.9\ 97925 \times 10^{8}$ m/sec $= 9.8357\ 11942 \times 10^{8}$ ft/sec

$= 1.8628\ 24231 \times 10^{5}$ mi/sec

λ(100 Mc/s) = 2.9 97925 meters = 9.8357 11942 feet

$= 1.8628\ 24231 \times 10^{-3}$ miles

1 meter = 39.370 07874 inches = 3.2808 39895 feet

$= 6.2137\ 11922 \times 10^{-4}$ miles

1 foot = 0.3048 meters

1 inch = 2.54 cm

1 statute mile = 1.6093 44000 km = 0.86897 62419 nautical miles

1 nautical mile = 1.852 km = 1.1507 79448 statute miles

1 radian = 57.295 77951 degrees

1 degree = 17.453 29252 milliradians

$\pi = 3.1415\ 92654$

$e = 2.7182\ 81828$

Radius of the earth for which 1' = 1 nautical mile is 3437.74677 nautical m

= 3956.08833 statute miles

= 6366.70702 km

The National Bureau of Standards follows the recommendations of the International Committee on Weights and Measures to use new prefixes for denoting multiples and sub-multiples of units. In addition to the 8 numerical prefixes in common use, which are given in the table below, the Committee expanded the list by adding the 4 prefixes marked with an asterisk. Thus, for example, 10^{-12} farad is called 1 picofarad, and is abbreviated 1 pf.

Multiples and Sub-multiples	Prefixes	Symbols	Pronounciation
$1\,000\,000\,000\,000 = 10^{12}$	tera*	T	tĕr′ȧ
$1\,000\,000\,000 = 10^{9}$	giga*	G	jī′gȧ
$1\,000\,000 = 10^{6}$	mega	M	
$1\,000 = 10^{3}$	kilo	k	
$100 = 10^{2}$	hecto	h	
$10 = 10$	deka	dk	
$0.1 = 10^{-1}$	deci	d	
$0.01 = 10^{-2}$	centi	c	
$0.001 = 10^{-3}$	milli	m	
$0.000\,001 = 10^{-6}$	micro	μ	
$0.000\,000\,001 = 10^{-9}$	nano*	n	nā′nō
$0.000\,000\,000\,001 = 10^{-12}$	pico*	p	pī′cō

U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, Secretary

NATIONAL BUREAU OF STANDARDS
A. V. Astin, Director

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D.C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

Radiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics. Electrolysis and Metal Deposition.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Crystal Growth. Physical Properties. Constitution and Microstructure.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Applications Engineering.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Solid State Physics. Electron Physics. Atomic Physics.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Molecular Kinetics. Mass Spectrometry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time Interval Standards. Electronic Calibration Center. Millimeter-Wave Research. Microwave Circuit Standards.

Radio Systems. High Frequency and Very High Frequency Research. Modulation Research. Antenna Research. Navigation Systems.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

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