CHAPTER 11
RADIO WAVE PROPAGATION

1. INTRODUCTION

The science of radio wave propagation begins when the waves leave the radio transmitter antenna and ends when the waves enter the receiver antenna. A single chapter of a book cannot begin to cover a field as large as this science encompasses, and no attempt is made to do so. Sufficient information is provided in this chapter to familiarize the reader with radio wave propagation to the extent that he will be able to solve practical propagation problems. This chapter includes brief explanations of how sky wave transmission takes place, how the ionosphere is formed and its composition, ionospheric absorption of sky wave field intensity, noise limitations, and effects of different types of service. A practical problem is included to illustrate how the feasibility of a good communication link between two points is determined. This problem includes not only the feasibility of sky wave communication but also the feasibility of ground wave communication. The results of such a study provide information which can be used to improve the communication link, such as the lowest useful high frequency (LUHF) which can be employed and the lowest effective radiated power which can be used. The illustrative problem used is based on a vertically polarized wave, such as is propagated from a whip or vertical antenna, and is over a path length less than 2000 kilometers. No attempt is made here to investigate communication links greater than 2000 kilometers.

2. FORMATION OF THE IONOSPHERE

When an electromagnetic wave impinges on an atom, it is capable of moving an electron from an inner orbit to an outer orbit. When this occurs, the electron has absorbed energy from the wave. If the frequency of this incident wave is sufficiently high, such as in ultraviolet waves, an electron may be knocked completely out of an atom. When this occurs, a positively charged atom, called a positive ion, remains in space along with the negatively charged, free electron. The rate of ion and free-electron formation depends upon the density of the atmosphere and the intensity of the ultraviolet wave. However, as the ultraviolet wave produces positive ions and free electrons, its intensity diminishes. Therefore, the ionized region will tend to form in a layer, forming few positive ions and free electrons due to the less dense atmosphere when the ultraviolet wave is most intense, forming more positive ions and free electrons due the more dense atmosphere when the ultraviolet wave is of moderate intensity, and again forming few positive ions and free electrons due to the low intensity of the ultraviolet wave in the most dense atmosphere. This relationship between ultraviolet wave intensity, rate of ionization, and atmospheric density is shown in figure 11-1.

The formation of positive ions and free electrons is not, in itself, sufficient information to account for the existence of an ionic layer, because the positive ions and free electrons tend to recombine due to the inherent attraction of their unlike charges. The recombination rate is directly related to the molecular density of the atmosphere, because the more dense the atmosphere the smaller is the mean free path of the free electrons. The recombination rate is also directly related to the density of positive ions and free electrons. Therefore, as the ultraviolet waves continue to produce positive ions and free electrons, a free electron density will be reached where the recombination rate just equals the rate of formation. In this state of equilibrium, a free electron density exists for every set of given conditions, although any particular electron may be free for only a short time.

That more than one ionic layer exists is explained by the existence of different ultraviolet wave frequencies. The lower frequency ultraviolet waves tend to produce a higher altitude ionic layer, expending all of their energy at the high altitude. On the other hand, the higher frequency ultraviolet waves tend to penetrate deeper into the atmosphere before producing appreciable ionization. In addition to the ultraviolet waves from the sun, particle radiation caused by thermonuclear explosions on the sun, cosmic rays, and meteors produce ionization of the earth's atmosphere, particularly in a higher altitude layer.

3. IONOSPHERIC ABSORPTION

For sky wave transmission, the transmitted electromagnetic wave must travel through the ionic layers. To do so, the incident wave interchanges energy with free electrons and ions. If this interchange of energy is completely reciprocating, the wave will emerge from an ionic layer with no loss of energy. On the other hand, if an ion or free electron collides with a neutral atom or recombines with its opposite, any energy the ion or electron may have received from the incident wave is given up and lost. Energy from the sky wave which is lost in this manner is said to be

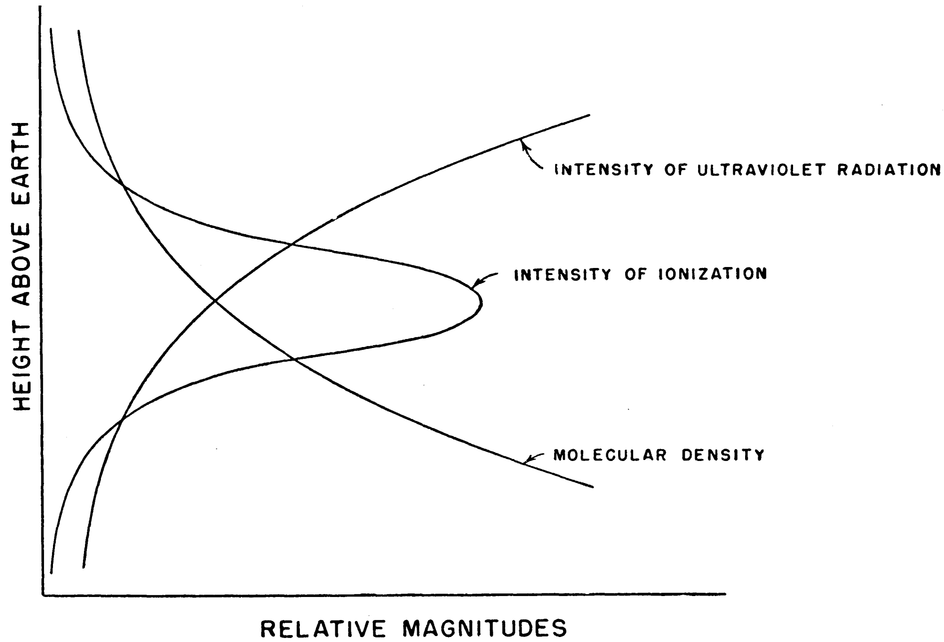


Figure 11-1. Formation of an Ionized Layer by a Single-Frequency Ultraviolet Wave

absorbed. This ionospheric absorption is greatest in the lower ionic layers because these layers exist in a denser atmosphere where the collision frequency is highest. Ionospheric absorption is discussed in greater detail in paragraph 6b. of this chapter.

4. STRUCTURE OF THE IONOSPHERE

One of the most useful techniques for exploring the ionosphere is to transmit r-f pulses vertically into the atmosphere and to receive the reflected pulse. The echo time is indicative of the height of the ionospheric layer, and the received magnitude of the pulse is indicative of the thickness of the ionospheric layer. When pulses of various r-f frequencies are transmitted, a critical frequency f_o can be determined, above which the vertical sky wave will not be reflected back to the earth. This critical frequency is indicative of the extent of ionization of the layer, with a higher critical frequency indicating greater ionization. These vertical soundings indicate that there are four distinct ionic layers as shown in figure 11-2. They are as follows:

D REGION -- This region is not always present, but when it does exist, it exists only in the daytime and is between 50 and 90 km above the earth, being the lowest of the four layers. This region is so highly ionized, and the collision frequency is so great that little or no sky wave reflection is obtained from it; the sky wave usually is totally absorbed.

E LAYER -- This layer exists only during daylight hours at a height between 90 and 140 km above the earth. This layer depends solely upon ultraviolet radiation from the sun, and it exists in an atmosphere where the ion-electron recombination rate is high. Since the E layer depends directly upon the sun, it is most dense directly under the sun. Seasonal variations occur in this layer because the sun's zenith angle varies to produce the seasons. Since the E layer exists in an atmosphere where the recombination rate is high, all of the ions and free electrons recombine shortly after sunset, and the layer disappears. Because E layer density follows the sun, points of equal latitude have the same E layer conditions at the same local time.

F_1 LAYER -- The F_1 layer exists at a height between 140 and 250 km above the earth during daylight hours. This layer behaves like the E layer during daylight; that is, it follows the sun. When the sun sets, the F_1 layer rises to merge with the next higher ionic layer, the F_2 layer.

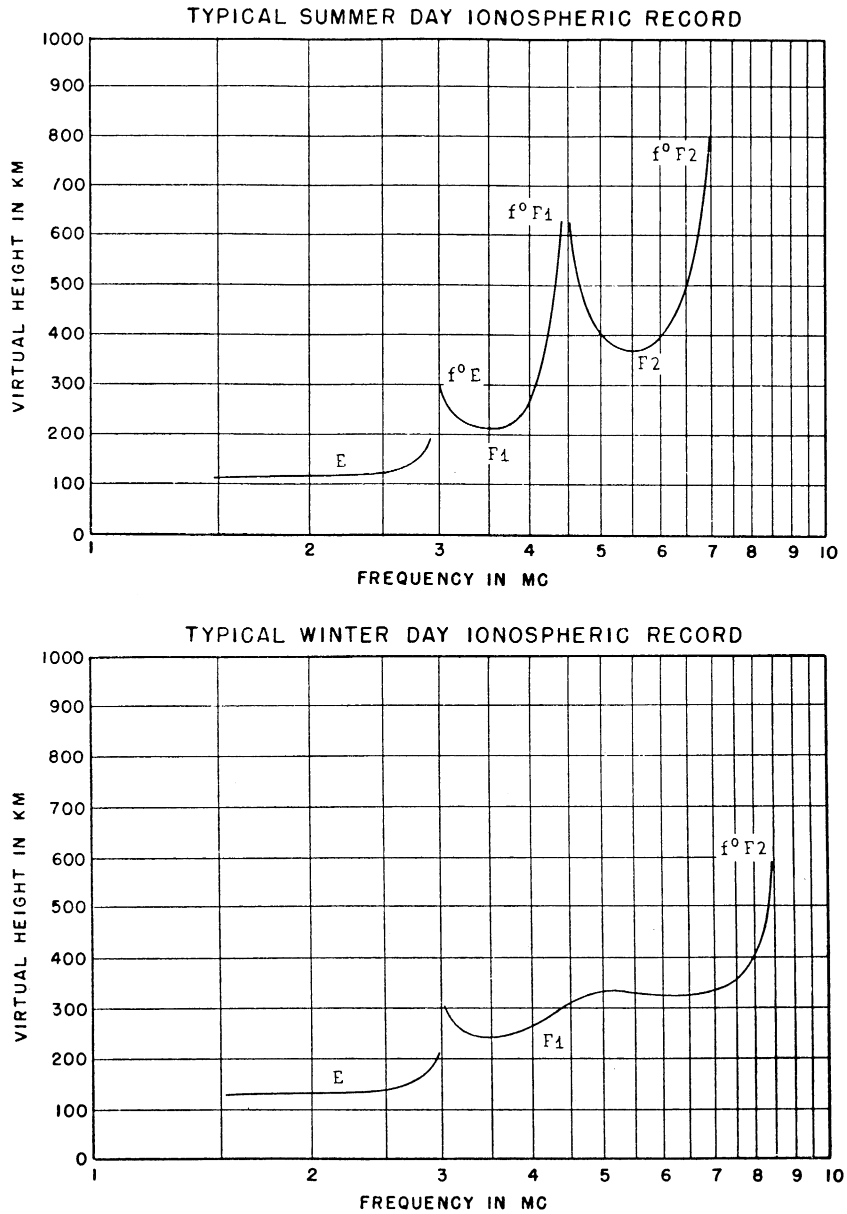


Figure 11-2. Typical Ionospheric Record

F_2 LAYER -- The F_2 layer is the highest and most useful ionic layer for sky wave transmission because it exists during the night as well as during the day. This layer is between 150 and 250 km above the earth during the night for all seasons of the year. During the day in the summer it is between 250 and 300 km high, and during the day in the winter it is between 150 and 300 km high. This variation in height is accounted for by the effect of solar heat on the layer which increases its height and decreases its ion density during the summer. The reduction of solar heat in the late afternoon causes the layer to descend. No complete explanation has been made for the existence of the F_2 layer, but it is known that it is considerably affected by particle radiation from the sun, which is evidenced by the strong influence that the earth's magnetic field has on the distribution of the F_2 layer. The effect of the earth's magnetic field results in the greatest ion density, and the highest critical frequency, in a region about 20° from the magnetic poles, rather than directly under the sun as in the case of the D and E layers. Since the earth's magnetic field is not evenly distributed, longitudinal variations exist in the F_2 layer for points of equal latitude at the same local time. For this reason, the earth is divided into zones which represent different degrees of magnetic intensity to facilitate plotting F_2 layer distribution. These three zones are called the East, West, and Intermediate zones (abbreviated E, W, and I) as shown on the world map, figure 11-3. Monthly predictions of F_2 layer distribution are then made by the Bureau of Standards for each of the three zones.

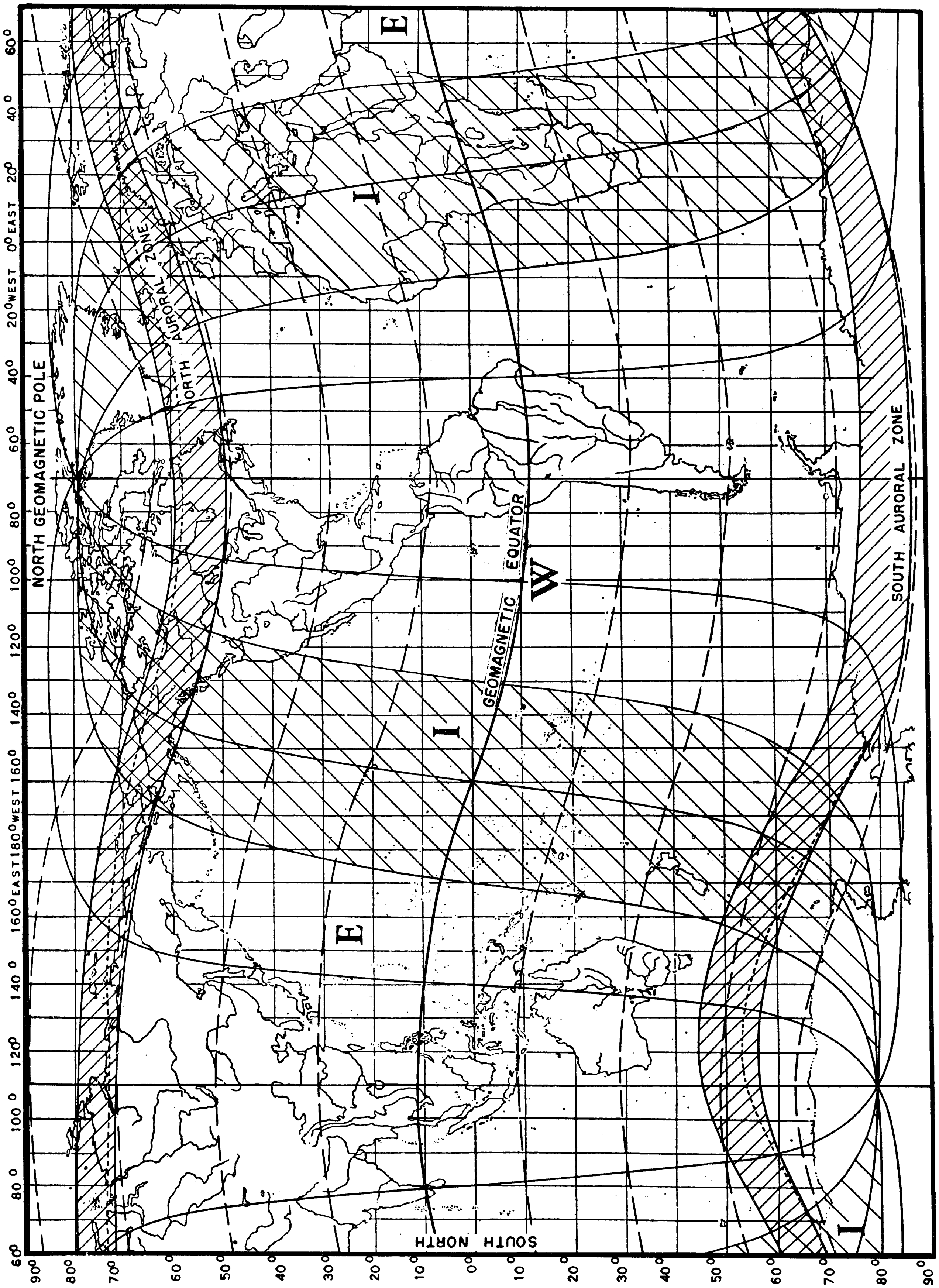


 Figure 11-3. Geomagnetic Co-ordinates as Related to East, West, Intermediate, and Auroral Zone

5. NATURAL PHENOMENA WHICH AFFECT IONIC LAYERS

a. SUNSPOTS

The sun is the major, if not the only, source of energy which produces ionization of the earth's atmosphere. Therefore, any solar disturbance produces variations in the ionic layers. Sunspots are evidence of such solar disturbance which affects the ionic layers. These sunspots appear as dark patches surrounded by a hazy grey edge and are presumably vortexes of enormous gas clouds. These gaseous clouds produce vast amounts of ultraviolet energy which affects the ionization of the earth's atmosphere. Therefore, the greater the number of sunspots, the greater the ultraviolet radiations and the greater the ionization. For this reason, the number of sunspots is indicative of ion density which, in turn, is a measure of the probability of sky wave communication. Sunspot activity is measured by the Wolf sunspot number method which takes into account not only the number of actual sunspots but also the number of sunspot groups. Observations of solar activity over the past 100 years have confirmed that sunspot activity is cyclic, the cycle repeating every 11.1 years. There are variations within this cycle and variations from cycle to cycle which make it necessary to know the predicted sunspot number for a given time in order to determine the probability of sky wave communication.

b. SUDDEN IONOSPHERIC DISTURBANCES

Occasionally daytime communication by high-frequency sky wave propagation is rendered impossible by abnormally great absorption. The onset of this condition is usually very sudden with recovery being more gradual, and the condition may last from a few minutes to several hours. This condition is known by several names, the most common being sudden ionospheric disturbance, abbreviated SID. This condition is also known as solar flare disturbance and Dellinger fade. An SID is apparently the result of a chromospheric eruption on the sun as evidenced by ionospheric absorption immediately following an eruption, by the absorption taking place in the lower ionic layers where the ion density is directly related to the sun, and by its occurrence only in the daytime. The result of an SID is a sudden increase in the ion density of the highly absorptive D region, as well as an increase in the ion density of the moderately absorptive E layer.

c. MAGNETIC STORMS

Magnetic storms are not to be confused with sudden ionospheric disturbances, although they both have the same effect in that they reduce the probability of communication by sky wave propagation. The magnetic storm is associated with solar activity, being more likely to occur during maximum sunspot conditions, and reoccurring in 27-day cycles, the rotation period of the sun. Magnetic storms are apparently caused by particle radiation from the sun, with the radiated particles being deflected by the earth's magnetic field. For this reason, the effects of a magnetic storm are most severe in the two geomagnetic pole regions. The origin of a magnetic storm may be the same solar eruption which produces an SID, but since particle radiation is much slower than ultraviolet radiation, the effect of the magnetic storm is not noticed until 18 to 36 hours after an SID. A magnetic storm has two phases with the first phase expanding the F_2 layer which reduces ion density. During this phase, the F_2 layer critical frequency becomes lower than normal due to the reduced ion density. The second phase is marked by a greater concentration of electrons in the highly absorptive D and E regions, especially in the geomagnetic polar regions. The increased absorption which results may prevent communication by sky wave propagation. A magnetic storm may last for several days, with its appearance being very sudden and recovery to normal very slow.

d. SPORADIC E LAYER

A sporadic E layer, abbreviated E_s, can not be accounted for by the processes which explain the normal E layer which exists at approximately the same height above the earth. Some investigators of this phenomenum believe it to be caused by particle radiation, possibly as a result of meteors entering the earth's atmosphere. The E_s layer can exist during both the day and the night, but its presence during the day is difficult to detect due to the presence of the normal E layer. The distribution of this layer cannot be predicted, but it is known to vary in thickness and ion density and is frequently patchy. It is also known that the likelihood of the existence of a sporadic E layer increases with distance from the equator. Its occurrence is frequent enough in the middle latitudes to render E_s sky wave propagation from 25 to 50 per cent of the time at frequencies up to 15 mc.

6. SKY WAVE TRANSMISSION

a. SKY WAVE REFLECTION

When sky wave propagation is used for communication, the electromagnetic wave from the antenna is transmitted toward an ionic layer at an oblique angle. The incident wave then is apparently reflected, at the same oblique angle, from the ionic layer back toward the receiving antenna. Figure 11-4 shows sky wave propagation paths which can be used. Actually the wave is not reflected, although this term is commonly used for convenience; the wave is bent back toward the earth by refraction, just as a prism refracts light.

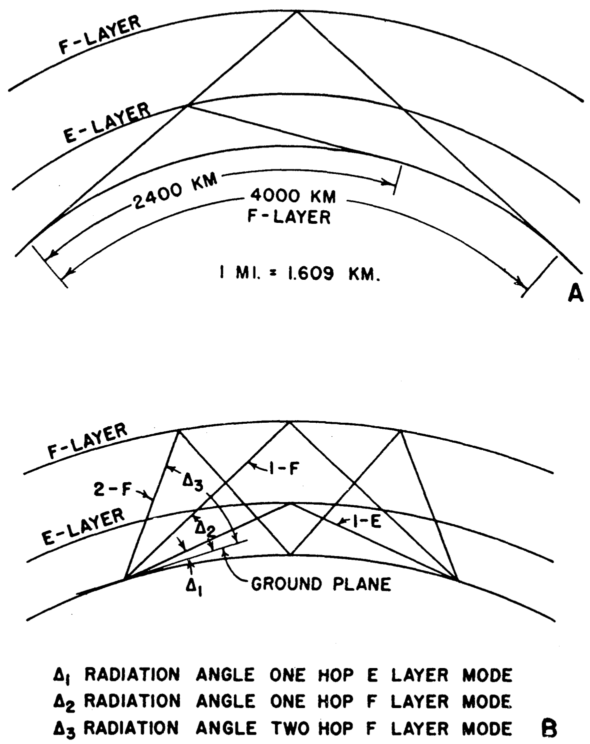


Figure 11-4. Distance Limitations for Single Reflection Transmission (A) and Modes of Transmission (B)

This bending process is a function of the refractive index of the ionic layer and behaves in accordance with Snell's law, which was originally discovered in connection with optical geometry. Roughly stated in terms of ionospheric refraction of a radio wave, this law is as follows: For a wave incident upon a densely ionized layer to be bent back toward the earth, the wave must pass from a medium with a high refractive index to a medium of low refractive index. Stated in mathematical terms, Snell's law is as follows:

$$\cos \Delta = \mu \cos \Theta \qquad (1)$$

where Δ and Θ are the angles as shown in figure 11-5

the refractive index

$$\mu = \frac{\text{wave velocity in free space}}{\text{phase velocity in the ionized medium}}$$

The wave velocity in free space is the speed of light, and this velocity generally is assumed for a normal atmosphere. The phase velocity in the ionized medium is greater than the speed of light and increases with increased ion density. That the phase velocity in an ionized medium is greater than the speed of light does not contradict the theory of relativity since phase velocity is defined as frequency times wave length. That the phase velocity can be greater than the speed of light then indicates an increase in wave length of a constant frequency being propagated in an ionized medium, not an increase in the velocity of propagation.

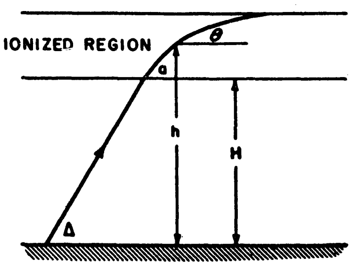


Figure 11-5. Refraction of a Radio Wave

Carrying the laws of optics further, the relationship for total reflection between two media having different refractive indexes is given by the following equation:

$$\cos \Delta = \frac{\mu_{ion}}{\mu_{air}}$$

Where the refractive index of the atmosphere is taken as unity, the equation for ionospheric reflection is:

$$\cos \Delta = \mu_{ion} \qquad (2)$$

If the wave is transmitted vertically, Δ equals 90° and $\cos \Delta$ equals 0. For the wave to be reflected under this condition, the refractive index of the ionosphere must then equal 0.

It can be shown that the refractive index of the ionosphere is a function of the ion density and of the frequency of the transmitted wave. This relationship is given by the following equation:

$$\mu = \sqrt{1 - 80.5N/f^2}$$

where N is the number of electrons per cubic meter

By substituting 0 for the refractive index, the condition where a vertically transmitted wave will be reflected, the critical frequency, f_o, is given by the following equation:

$$f_o = \sqrt{80.5N}$$

A vertically transmitted frequency greater than this value will penetrate an ionosphere of density N while a frequency less than this value will be reflected. We can then rewrite the equation for the refractive index in terms of the critical frequency as follows:

$$\mu = \sqrt{1 - \frac{f_o^2}{f^2}} \quad (3)$$

By substituting in equation (2), the following equation is obtained:

$$\cos \Delta = \sqrt{1 - f_o^2/f^2}$$

or by trigonometric transformation

$$f = f_o \csc \Delta \quad (4)$$

The significance of the study of vertical incidence to the problems of radio propagation is apparent from the above equation. If the critical frequency, f_o, for the ionosphere over a certain point is known, the frequency, f, which will just be reflected by the ionosphere over that point can be calculated. This is the maximum usable frequency MUF for the vertical radiation angle Δ. Frequencies above the MUF will penetrate the ionosphere; frequencies below the MUF will be reflected.

Equation (4) is derived on the assumption that both the earth and the ionosphere are parallel planes; this is not the case. However, the equation for a curved earth and curved ionosphere is of the same nature, although a little more complex. This relationship is as follows:

$$f = f_o \, k \sec \phi \quad (5)$$

where ϕ is the angle shown in figure 11-6

k sec ϕ is referred to as the corrected secant with the value of k being determined experimentally.

From the above relationship and a vast amount of practical experience, the MUF can be determined for any distance, geographic location, sunspot number, time of day, etc. These predictions are published by the Bureau of Standards three months in advance.

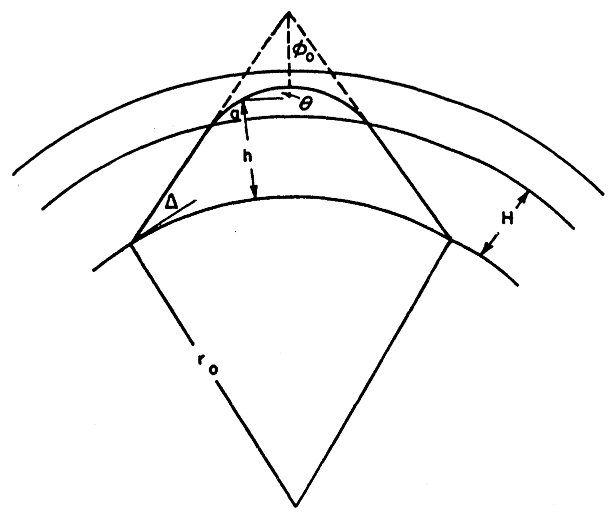


Figure 11-6. Ray Path for a Curved Earth and a Curved Ionosphere

b. SKY WAVE ABSORPTION

As stated in paragraph 3 of this chapter, a radio wave entering an ionic layer interchanges energy with the free electrons and ions. If the ions do not collide with gas molecules or other ions, all of the energy transferred to the ionosphere is reconverted back into electromagnetic energy, and the wave continues to be propagated with undiminished intensity. On the other hand, where ions and electrons engage in collisions, they dissipate the energy which they have acquired from the wave which results in attenuation of the wave. This attenuation, or absorption, is proportional to the product of the number of ions N and the collision frequency f_c. Therefore, the attenuation is ordinarily greatest in the region where the product of ion density and the collision frequency is greatest. This absorption is great when the deviation due to refraction is small. Conversely the absorption is small when the deviation is large. For this reason, absorption due to ionic collision is called nondeviative absorption when the absorption is appreciable and deviative absorption when absorption is small.

Nondeviative absorption is very important in most radio propagation problems. It is primarily of importance in daylight transmissions because it is present predominantly in the D and E ionic regions where the ion density is great, and the collision frequency is high. Since nondeviative absorption is related to ion density in the D and E layers, the absorption is related to the number of sunspots and the season of the year. The absorption also is related to the radio wave path, the time of transmission, and the refractive index. The relationship of the transmission path, refractive index, and time of transmission is called the diurnal absorption factor K. Although a mathematical equation exists for computing K, the variables involved are so difficult to measure that using the equation for determining K is impractical, except in special cases. The diurnal absorption factor usually is obtained from absorption index charts, with a different chart being used for different months of the year. The empirical equation $K = 0.142 + 0.858 \cos \psi$, where ψ is the sun's zenith angle, is fairly accurate for times near sunrise and sunset. A residual seasonal variation factor M, beyond that involved in the diurnal absorption factor, has been determined for each month of the year. The effect of the number of sunspots on absorbtion is called the solar activity factor S. This value is obtained from a graph relating the predicted sunspot number, SSN, with solar activity factor. From these three factors, K, M, and S, the corrected nondeviative absorbtion is determined by the following equation:

Corrected K = K x M x S

Auroral absorption K_a must also be considered when the transmission path travels through an auroral zone. The auroral zones are the zones of highest magnetic activity which are centered about 20° from the earth's magnetic poles. The auroral absorption index has been determined and plotted for these regions. Where an auroral absorption factor exists, it should be added to the corrected diurnal absorption factor to obtain the total absorption.

A third type of absorption, due to the earth's magnetic field, also contributes toward absorption of radio waves, but this absorption usually can be neglected. When an electromagnetic wave is propagated in the ionosphere, the wave is resolved into circularly polarized components which impart motion to the electrons and ions. When the propagated wave is in the direction of the earth's magnetic field, the magnetic field causes these electrons to rotate at a gyromagnetic frequency in a plane perpendicular to the direction of the wave. When the wave and field produce rotations in the same direction, the electrons rotate in larger orbits. This, in turn, produces more electron collisions with a consequential loss of energy and an increase in absorption. Similarly, if the wave and field produce rotations in opposite directions, the electrons rotate in smaller orbits which reduces absorption.

c. SKY WAVE FIELD INTENSITY

(1) GENERAL

To have effective radio communication, the received signal strength must be sufficient to overcome the effects of various noises. To determine the median sky wave field intensity at the receiving station, it is necessary to know (1) the gain of the transmitting antenna and of the receiving antenna (2) the power output of the transmitter, (3) the transmission path, (4) the total absorption, and (5) the operating frequency.

(2) OPERATING FREQUENCY

The operating frequency is determined first. This is done best by using "Basic Radio Propagation Predictions" which are published monthly, three months in advance of their effective date by the Central Radio Propagation Laboratory of the Bureau of Standards. Examples of these prediction charts are included in this chapter, and their use is discussed in the example problem which follows. From these prediction charts, the maximum usable frequency (MUF) and the frequency of optimum traffic (FOT) can be determined for any propagation path for any hour of the day. Transmission at the FOT is desirable because it reduces the possibility of propagating by more than one mode (i.e., 1-hop E, 1-hop F_2, 2-hop F_2), and atmospheric noise is usually less.

(3) ANTENNA GAIN

After determining the operating frequency, the next step is to determine the gain of the transmitting antenna. This gain depends on (1) the elevation angle of the radiated energy, (2) the length of the antenna, for a simple monopole, in terms of wave length, and (3) the type of ground in the vicinity of the antenna. The gain of the antenna is referred to a standard antenna, which may be an isotropic antenna, half-wave dipole in free space, or a short vertical element over perfectly conducting ground. The short vertical element is chosen as the reference in the problem which follows, and antenna gains are in terms of decibels above or below the gain of this short vertical element. The reference antenna provides a received field intensity of 186.3 mv/m at 1 mile with a 1 kw input, measured along the ground plane. The gain of the transmitting antenna is the square of the ratio of the field intensity of the actual antenna at 1 mile with 1 kw input divided by 186.3 mv/m. This gain, expressed in equation form, is as follows:

$$\text{Gain} = \left[\frac{\text{Field intensity in mv/m at 1 mile produced in the required direction by the actual antenna with 1 kw of input power}}{186.3 \text{ mv/m}}\right]^2$$

Several graphs are included in this chapter which show the gain of whip antennas versus frequency for various radiation angles.

The receiving antenna characteristics are defined in terms of effective area and effective height. That is, a receiving antenna in an electromagnetic field of a given power density will yield input power to the receiver equal to the product of the power density and the area of the antenna. In equation form, the expression for this relationship is as follows:

$$P = P_d \times A \qquad (6)$$

where P is power in watts,
P_d is power density in w/m^2, and
A is effective area, and is equivalent to $\frac{G\lambda^2}{4\pi}$ with G being the gain of the receiving antenna at the particular radiation angle.

Similarly, for vertical antennas the input voltage is given by the following relationship:

$$V = E \times h \qquad (7)$$

where V is voltage in uv,

E is field intensity in uv/m, and

h is the effective height in meters

An expression similar to equation (6) may be written in terms of input voltage, and is as follows:

$$V^2 = \frac{E^2}{377} \times \frac{g_r Z_{in} \lambda^2}{4\pi} \qquad (8)$$

where E is field intensity in uv/m,

377 ohms is the impedance of free space,

g_r is the gain of the receiving antenna at a particular radiation angle in dimensionless units,

Z_{in} is the input impedance in ohms of the receiver, and

λ is the wave length in meters.

Equation (8) can be rewritten in logarithmic form as follows:

$$V_{(db)} = 20 \log E + 10 \log Z_{in} + 20 \log \lambda + G_r - 38.8$$

where V is db > 1 uv

G_r is gain in db of receiving antenna

Several graphs are included in this chapter showing antenna gain versus frequency of some typical vertical antennas.

(4) FADING

Due to variations in the ionosphere, the sky wave field intensity varies from minute to minute, day to day, month to month, and year to year which causes signal fading. To increase the reliability of communication, it is necessary to increase the median level of the system output to lessen the probability that the received field intensity will go below the level required for reception. The atmospheric noise level also is subject to variations so that a further increase in output is required to increase the probability that the received signal level is sufficient to overcome the noise. Curves of slow and rapid variations of sky wave field intensity and variations of atmospheric noise are included in this chapter. Reference to these curves indicates that for a 95 per cent reliable system it is necessary to increase the median level of the system output by 7.8 db to overcome slow variations of sky wave field intensity, 11.3 db to overcome rapid variations of sky wave field intensity, and 13 db to overcome slow variations of atmospheric noise. Therefore, for communication 95 per cent of the time, it is necessary to increase the system output by a total of (7.8 + 11.3 + 13) db, a total of 32.1 db, above the level which will provide communication 50 per cent of the time.

Polarization fading and selective fading should also be considered in evaluating the probability of communication. Polarization fading is due primarily to a plane wave front being split into randomly polarized waves by the earth's magnetic field. With a linear receiving antenna, the received field intensity is attenuated by 3 db due to polarization fading. Selective fading is due primarily to two signal sources arriving from the same transmitting antenna via different paths. This is the result of ionospheric irregularities, propagation by more than one mode, or interference between the sky wave and the ground wave. The magnitude of the two received signals may be fairly close together but out of phase, so that one signal cancels the other. The received field intensity then fluctuates as the phase relationship varies between the different, incident component waves. The effects of selective fading can be reduced by diversity reception, where two or more antennas are used and so spaced that one antenna is not correlated to the received field intensity of another antenna. A diversity gain results from such a receiving system, but such a system is impractical on shipboard. See figure 11-14 for diversity gains.

(5) ABSORPTION

The total absorption factor, discussed in paragraph 6b of this chapter, must be determined in order to obtain the median incident sky wave field intensity. Graphs of median incident field intensity of the short-element, reference antenna versus frequency for various absorption factors, various modes of propagation, and various distances are included in this chapter. Where the absorption factor is zero, these curves indicate that there is no variation of median incident field intensity with frequency, so that the K = 0 curve is a straight horizontal line. The median incident field intensity then is an inverse function of the geometric length of the sky wave path plus a 3 db depolarization loss. For the reference antenna (which produces a field intensity of 300 mv/m at 1 km) and a 200 km communication link, the losses when K = 0 are represented by the loss in field strength due to traveling the additional 199 km plus 3 db. The geometric length of the sky wave path for a 200 km communication link with 1-hop E propagation is approximately 295 km. The sky wave path length is a function of the height of the ionic layer and is determined as shown in figure 11-7 for short transmission paths. For a two-hop path, 4 db attenuation must be added due to the ground reflection. The median

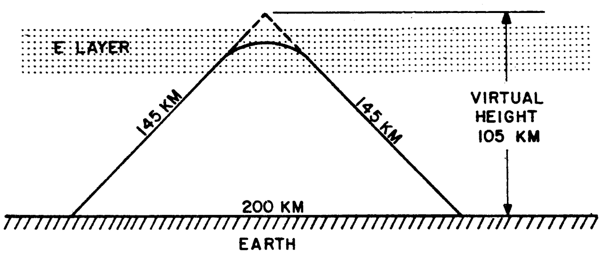


Figure 11-7. Geometric Length of 1-Hop E Layer Sky Wave Propagation Path; Length Equals 190 Km

incident sky wave field intensity curves included in this chapter are based on an E layer virtual height of 105 km and an F_2 layer virtual height of 320 km.

(6) NOISE

A satisfactory communication system exists only when the received signal level is sufficient to override the noise level at the output of the receiving system. This implies that there is a minimum required field intensity for satisfactory communication. This minimum required field intensity is dependent upon the receiving antenna, the receiver bandwidth, the quality of the service required, the type of modulation, the noise produced within the receiver, and the level of noise at the receiving location. The noise which must be overcome by the field intensity is of two types, random noise and impulse noise, and is from two sources, the atmosphere and the receiver. Random noise may be generated from distant thunderstorms, resistive components and tubes in the receiver, and from the cosmic noise of interstellar space. (Little is known of cosmic noise, but it is seldom a limiting factor for communication below 30 mc.) Although random noise is irregular, its average level can be measured, and it exhibits a characteristic average power distribution which is constant over the frequency spectrum. Impulse noise may be generated by ignition systems and local thunderstorms, and it is characterized by discrete, well-separated noise pulses having certain phase relationships.

Atmospheric noise is attributed to world-wide effects of thunderstorm activity. Atmospheric noise is highest in the equatorial regions, where thunderstorms are most frequent, and varies seasonally at the higher latitudes, being highest in the summer months. Atmospheric noise is also higher overland than oversea, because thunderstorms are more frequent overland. Thunderstorm activity also shows diurnal variations, being more frequent between 1200 and 1700 local time, which produces diurnal atmospheric noise conditions. Storms which are at a distance from the receiving station produce random noise while local storms produce impulse noise. Prediction of the impulse noise from local storms is not feasible, but prediction of the random noise from distant storms is feasible. This chapter includes world noise distribution charts from which can be obtained the noise grade for any receiving site. Minimum required incident field intensity curves for overcoming atmospheric noise are also provided. By using the curve for the proper noise grade, proper season, and proper local time, the field intensity required to overcome atmospheric noise can be determined.

Receiver system noise consists of antenna noise, thermal noise in the antenna circuit, tube noise, and thermal noise in the input circuit. If a receiver were perfect, the only noise in the receiver output would be as a result of the thermal noise in the antenna circuit and a maximum signal-to-noise ratio would result, as explained in paragraph 2a, chapter 3. A measure of the receiver system noise is a ratio of actual output noise power to the noise power that would result from the antenna thermal noise only. This ratio is called the noise figure of the receiver and may be expressed in terms of signal-to-noise ratios as follows:

$$NF = \frac{S/N \text{ of ideal receiver}}{S/N \text{ of actual receiver}}$$

where S/N is the ratio of signal power to noise power or signal voltage squared to noise voltage squared

Since the signal power is the same in both the numerator and denominator, the above equation can be reduced to the following equation:

$$NF = \frac{\text{actual noise power}}{\text{ideal noise power}}$$

or

actual noise power = NF x ideal noise power

or

actual noise voltage squared = NF x ideal noise voltage squared

By substituting a value given in physical parameters for the ideal noise voltage, the equation for actual noise can be expressed as follows:

$$V_n^2 = NF \times KTB$$

where V_n^2 is the actual noise voltage squared
NF is the noise figure
K is Boltzmann's constant, 1.38×10^{-23}
T is the absolute temperature
B is the bandwidth in cycles per second

Where the receiver input circuit matches the antenna resistance, a theoretical noise figure of 2 is possible. Expressed in decibels, this is equivalent to 3 db. In practice, noise figures of up to 7 db are acceptable. This chapter includes curves showing minimum required field intensities in the presence of set noise. By using the curve for the proper antenna and proper vertical angle of wave arrival, the field intensity required to overcome set noise can be determined.

Set noise and atmospheric noise are not additive since they are both random noise. Therefore, if the field intensity required to overcome set noise is greater than the field intensity required to overcome atmospheric noise, the field intensity required to overcome set noise will also overcome atmospheric noise. Conversely, if the field intensity required to overcome atmospheric noise is greater than the field intensity required to overcome set noise, the field intensity required to overcome atmospheric noise will also overcome set noise. That is, the greater of the two field intensities will overcome both atmospheric and set noise.

(7) SERVICE GAIN

A service gain factor is required to compensate for the generalizations made to obtain the atmospheric noise curves and the set noise curves. These curves are determined on the basis of a double sideband, speech-grade radiotelephony service, 6-kc bandwidth, 100 per cent modulation, during 90 per cent of the days. The curves are also based on a required S/N ratio of 13.8 db to obtain 90 per cent intelligibility. For types of service other than this standard, the field intensity required to overcome noise will be different. Service gain tables for both sky wave and ground wave propagation are included in this chapter. In the table of service gains for sky wave propagation, the standard double sideband radiotelephony signal indicates a service gain of 8 db. This is a result of compensating for fading signals and means that the received field intensity must be increased 8 db to compensate for rapid signal variations as shown in the rapid variation of sky wave field intensity curve, also included in this chapter.

d. LOWEST USEFUL HIGH FREQUENCY

The lowest useful high frequency, LUHF, (sometimes LUF for lowest useful frequency) is the lower limiting frequency which will provide satisfactory communication for a given link. The LUHF is the frequency at which the received field intensity just equals the required field intensity for reception. The received field intensity depends on the antennas, path length, and absorption, and it generally increases with frequency. The required field intensity for reception depends on noise limitations, and it decreases with frequency. Therefore, by comparing the received median field intensity at various frequencies with the required field intensity for the same frequencies, the LUHF can be determined. To determine the LUHF, it must be kept in mind that the required field intensity must be adjusted for service gain.

e. MAXIMUM USABLE FREQUENCY

The maximum usable frequency, MUF, is the upper limiting frequency at which a communication circuit may be operated. The MUF, as determined from available ionospheric predictions, is actually a monthly median of the highest usable daily frequencies for a particular sky wave path at a particular hour of the day. The geographic location of reflection points, the time of day, season, and sunspot number all affect the MUF. The MUF for path lengths less than 4000 km is determined by the ionospheric conditions at the midpoint of the path. It is taken as the highest of the three maximum frequencies which will be reflected from the E layer, sporadic E layer, or F_2 layer. The charts of median zero MUF and median 4000 MUF predicted for the proper month, included in this chapter, are used to determine the MUF for a given communication link.

The MUF represents the median maximum usable frequency. That is, 50 per cent of the days the actual maximum usable frequency will be less than the median MUF, and 50 per cent of the days the actual maximum usable frequency will be greater than the median MUF. For this reason, it is desirable to operate at a frequency which is slightly less than the median MUF to increase communication reliability to 90 per cent. Where F_2 propagation is used, this frequency of optimum traffic, FOT, (sometimes OWF for optimum working frequency) is taken as 85 per cent of the MUF. Where E and F_1 propagation is used, the FOT is taken as the MUF for E propagation, because the MUF variation from day to day is so small.

f. LOWEST EFFECTIVE POWER

The effective radiated power in kilowatts is the product of the antenna input power in kilowatts and the antenna gain, with respect to a short dipole reference antenna. The lowest effective power, LEP, is the minimum transmitted antenna power required to give satisfactory communication at a particular frequency. The difference between the received field intensity, determined in decibels with respect to the reference antenna radiation (300 mv/m at 1 km), and the field intensity required for reception, determines the LEP.

7. GROUND WAVE PROPAGATION

Ground wave propagation is propagation of r-f energy along the curved surface of the earth, without using the earth's ionosphere. Where a ground wave is transmitted beyond the line of sight, the conductivity of the earth's surface acts as a wave guide and bends the wave around the curved surface. Since fading is due primarily to ionospheric fluctuations, there is no fading associated with ground wave propagation. However, the extremely high losses associated with ground wave propagation make it impractical for most long distance transmissions. The received field intensity of a ground wave depends upon the type of terrain over the transmission path, the transmitting and receiving antennas, the power output, frequency, and antenna heights.

Only vertical polarization, such as is obtained from vertical and whip antennas, is practical for ground wave propagation. Horizontal polarization results in extremely high losses due to a short circuiting effect of the earth. Even with vertical polarization, the received field intensity of a ground wave is far below that of the direct, free-space field. The antenna height also affects ground wave propagation. However, where the antenna is considered to be at ground level, which is usually the case aboard ship, the antenna-height gain factor is neglected.

The terrain over the transmission path is an important consideration because it is the earth's surface which bends the ground wave, and it is the earth's surface which absorbs the r-f energy. For purposes of determining the received field intensity, the terrain is divided into three categories: (1) poor soil, (2) good soil, and (3) sea water. Because of the high conductivity over sea water, ground wave propagation over sea water for fairly long distances is very practical for frequencies below 30 mc. It is generally desirable to operate at the lower end of the high-frequency band because less attenuation is suffered. Graphs are included in this chapter which show ground wave field intensity versus distance for various frequencies and various types of terrain.

For line of sight transmissions, the received field intensity is composed of a direct wave and a ground-reflected wave. If the two received waves are in the vicinity of 180° out of phase, the received signal level will be very low. Conversely, if the two received waves are in phase, the received signal will be almost twice as strong as the signal resulting from the direct wave. Therefore, for line of sight transmissions, the received signal level varies from near zero to twice the signal resulting from the direct wave, depending upon the transmission path length.

8. CHARTS AND GRAPHS

The following charts and graphs are included because they are typical of the information necessary to solve a propagation problem. However, the ones included do not make a complete set. Some of the charts and graphs are used in the example problem which follows. The charts and graphs which are included are as follows:

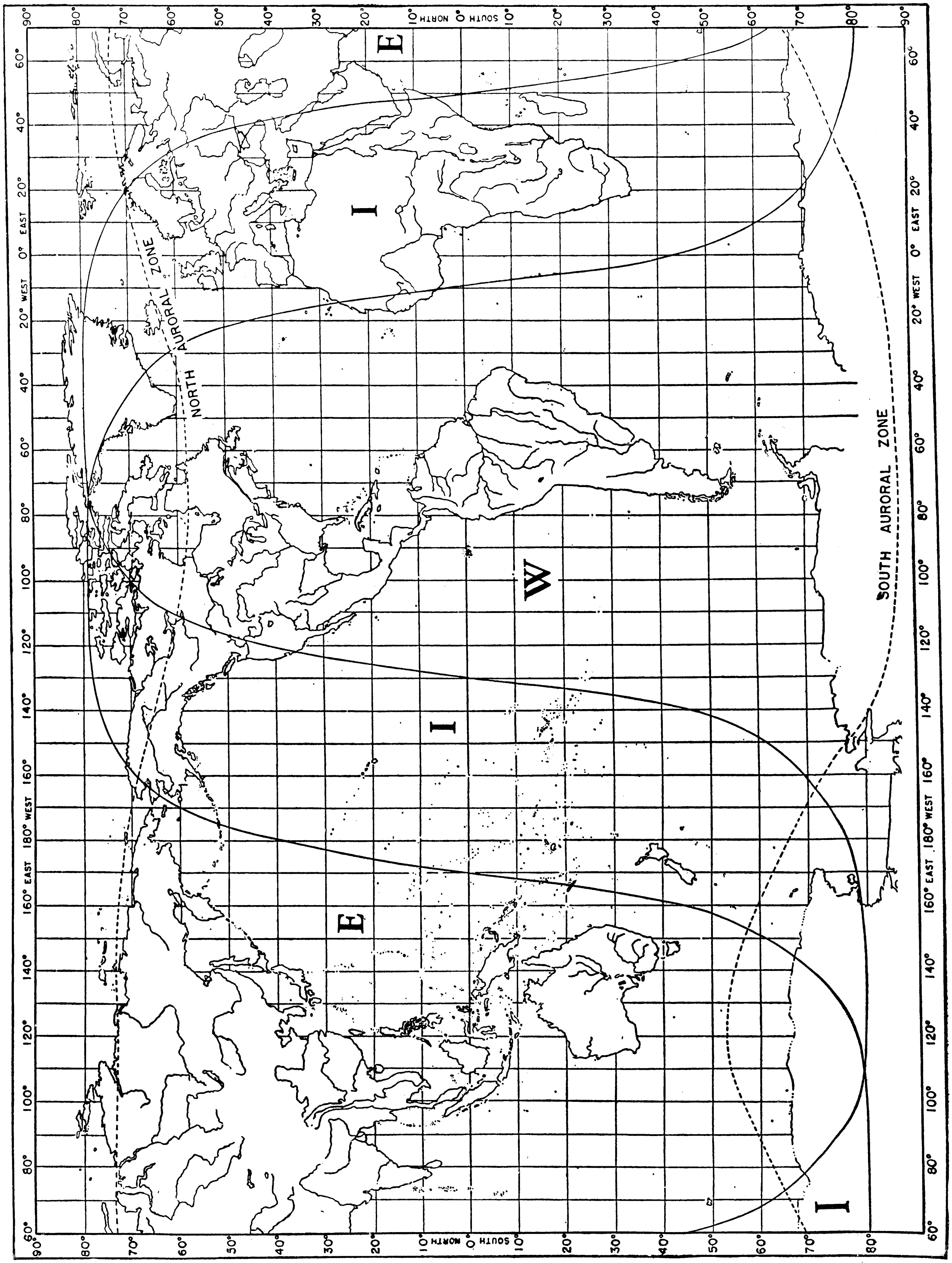


Figure 11-8. World Map Showing Zones Covered by Predicted Charts, and Auroral Zones

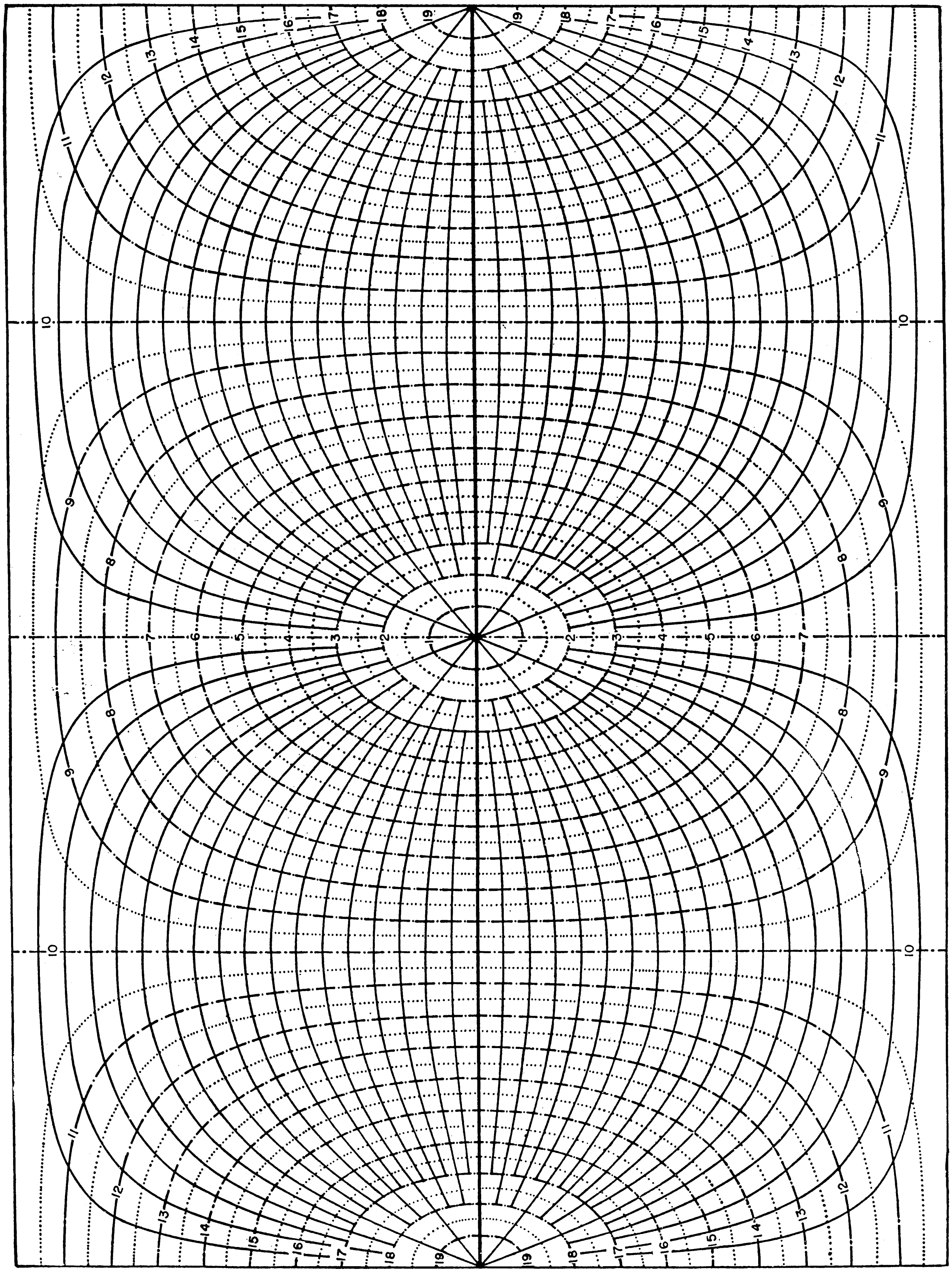


Figure 11-9. Great Circle Chart Centered on Equator; Solid Lines Represent Great Circles; Numbered Dot-Dash Lines Indicate Distances in Thousands of Kilometers

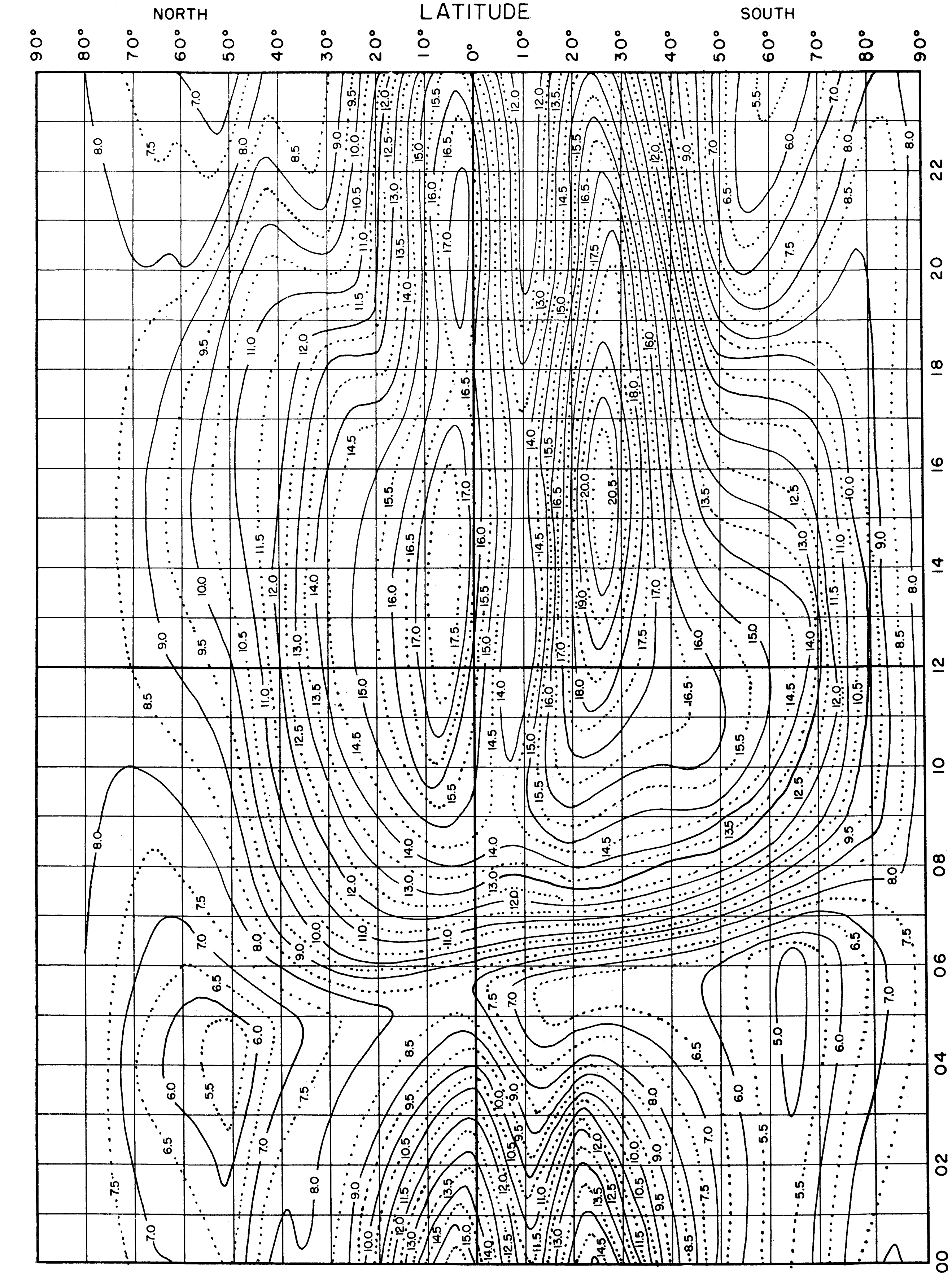


Figure 11-10. Median F_2-Zero-MUF, in Mc, W Zone, Predicted for April 1957

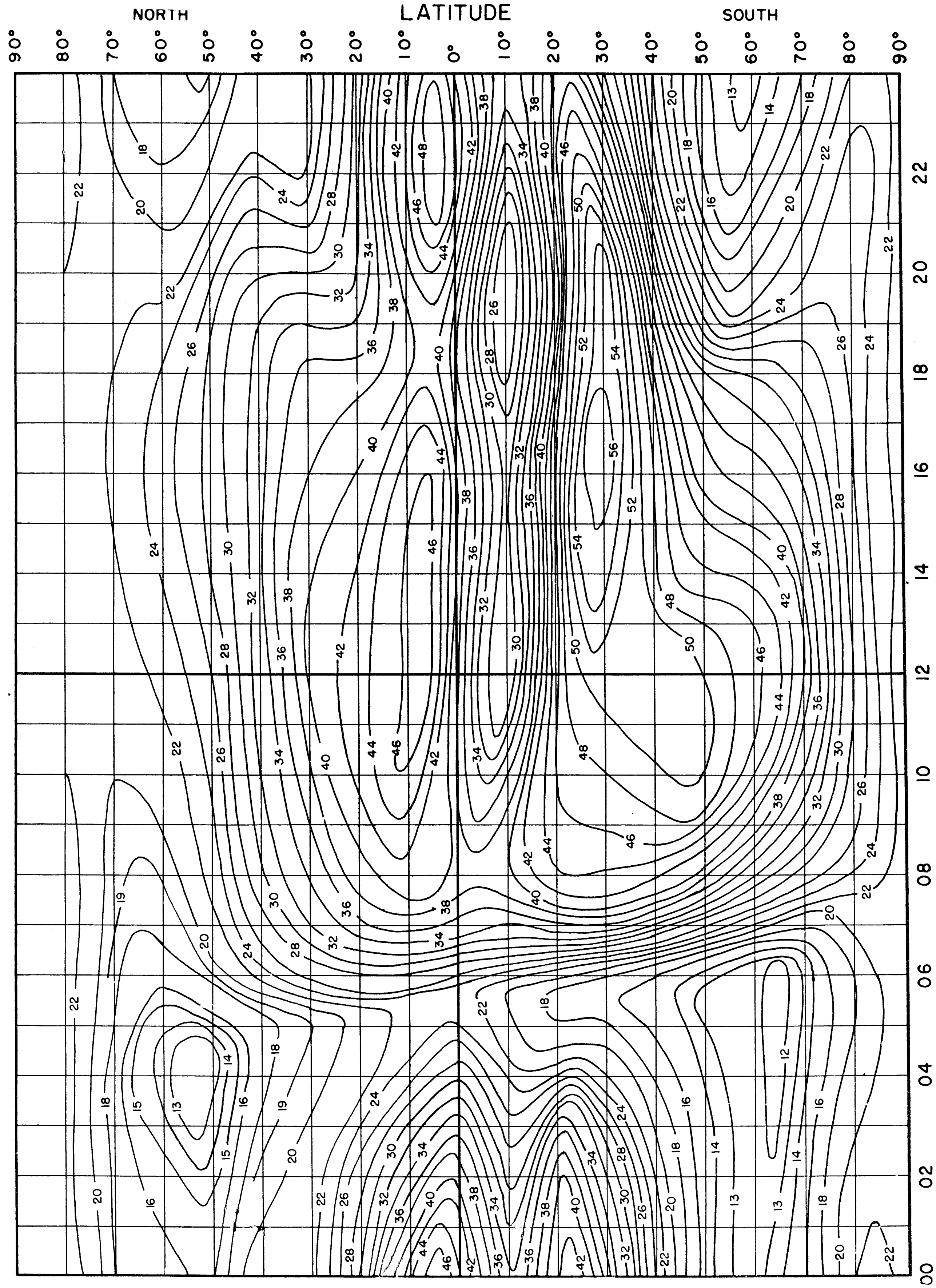


Figure 11-11. Median F_2-4000-MUF, in Mc, W Zone, Predicted for April 1957

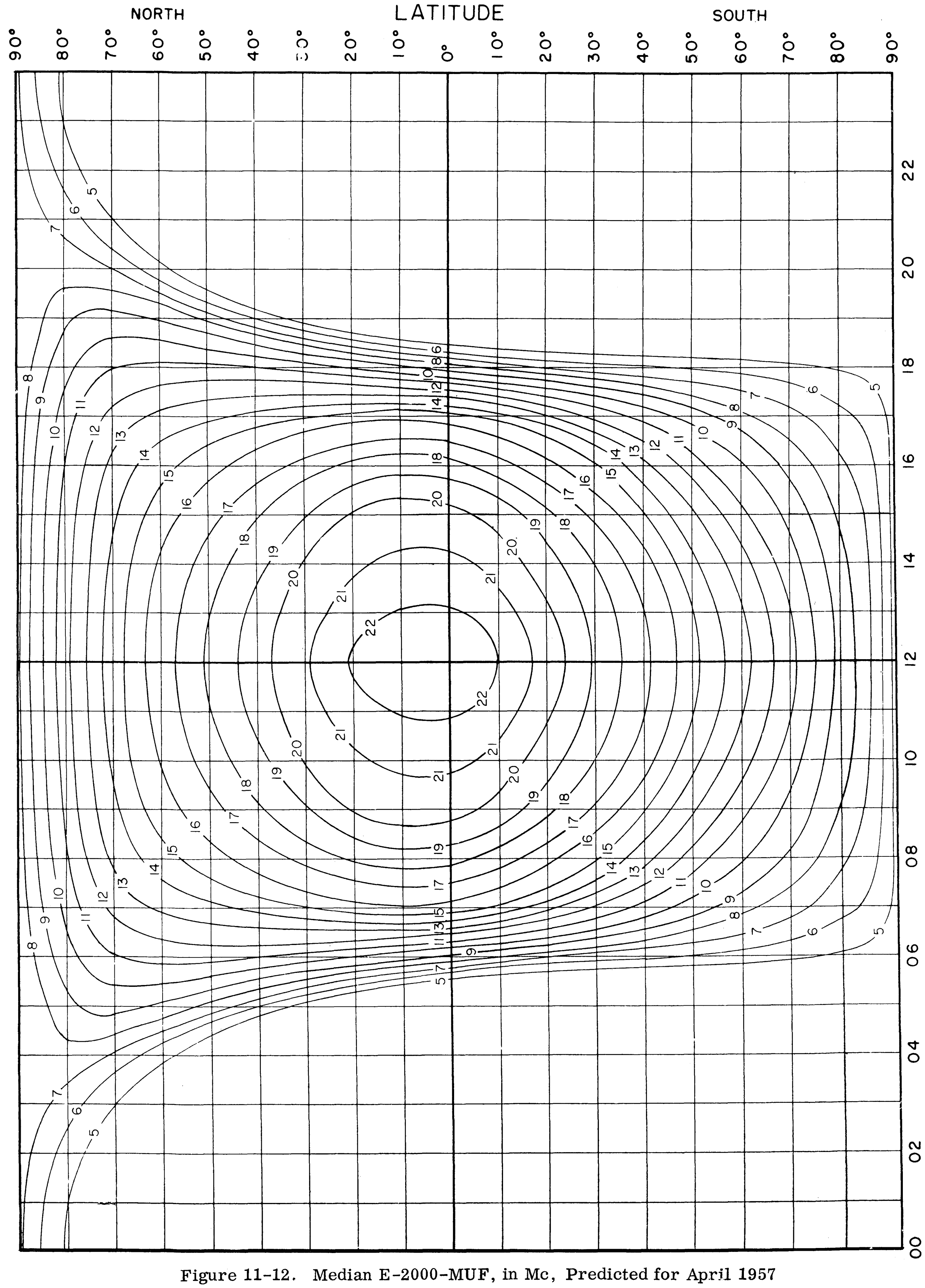


Figure 11-12. Median E-2000-MUF, in Mc, Predicted for April 1957

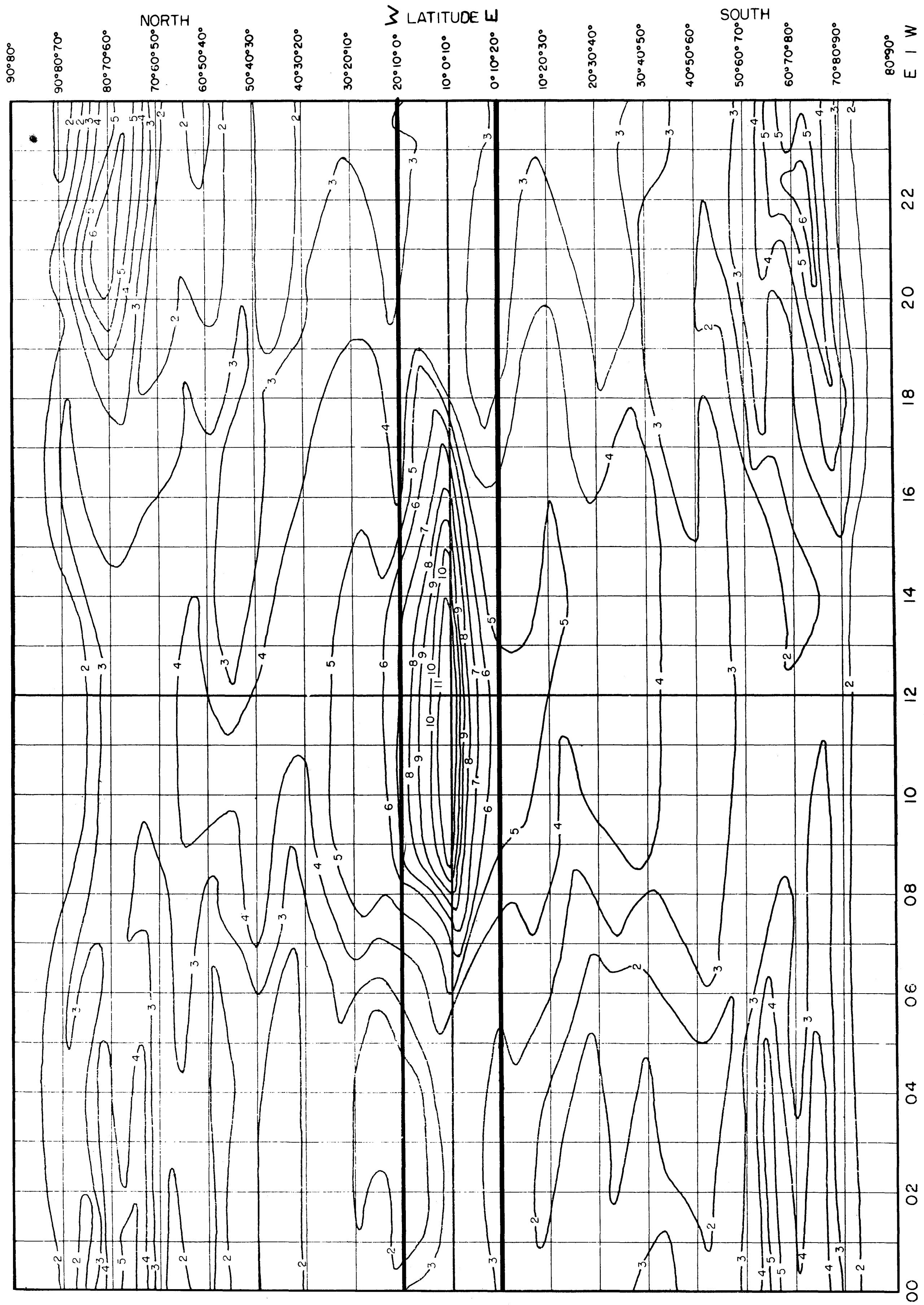


Figure 11-13. Median fE_s, in Mc, Predicted for April 1957

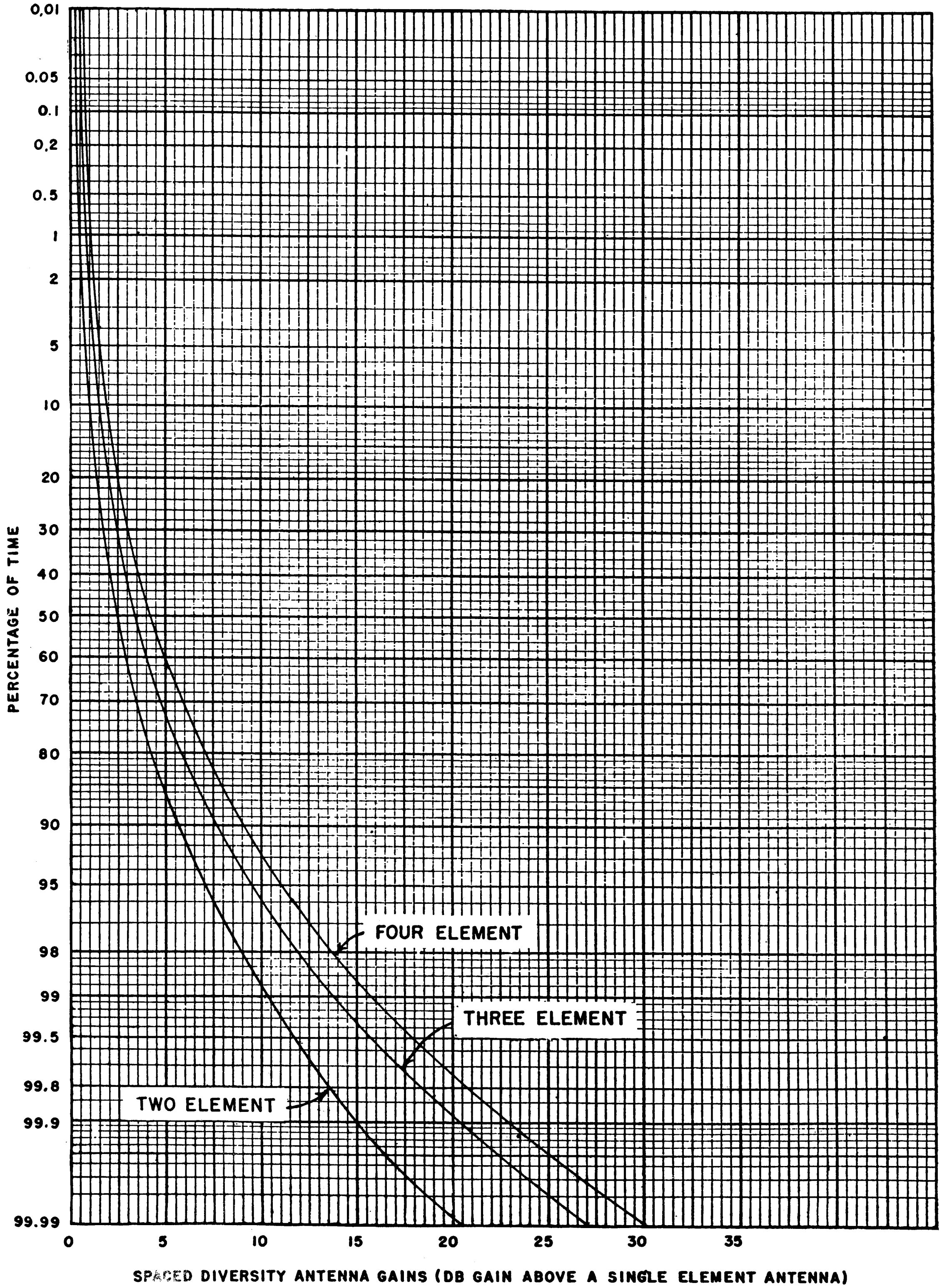


Figure 11-14. Gains of Spaced Diversity Receiving Antennas for Rapidly Fading Signals

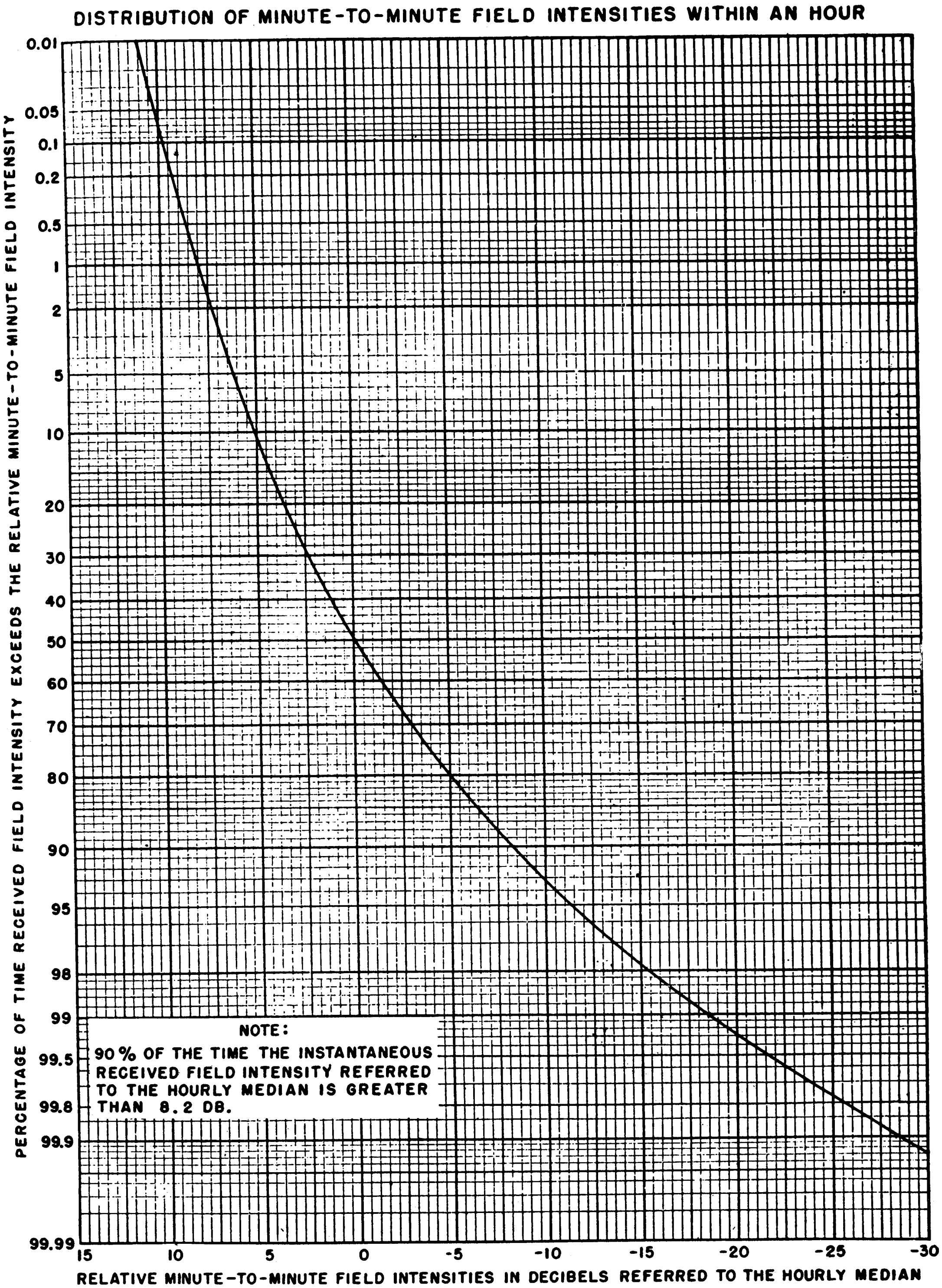


Figure 11-15. Rapid Variation of Sky Wave Field Intensity

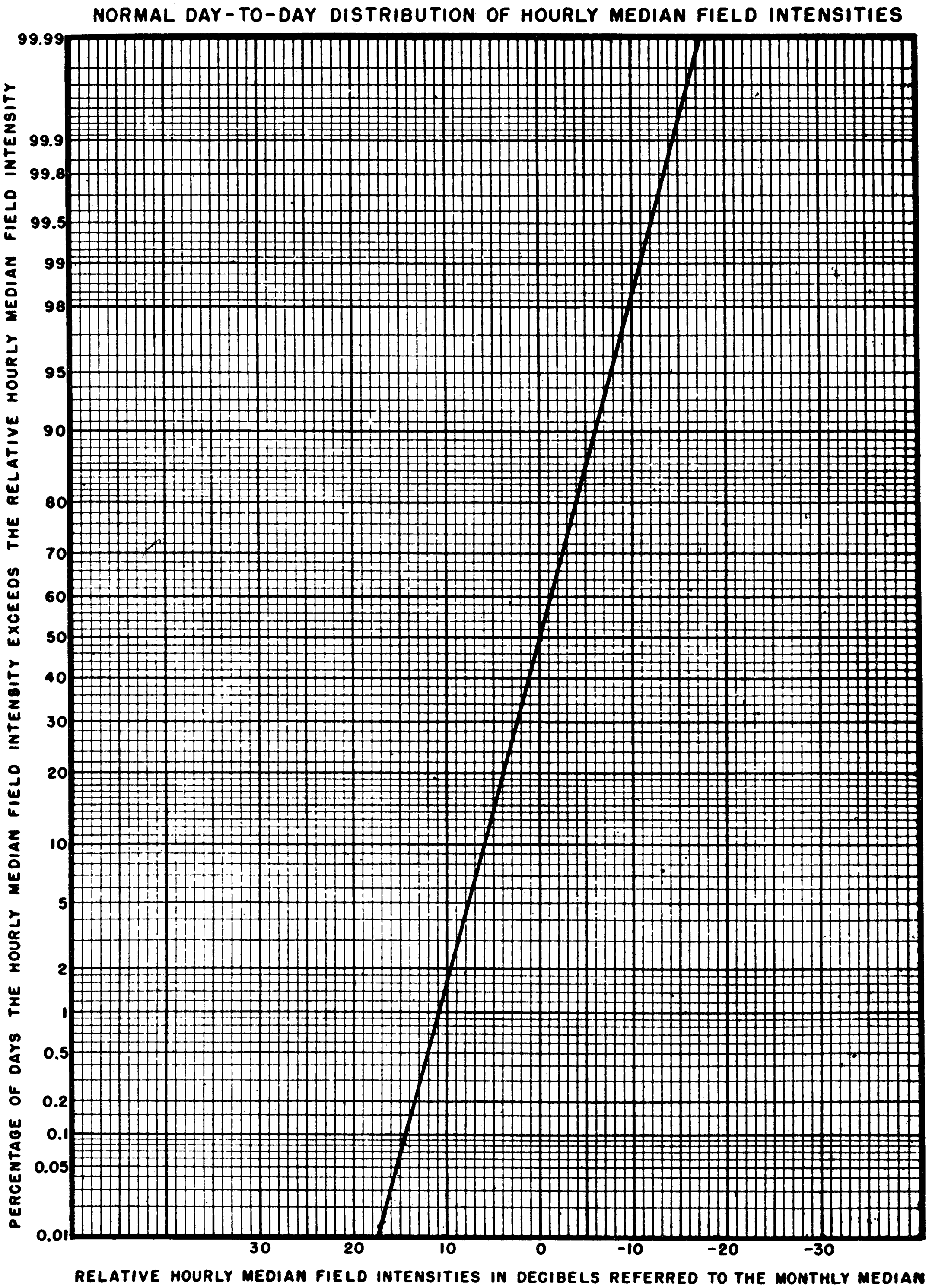


Figure 11-16. Slow Variation of Sky Wave Intensity

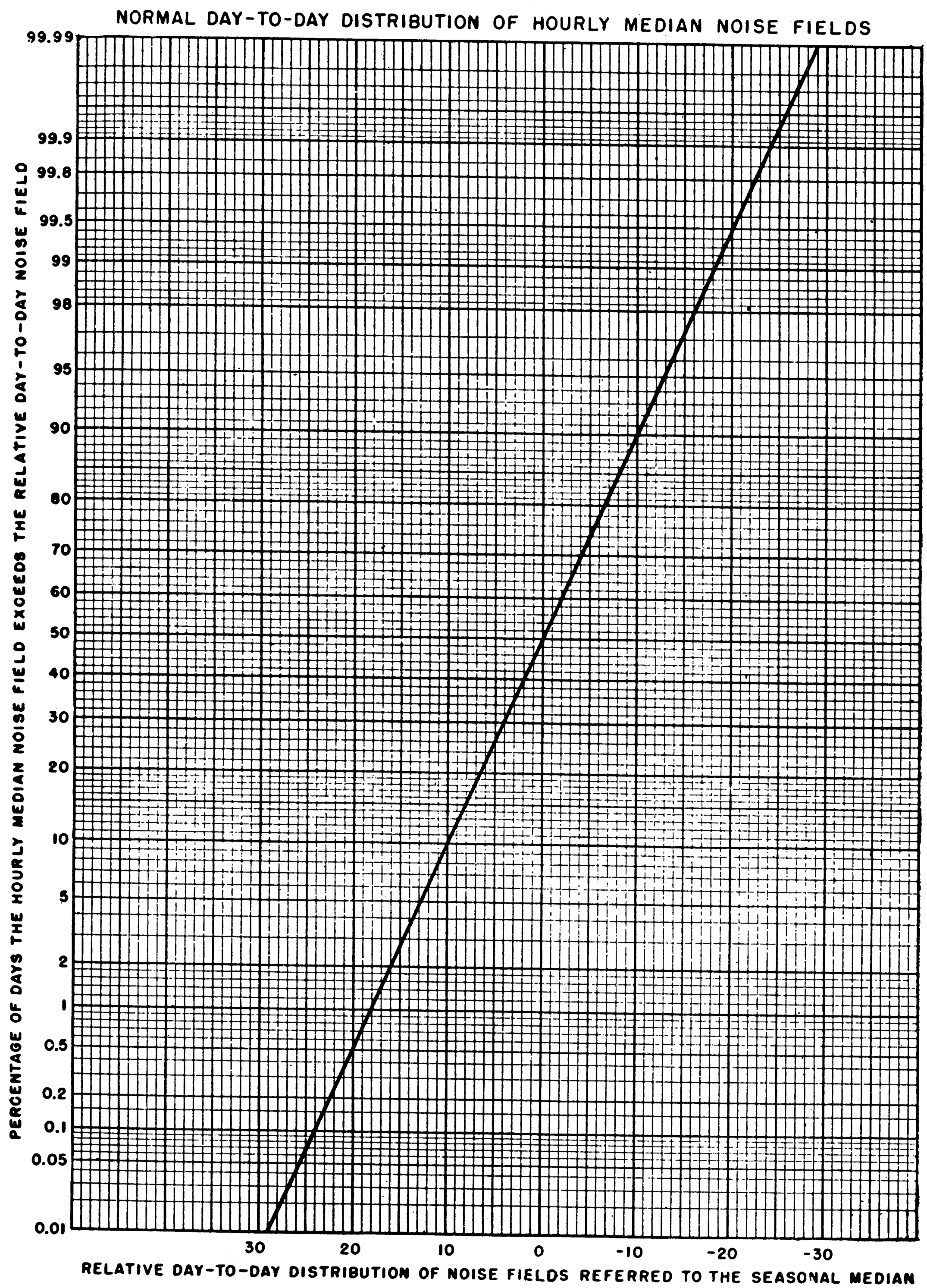


Figure 11-17. Slow Variation of Atmospheric Noise

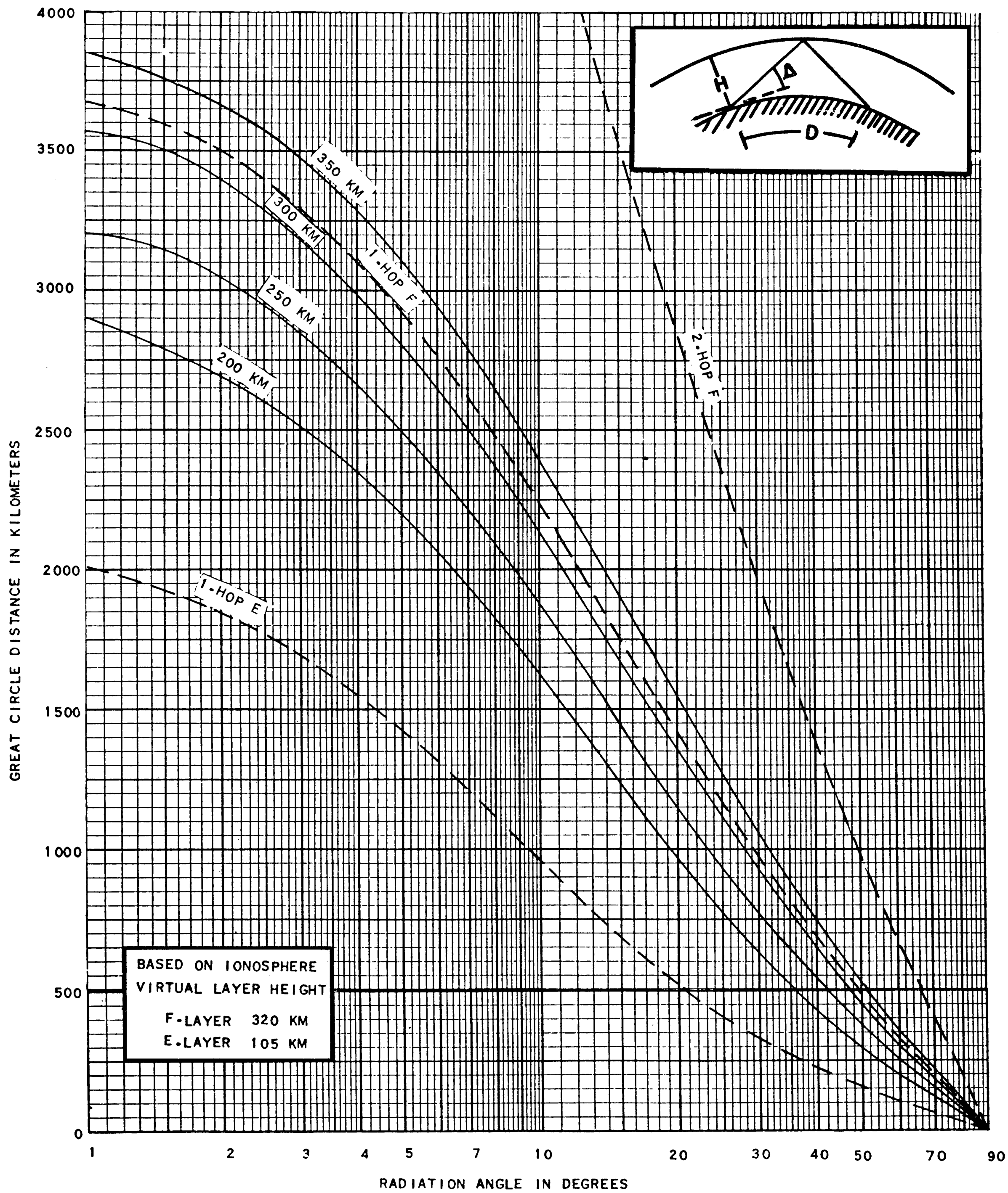


Figure 11-18. Radiation Angle Versus Great Circle Distance Curves

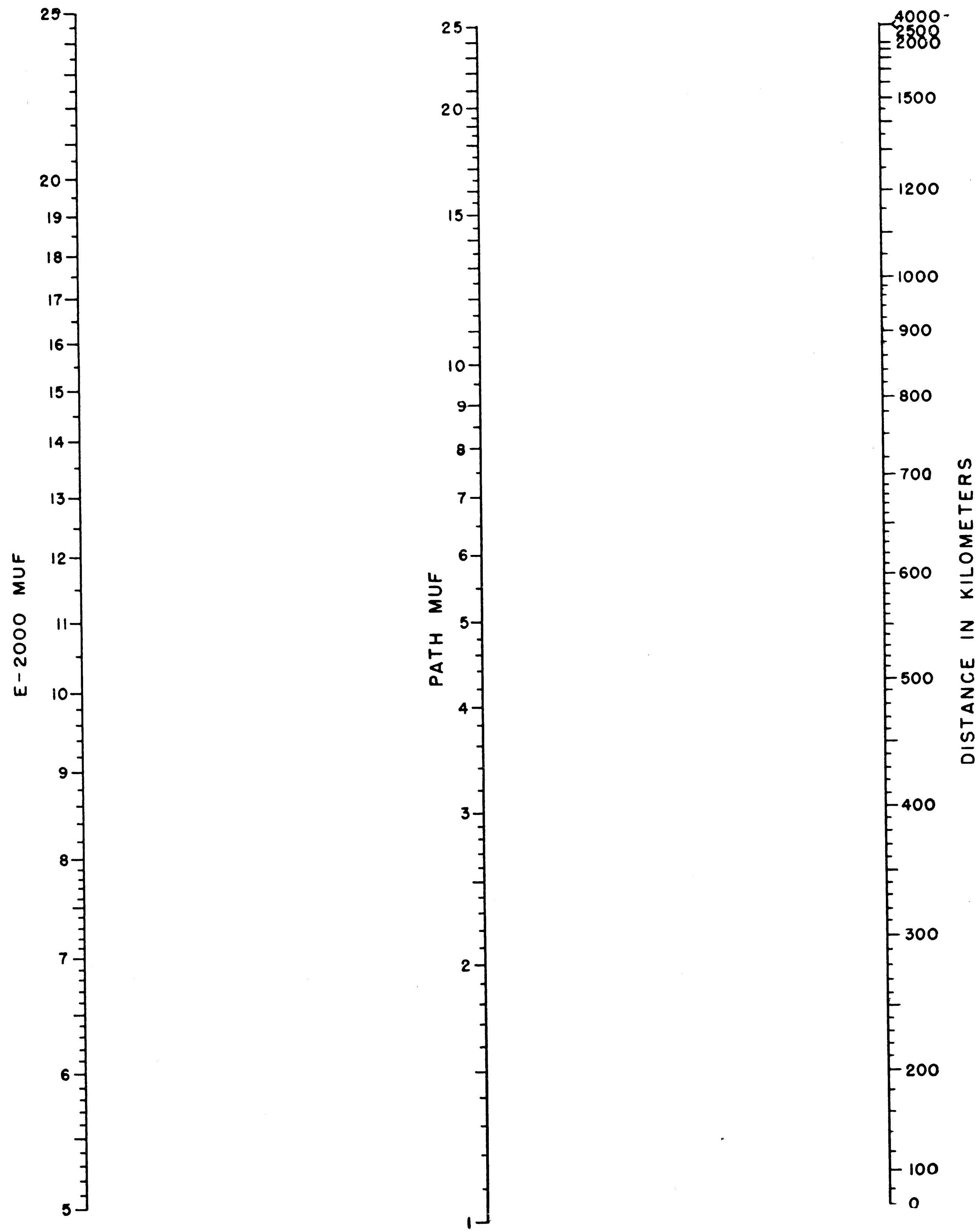


Figure 11-19. Nomogram for Transforming E-2000 MUF to Equivalent MUF's and Optimum Working Frequencies Due to Combined Effect of E Layer and F_1 Layer at Other Transmission Distances

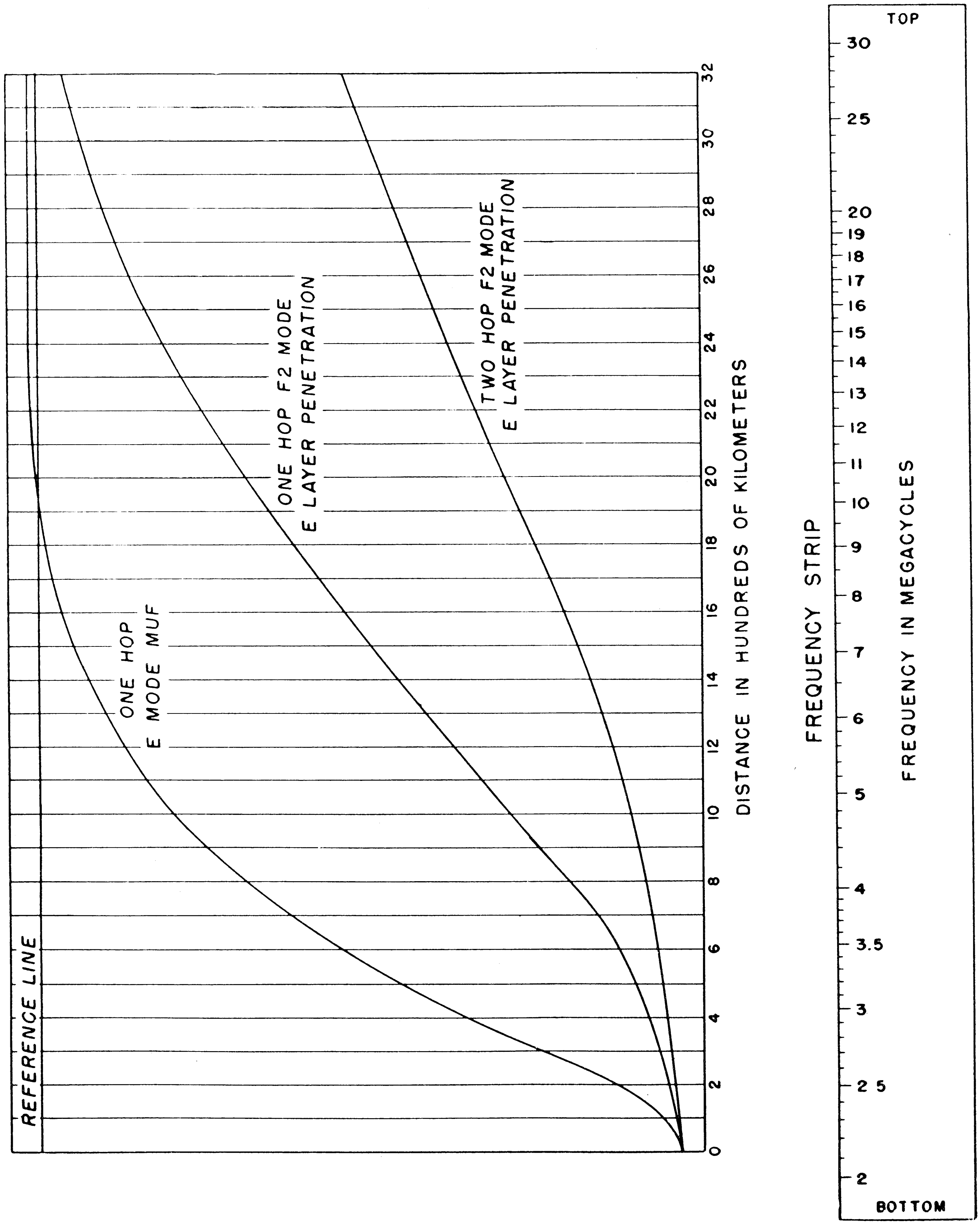


Figure 11-20. E Layer MUF and Penetration Nomogram

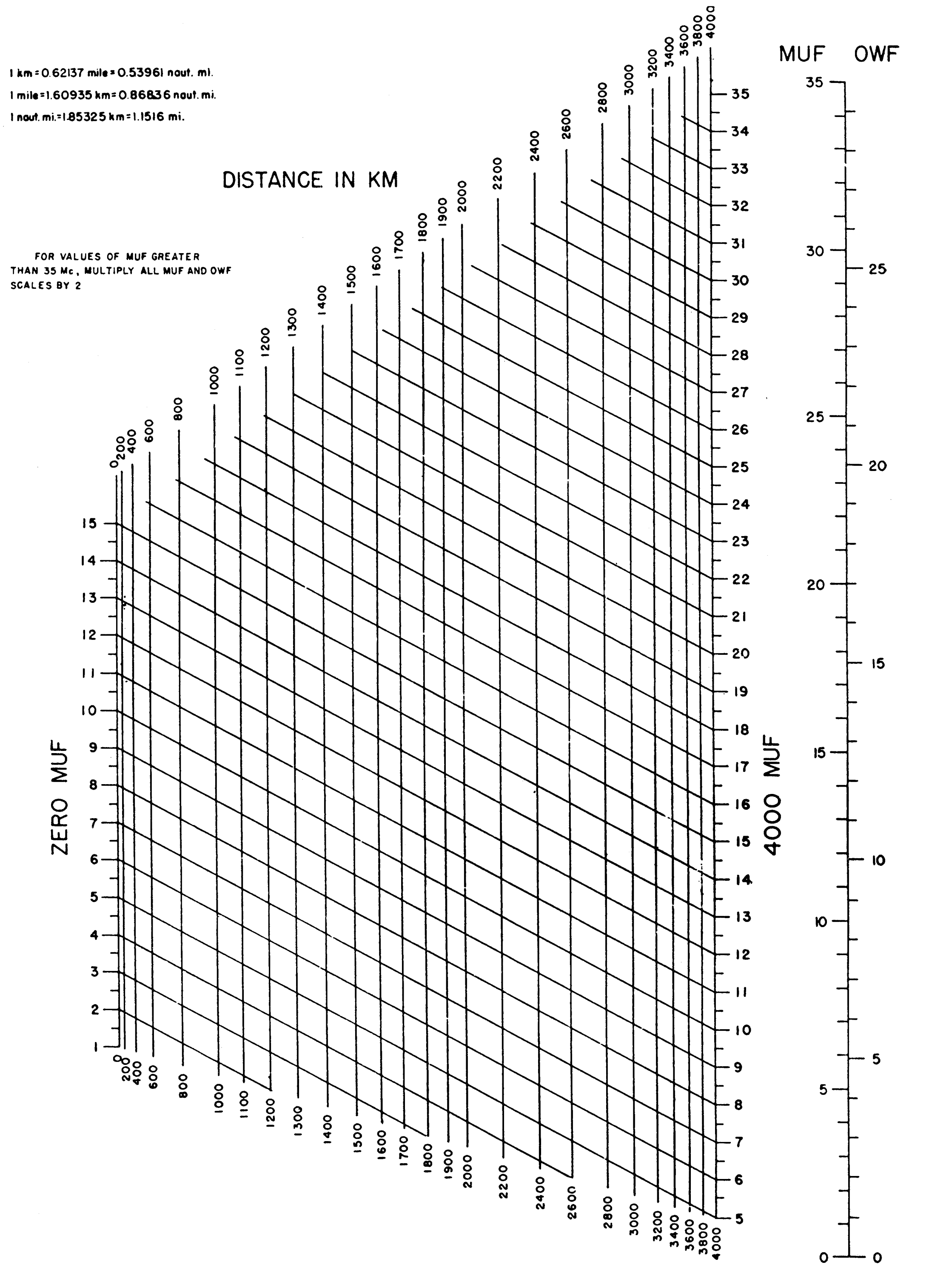


Figure 11-21. Nomogram from Transforming F_2 ZERO MUF and F_2 4001 MUF to Equivalent MUF's at Intermediate Transmission Distances; Conversion Scale for Obtaining Optimum Working Frequencies

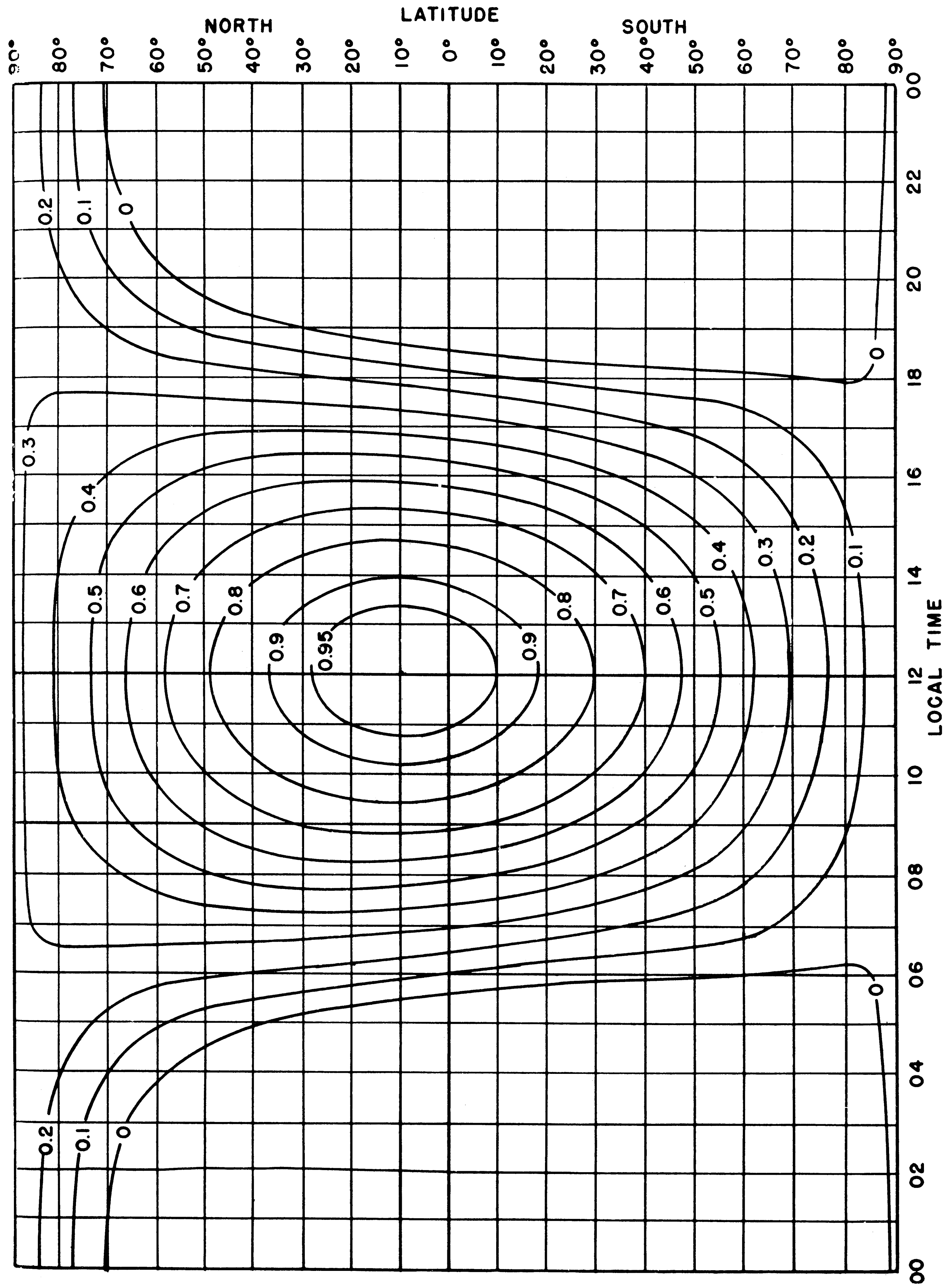


Figure 11-22. Absorption Index Chart (Excluding Auroral Absorption) for April

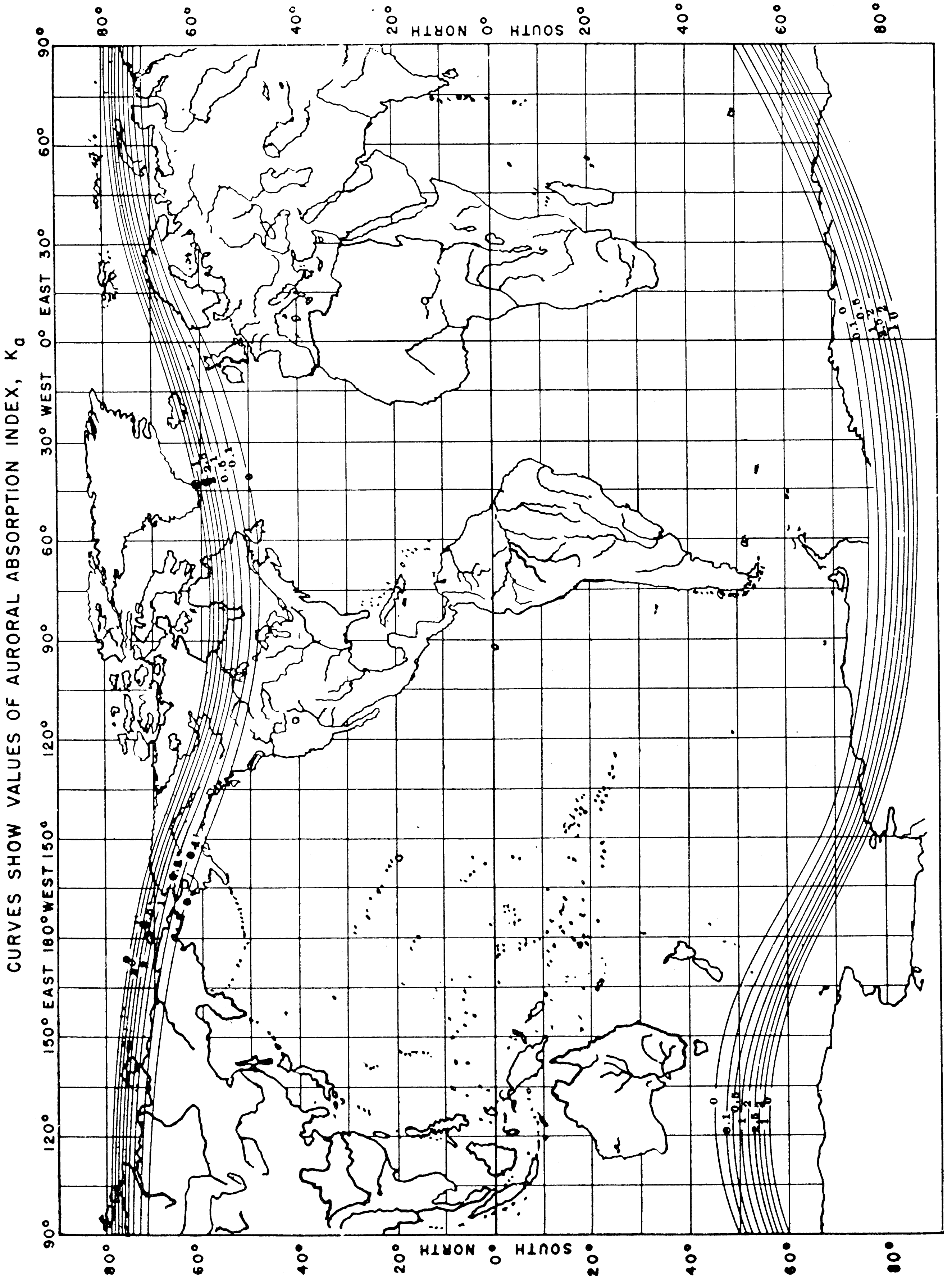


Figure 11-23. Auroral Absorption Chart

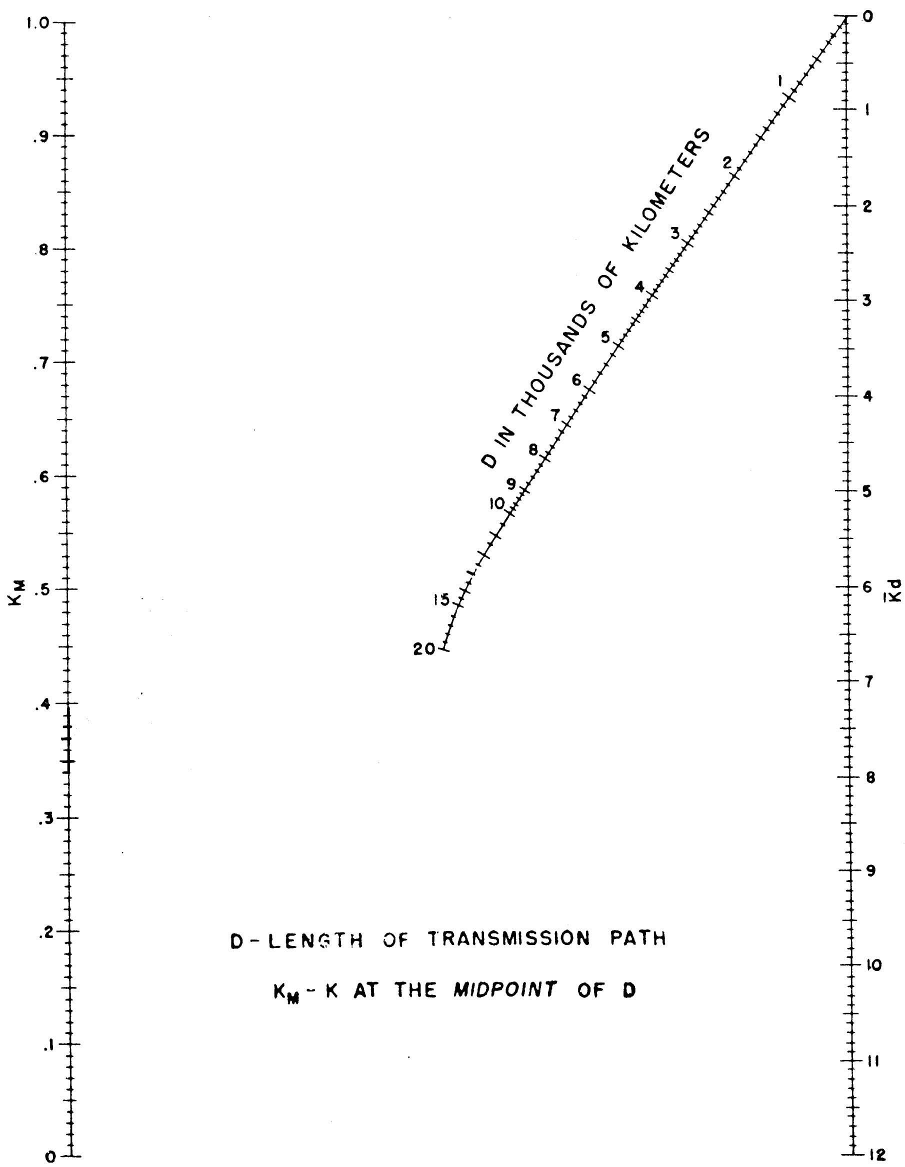
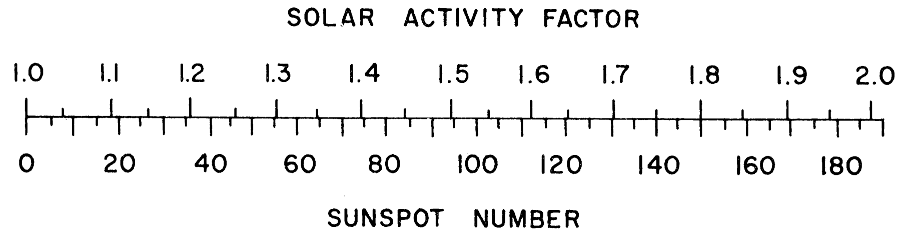


Figure 11-24. K_d Nomogram, Transmission Path Entirely in the Day Region



The solar activity factor is obtained from the predicted twelve month running average sun spot number. Predictions of this sun spot number are made three months in advance. The solar activity factor must be multiplied by the seasonal correction factor shown below to obtain the K or Kd correction factor.

SEASONAL CORRECTION FACTORS

MONTH	BOTH TERMINALS		ONE TERMINAL N. LAT AND OTHER S. LAT
	N. LAT	S. LAT	
Jan	0.9	0.7	0.8
Feb	0.9	0.7	0.8
Mar	0.8	0.8	0.8
Apr	0.8	0.8	0.8
May	0.7	0.9	0.8
Jun	0.7	0.9	0.8
Jul	0.7	0.9	0.8
Aug	0.7	0.9	0.8
Sep	0.8	0.8	0.8
Oct	0.8	0.8	0.8
Nov	0.9	0.7	0.8
Dec	0.9	0.7	0.8

Figure 11-25. K or K_d Correction Factors

Type of Service	Conditions	Bandwidth	Signal Strength in Decibels Above Reference Level
Double sideband radiotelephony	Speech grade quality at 100% modulation. 90% of the hour	6 kilocycles	8
Double sideband radiotelephony	High quality commercial service. 90% of the hour	6 kilocycles	33
Standard broadcast	High quality service	10 kilocycles	27
Single sideband radiotelephony	Speech grade quality, carrier suppressed 10 db, 90% of the hour	3 kilocycles	-1
Single sideband radiotelephony single channel	High quality, carrier suppressed 10 db, 90% of the hour	3 kilocycles	24
Single sideband radiotelephony, 2 channel	High quality, carrier suppressed 25 db, 90% of the hour	3 kilocycles	26
Manual continuous wave radiotelegraphy	15 words per minute, 90% of the hour	2 kilocycles	-9
Modulated manual continuous wave radio-telegraphy	30 words per minute, 90% of the hour	2 kilocycles	-5
Machine speed radiotelegraphy	150 words per minute, 2 element spaced diversity, 99.9% of the hour	1.5 kilocycles	3
Modulated machine speed radiotelegraphy	150 words per minute, 2 element spaced diversity, 99.9% of the hour	3 kilocycles	6
Carrier shift radioteletypewriter	150 wpm, 524 cycles shift each side of carrier, 2 element spaced diversity, 99.9% of the hour	1.7 kilocycles	5
Carrier shift diplex radioteletypewriter	150 wpm, 425 cycles shift each side of carrier, 2 channels operating simultaneously, 2 element spaced diversity, 99.9% of the hour	1.7 kilocycles	3
Interrupted carrier radioteletypewriter	150 words per minute, 2 element spaced diversity, 99.9% of the hour	3 kilocycles	8
Single sideband multitone radioteletypewriter	Single channel operation, carrier reduced 25 db, 2 element spaced diversity, 99.9% of the hour	3 kilocycles	8
Frequency modulation broadcast service	Broadcast quality	150 kilocycles	2
Facsimile	AM. subcarrier modulated, 2 element spaced diversity, 99.9% of the hour	6 kilocycles	11

Figure 11-26. Table of Service Gains, Sky Wave Communications, Fading Signal

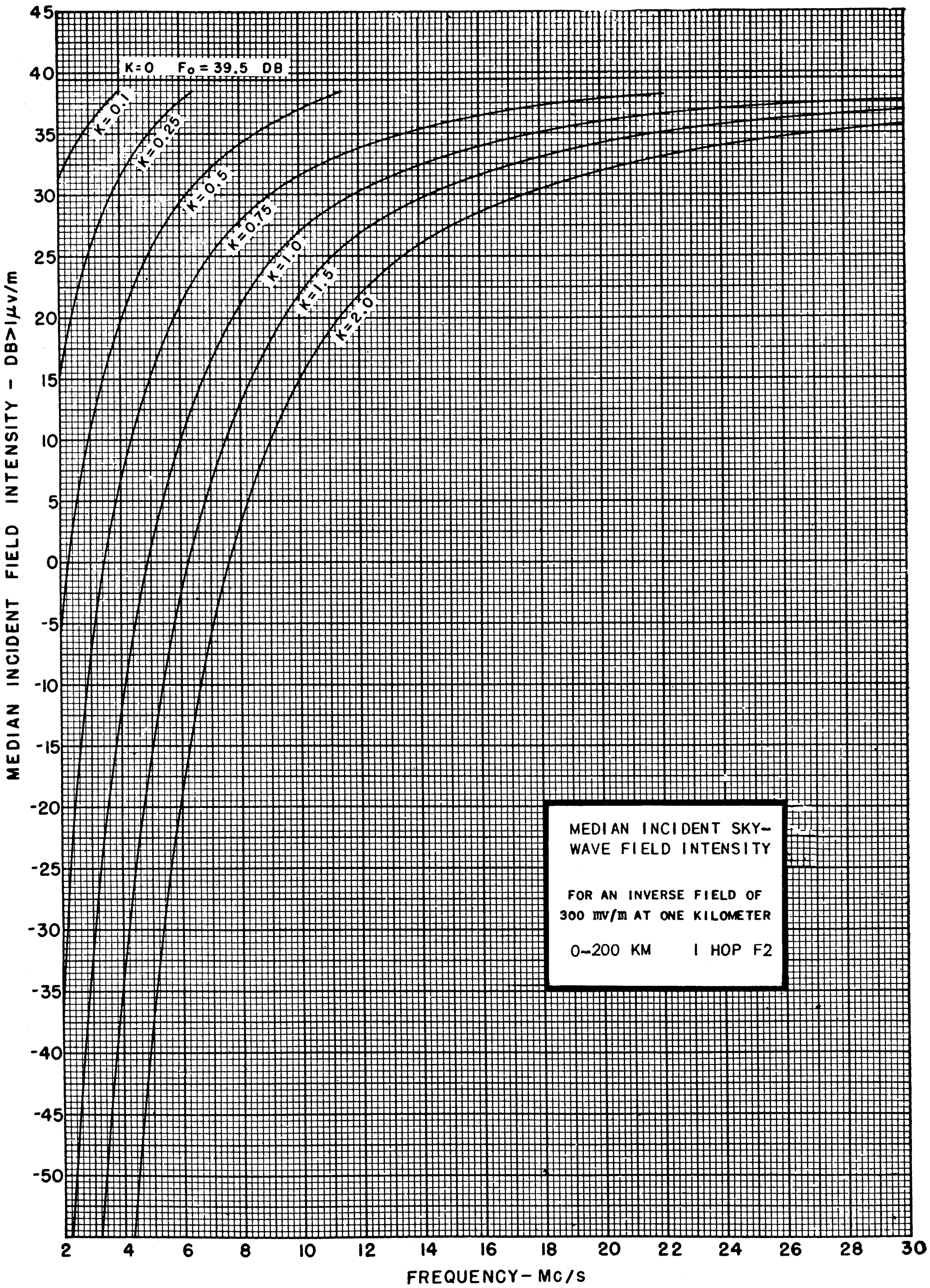


Figure 11-27. Median Incident Sky Wave Intensity, 0 to 200 km, 1-hop-F_2

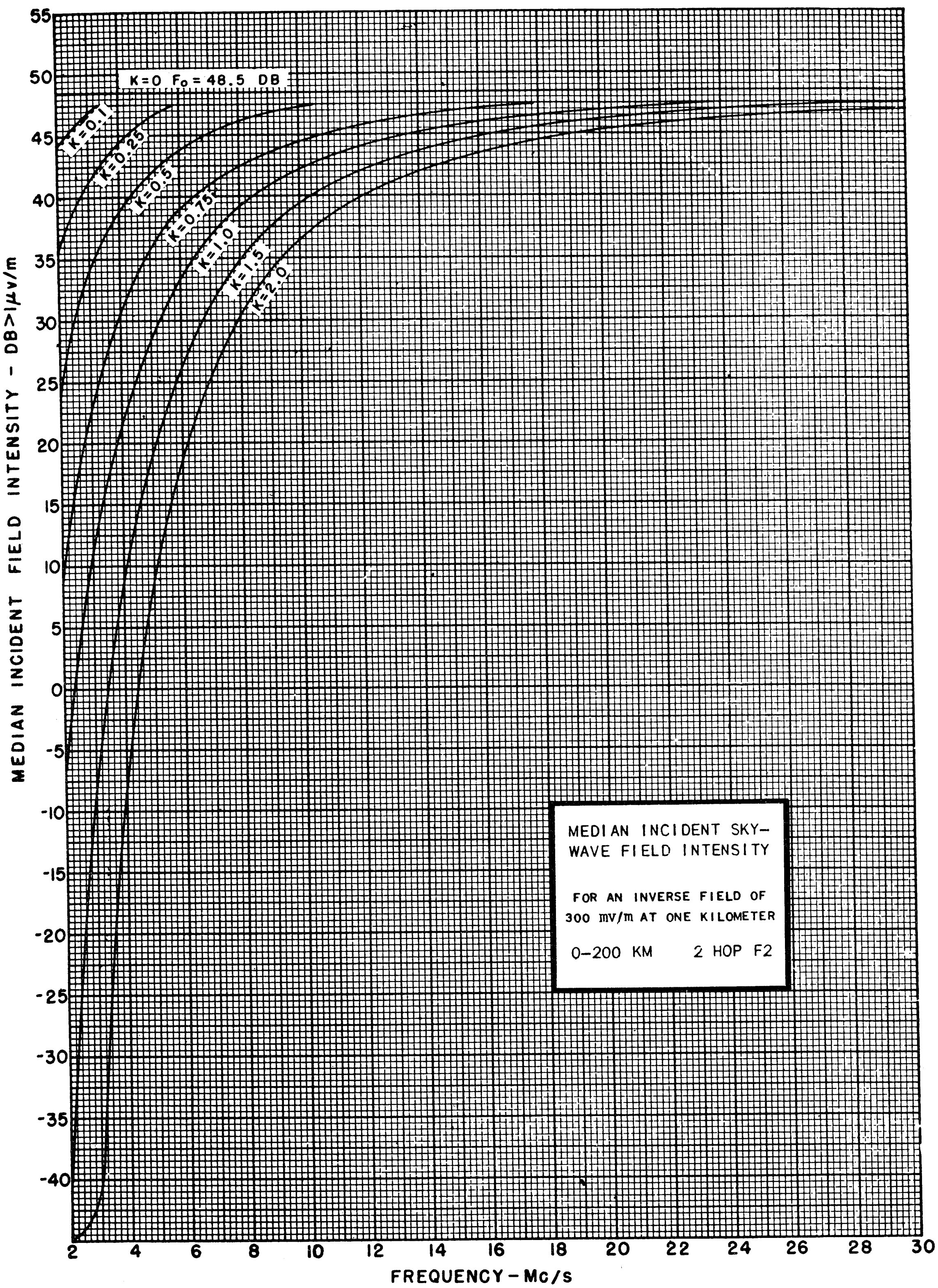


Figure 11-28. Median Incident Sky Wave Field Intensity, 0 to 200 km, 2-hop-F_2

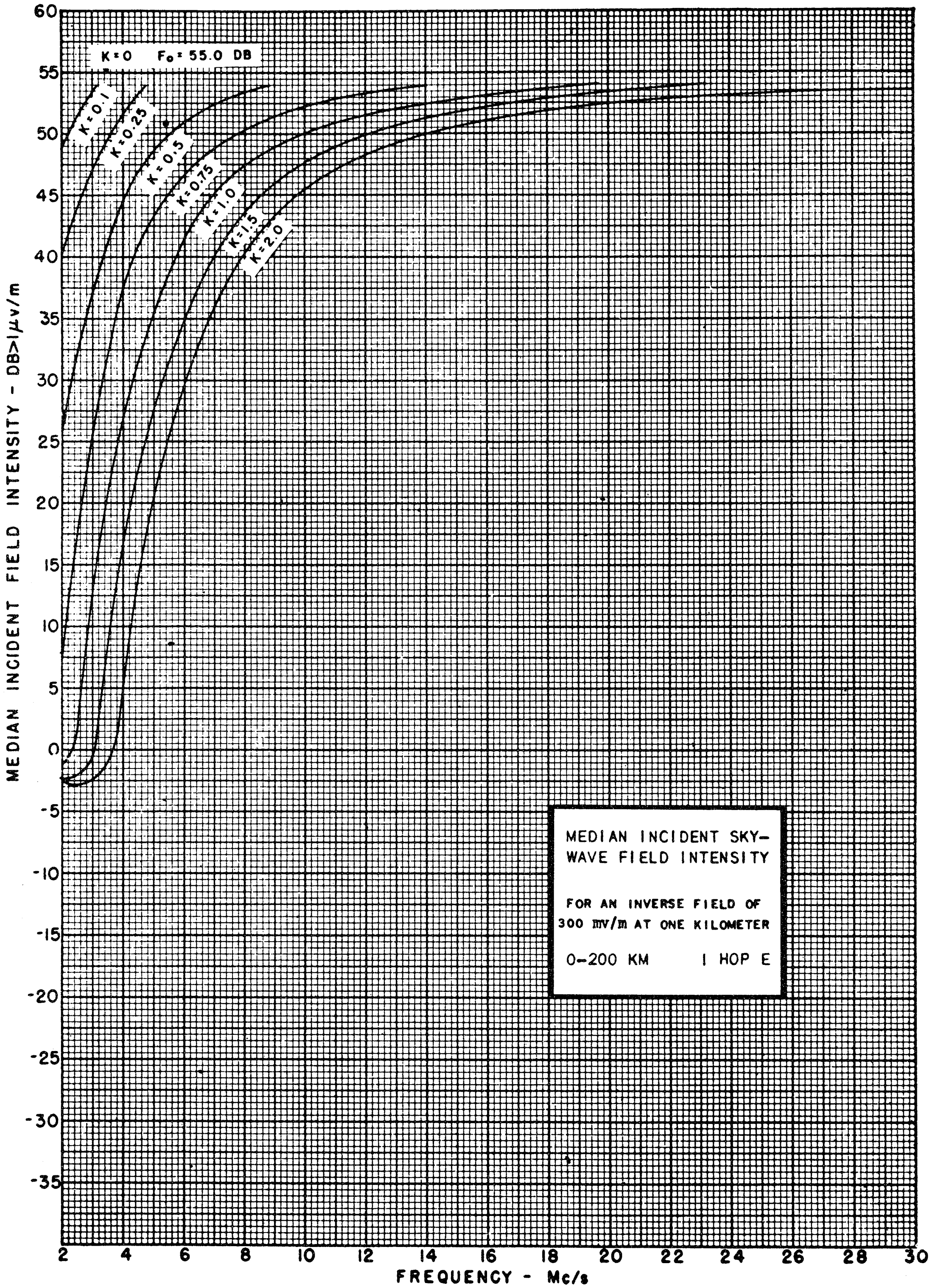


Figure 11-29. Median Incident Sky Wave Intensity, 0 to 200 km, 1-hop-E

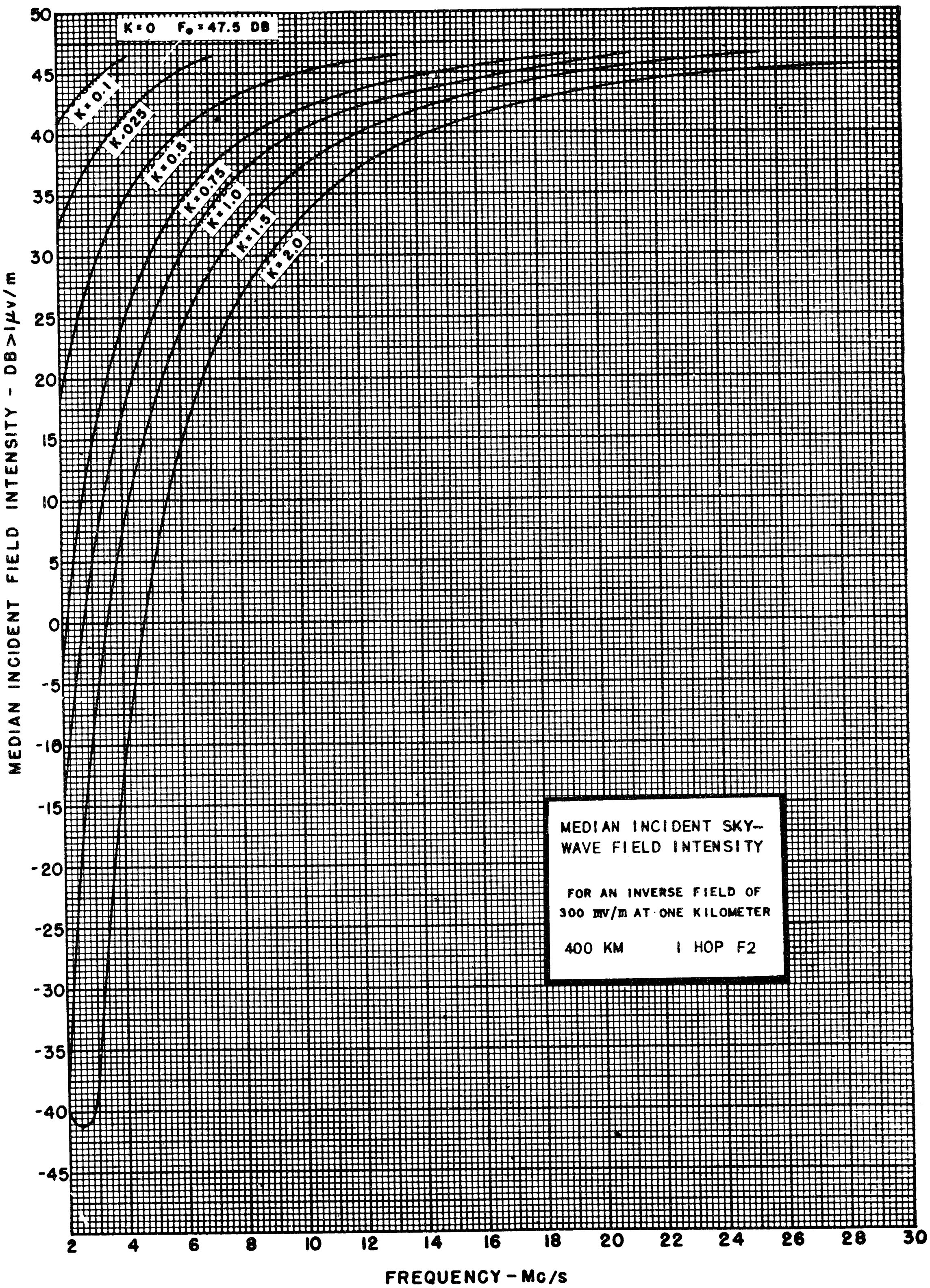


Figure 11-30. Median Incident Sky Wave Field Intensity, 400 km, 1-hop-F_2

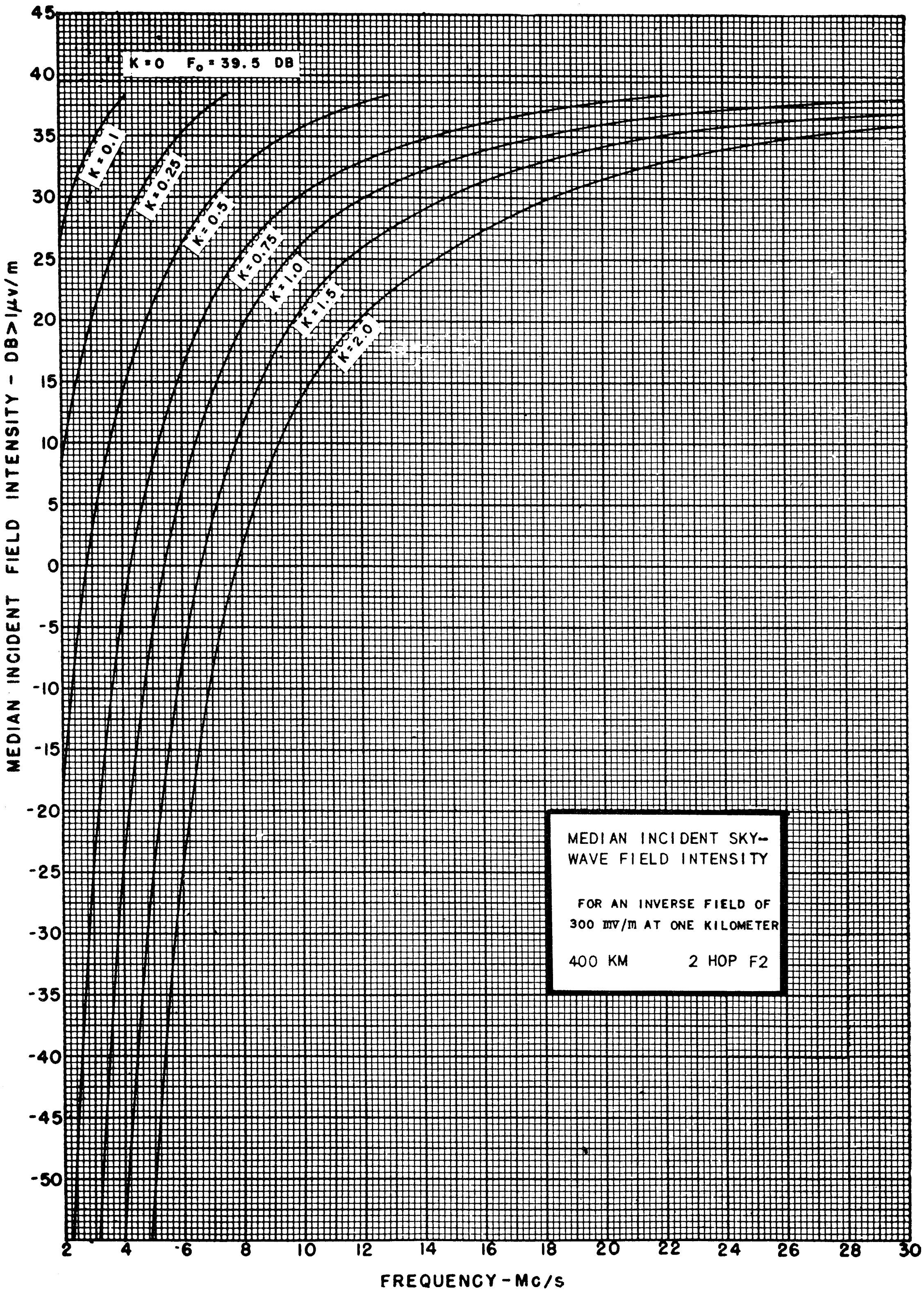


Figure 11-31. Median Incident Sky Wave Field Intensity, 400 km, 2-hop-F_2

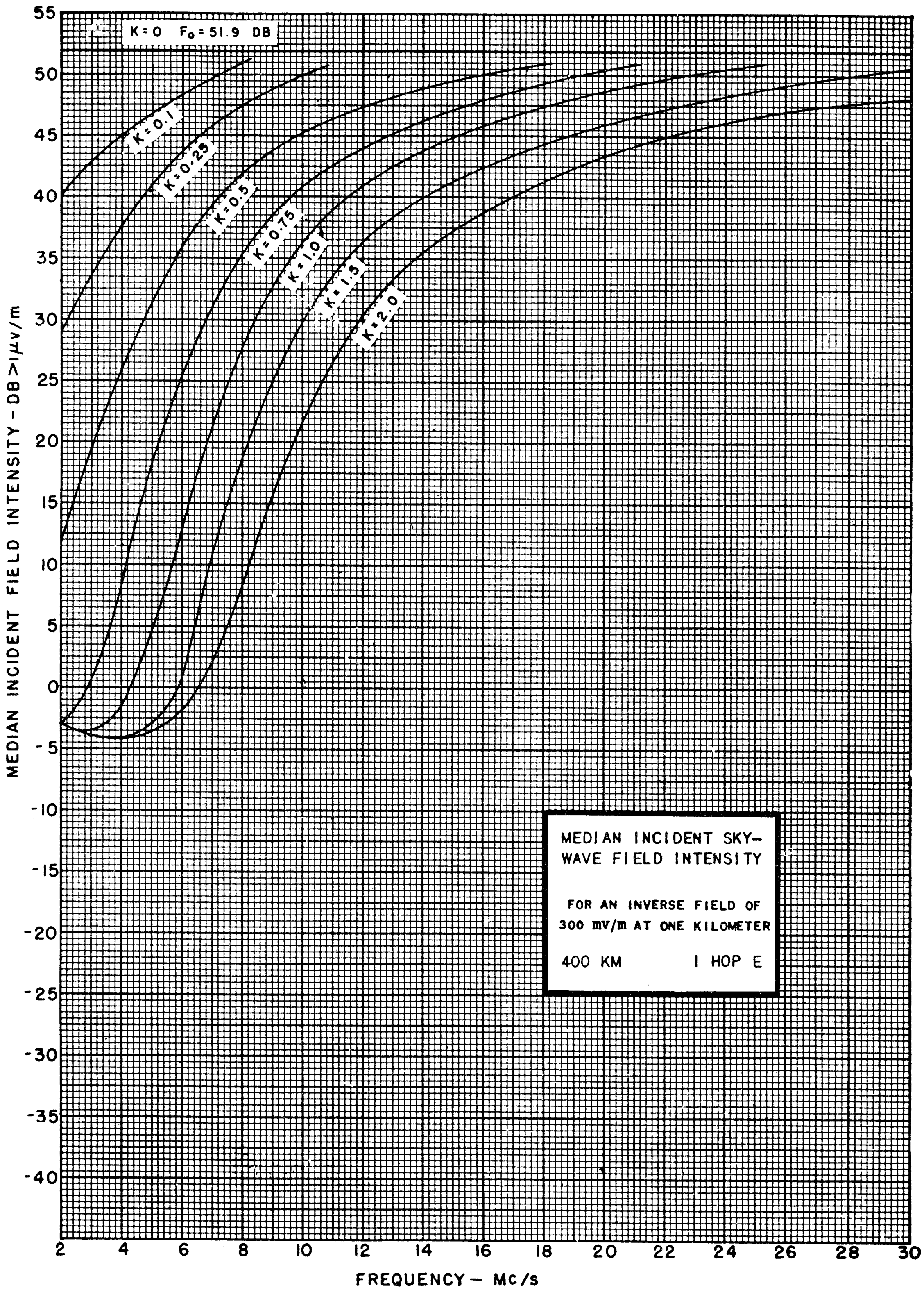


Figure 11-32. Median Incident Sky Wave Field Intensity, 400 km, 1-hop-E

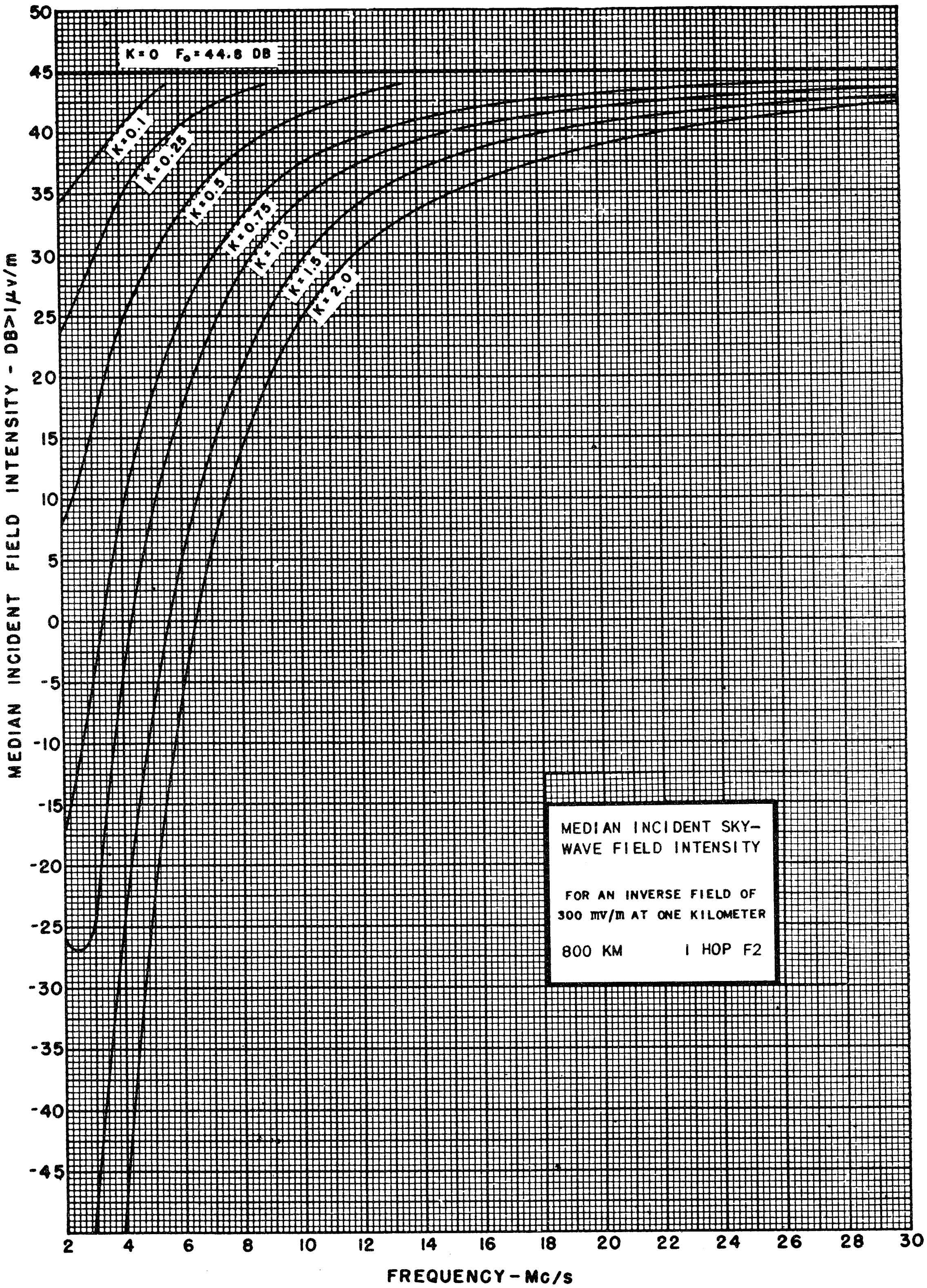


Figure 11-33. Median Incident Sky Wave Field Intensity, 800 km, 1-hop-F_2

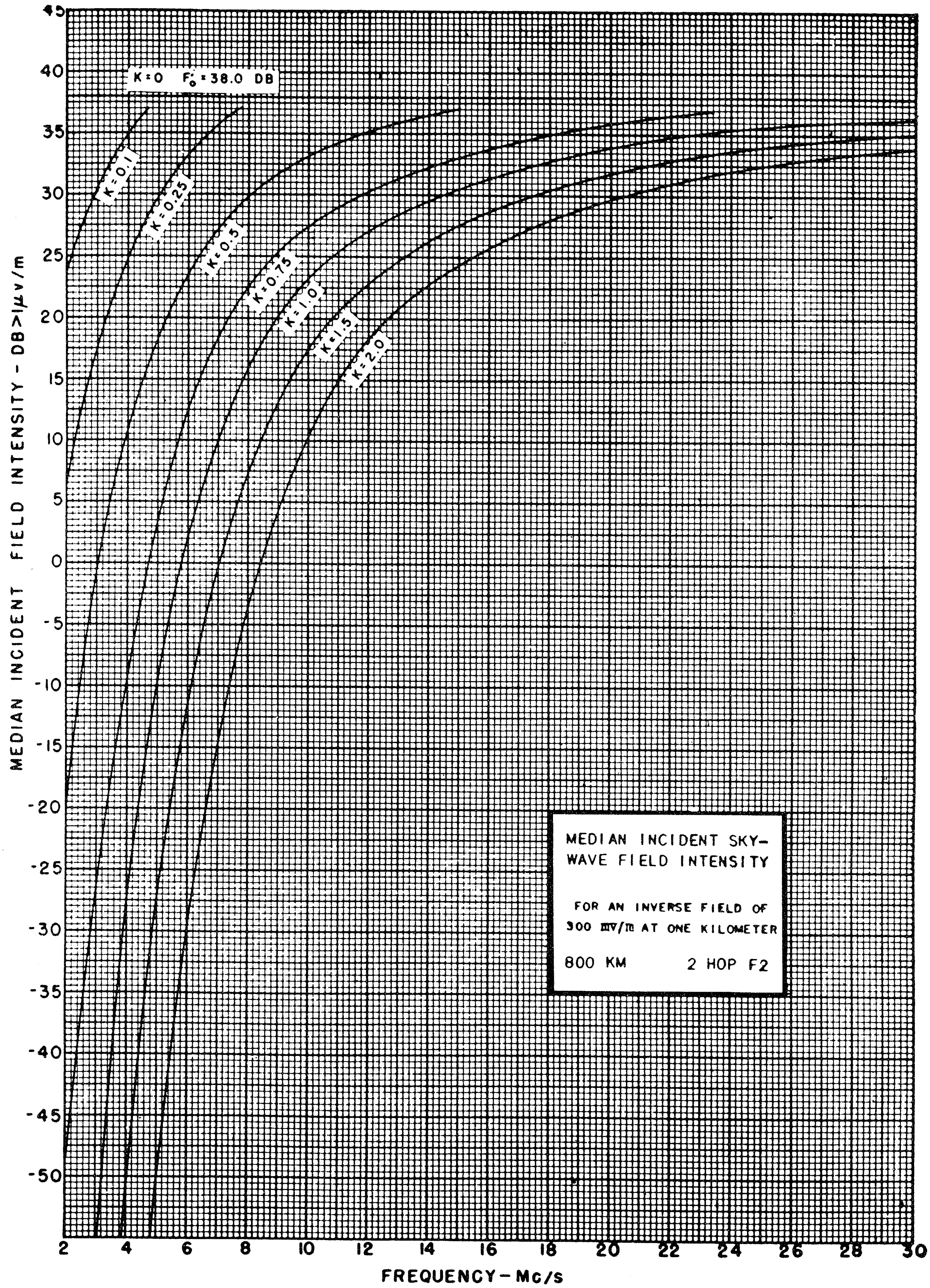


Figure 11-34. Median Incident Sky Wave Field Intensity, 800 km, 2-hop-F_2

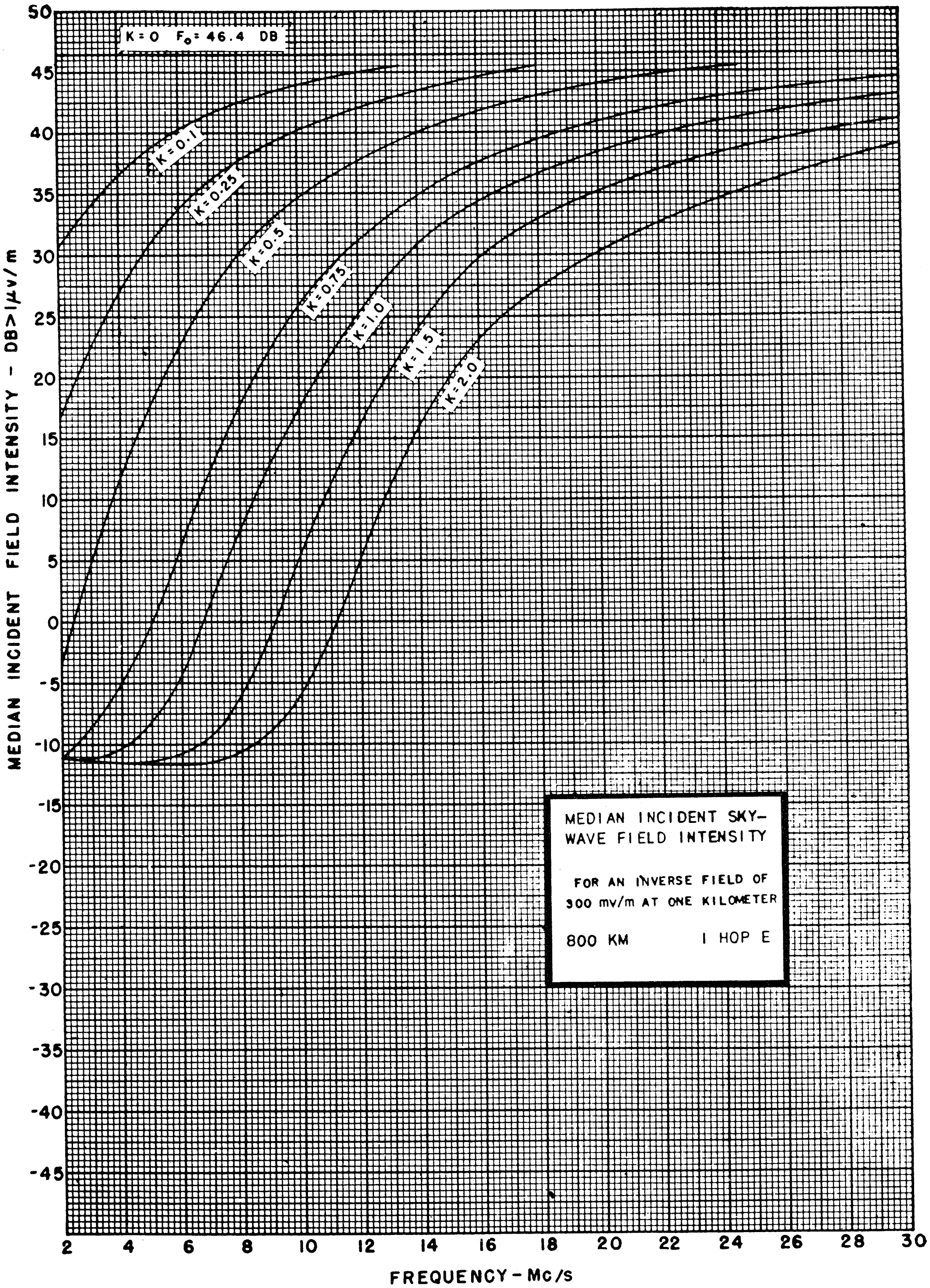


Figure 11-35. Median Incident Sky Wave Field Intensity, 800 km, 1-hop-E

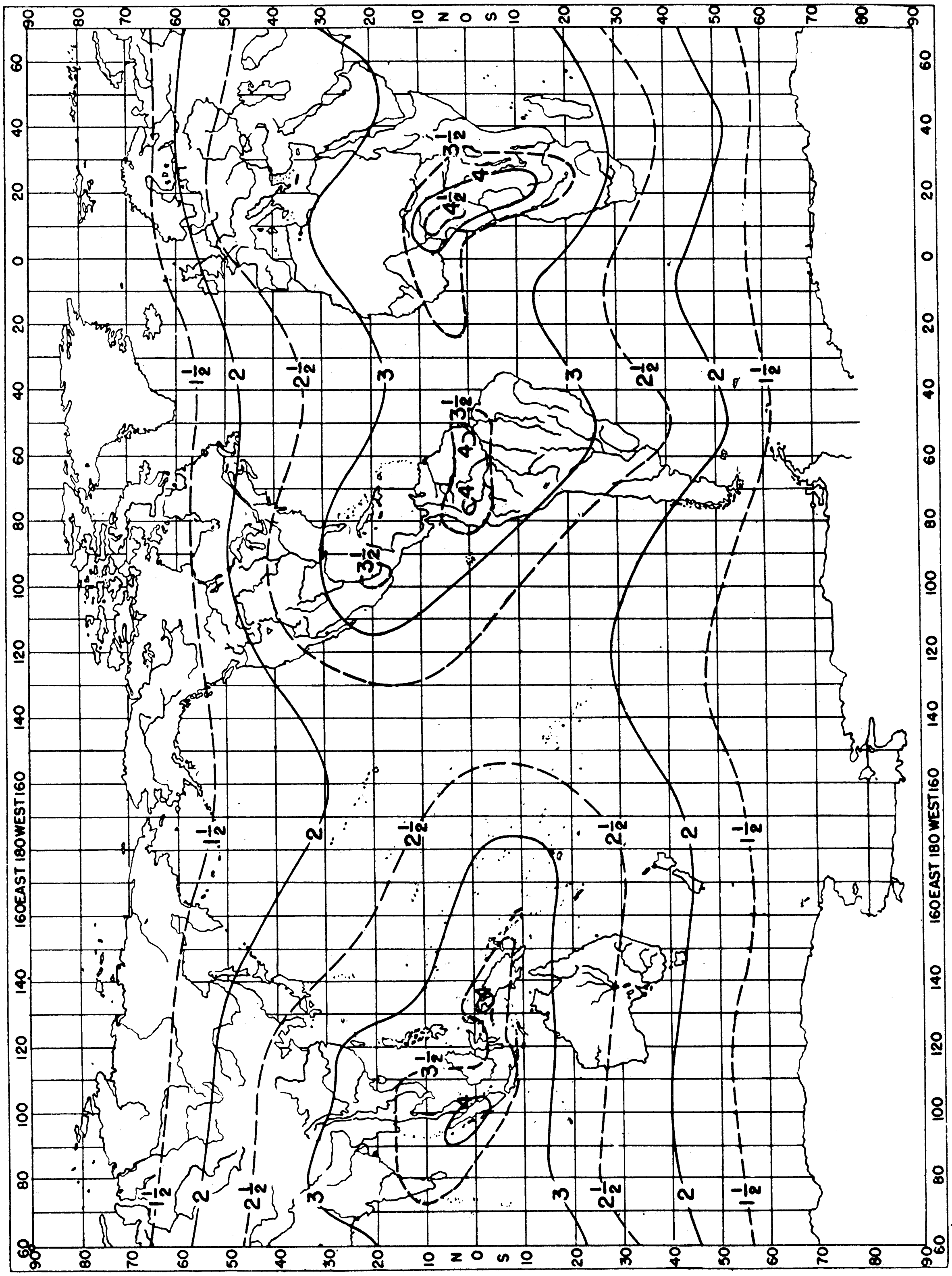


Figure 11-36. Noise Distribution Chart for March, April, and May

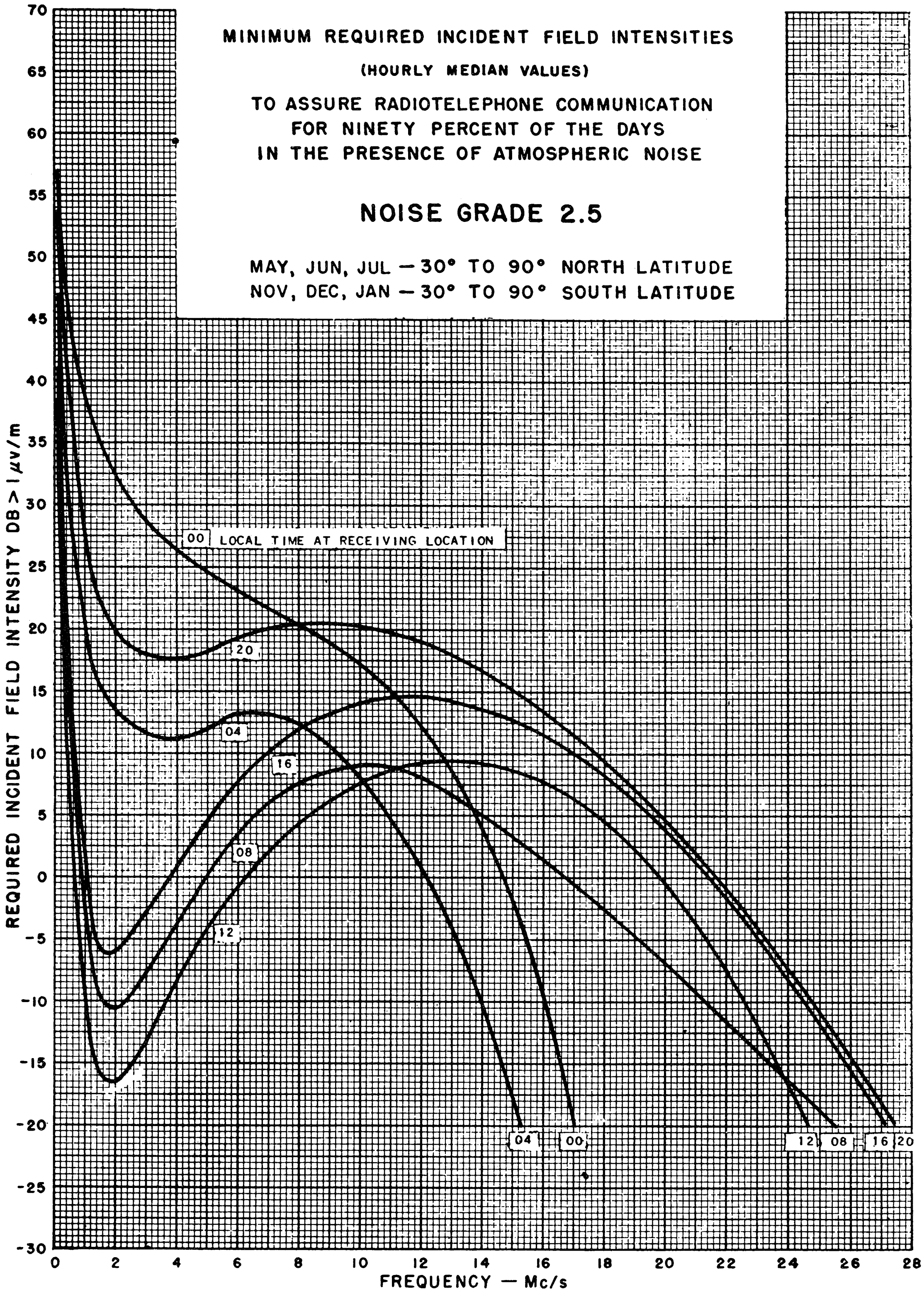


Figure 11-37. Minimum Required Incident Field Intensities, Noise Grade 2.5, Summer

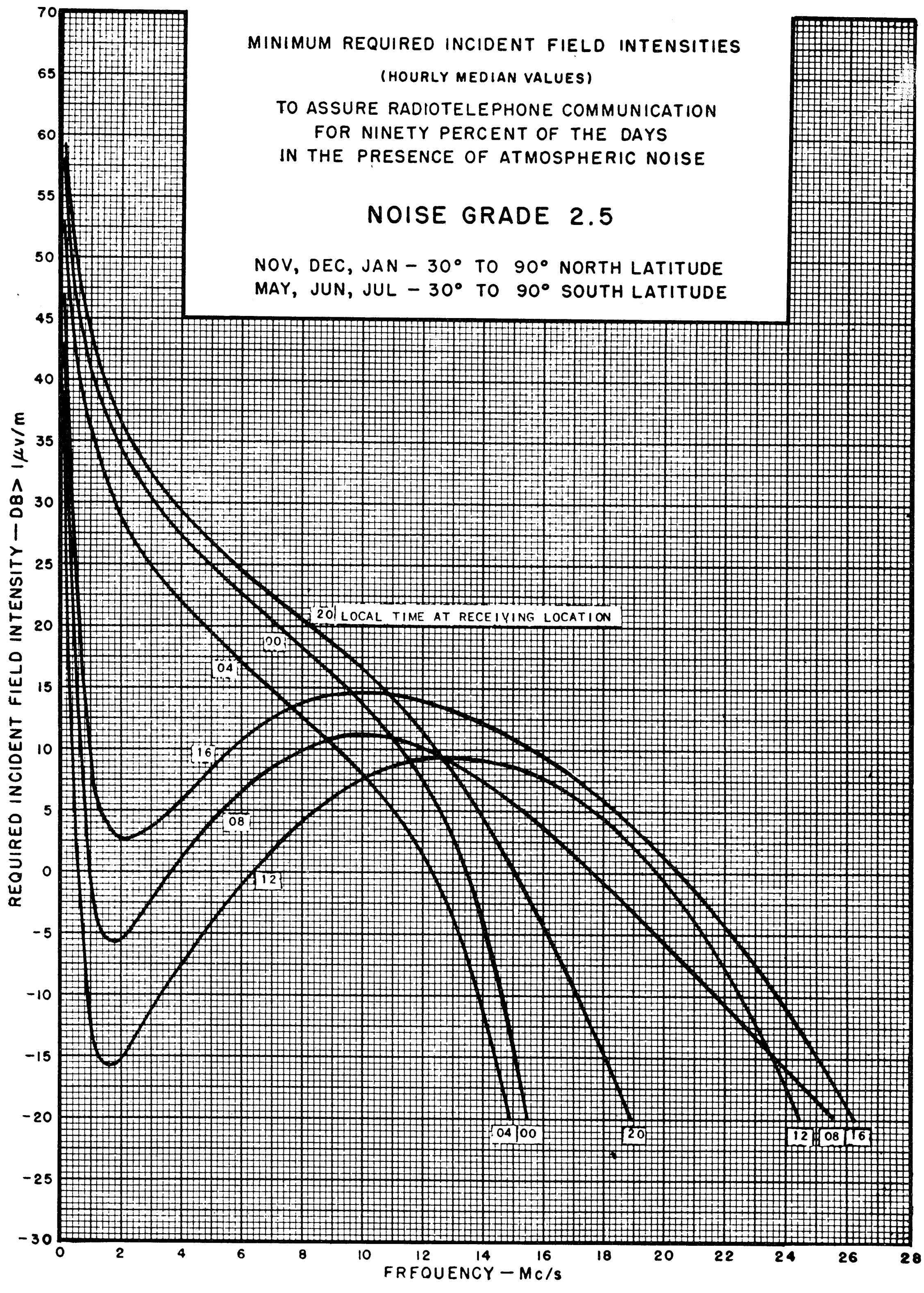


Figure 11-38. Minimum Required Incident Field Intensities, Noise Grade 2.5, Winter

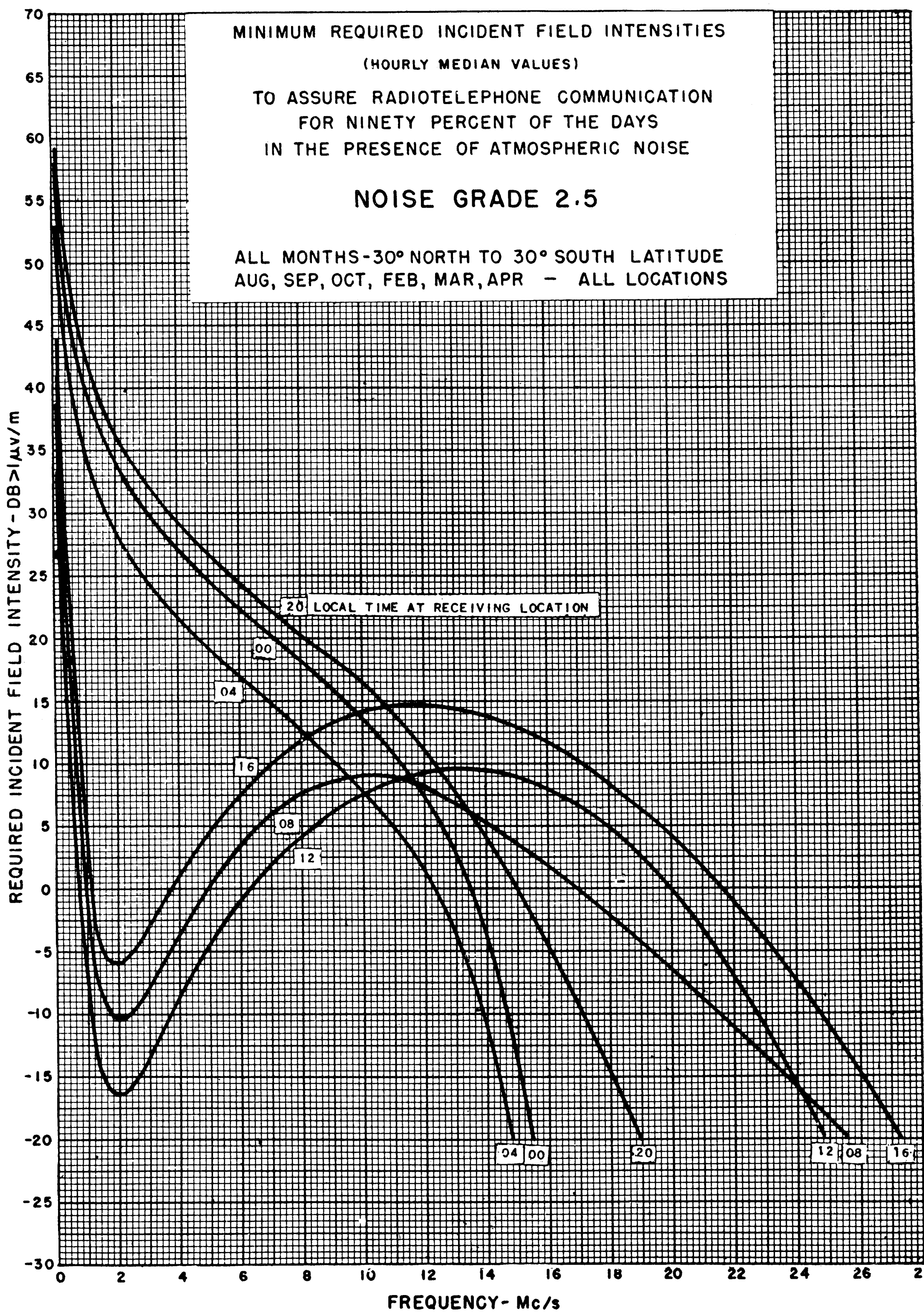


Figure 11-39. Minimum Required Incident Field Intensities, Noise Grade 2.5, Equinox

MINIMUM REQUIRED INCIDENT FIELD INTENSITIES
(HOURLY MEDIAN VALUES)
TO ASSURE RADIOTELEPHONE COMMUNICATION
FOR NINETY PERCENT OF THE DAYS
IN THE PRESENCE OF SET NOISE ONLY

AND

DISCRIMINATION GAINS WHEN RECEIVING
IN THE PRESENCE OF ATMOSPHERIC NOISE

FOR

15' WHIP ANTENNA

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL
MEASURED FROM THE HORIZONTAL PLANE

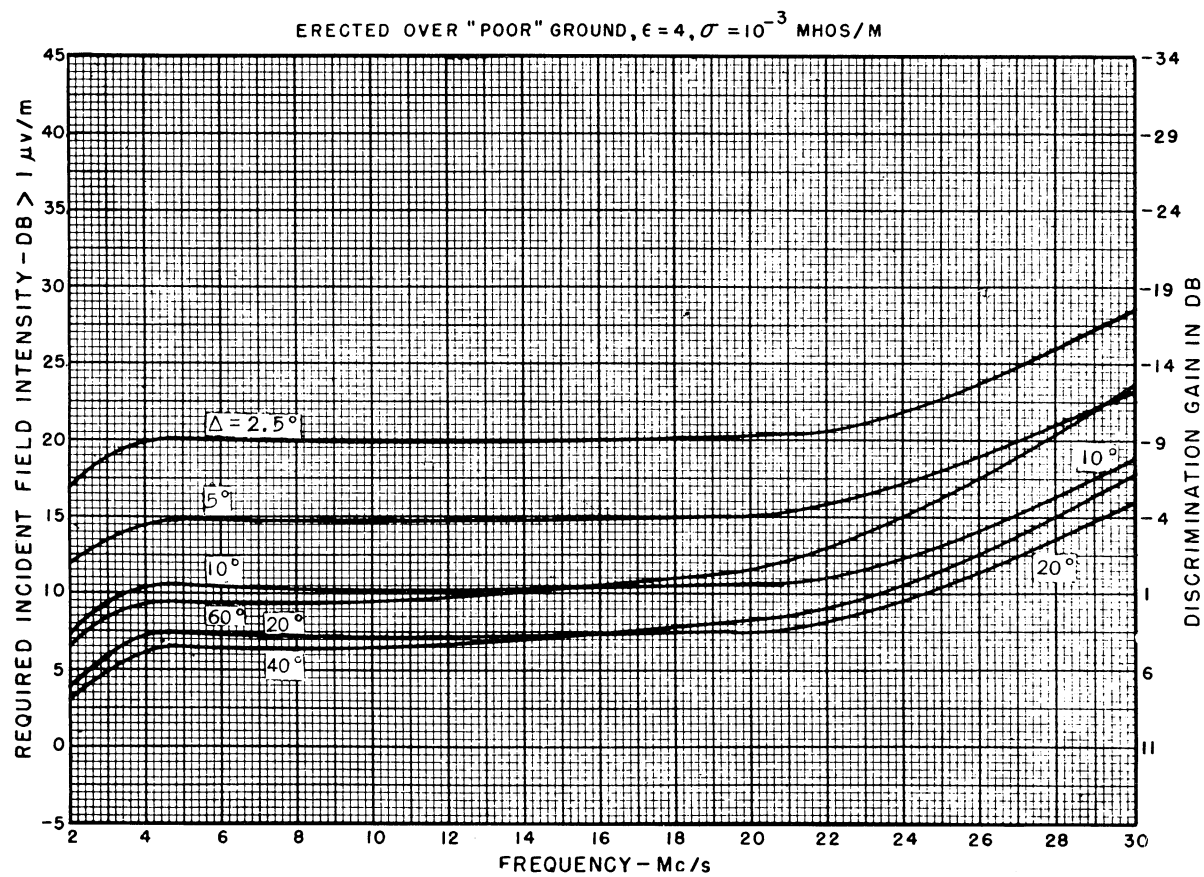


Figure 11-40. Minimum Required Incident Field Intersities and Discrimination Gain, 15-foot Whip Antenna

MINIMUM REQUIRED INCIDENT FIELD INTENSITIES
(HOURLY MEDIAN VALUES)
TO ASSURE RADIOTELEPHONE COMMUNICATION
FOR NINETY PERCENT OF THE DAYS
IN THE PRESENCE OF SET NOISE ONLY

AND

DISCRIMINATION GAINS WHEN RECEIVING
IN THE PRESENCE OF ATMOSPHERIC NOISE

FOR

λ/4 GROUNDED VERTICAL ANTENNA

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL
MEASURED FROM THE HORIZONTAL PLANE

ERECTED OVER "POOR" GROUND, $\epsilon = 4, \sigma = 10^{-3}$ MHOS/M

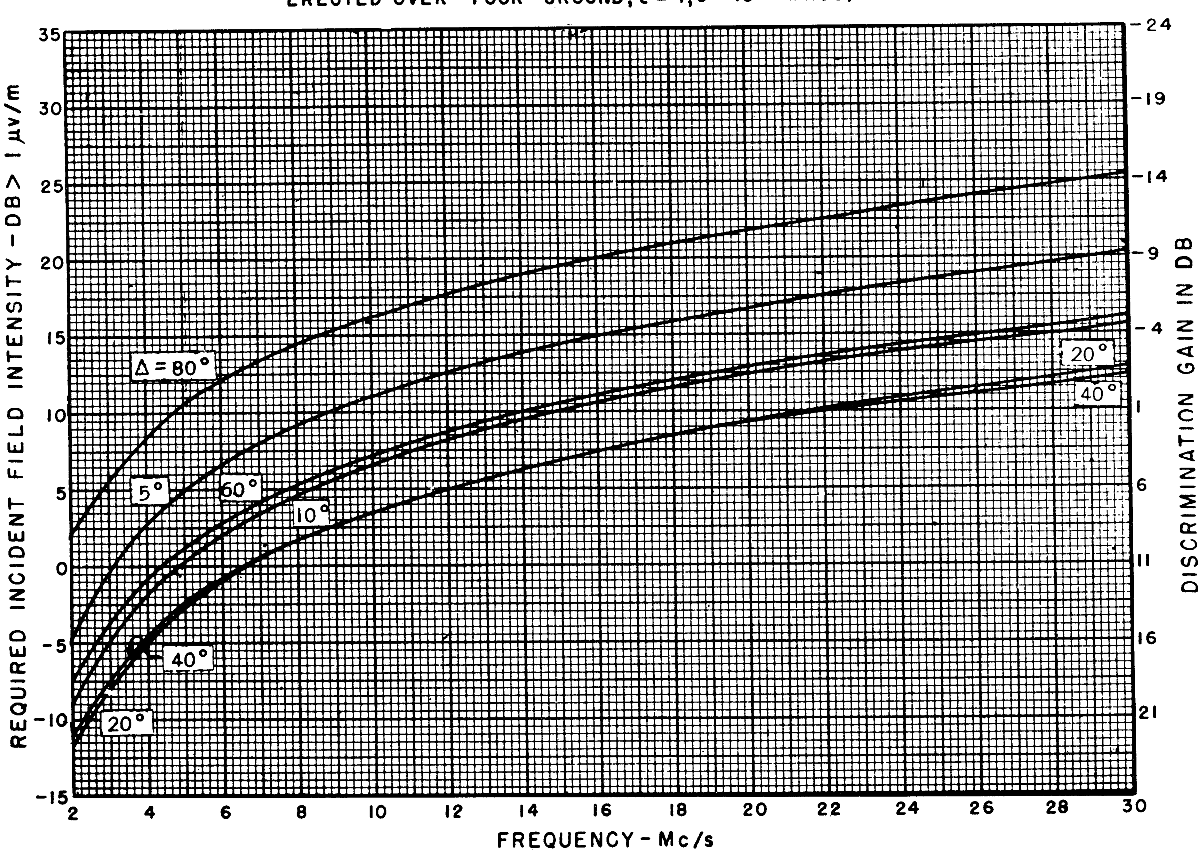


Figure 11-41. Minimum Required Incident Field Intensities and Discrimination Gain, 1/4-Wave Grounded Vertical Antenna

MINIMUM REQUIRED INCIDENT FIELD INTENSITIES
(HOURLY MEDIAN VALUES)
TO ASSURE RADIOTELEPHONE COMMUNICATION
FOR NINETY PERCENT OF THE DAYS
IN THE PRESENCE OF SET NOISE ONLY

AND

DISCRIMINATION GAINS WHEN RECEIVING
IN THE PRESENCE OF ATMOSPHERIC NOISE

FOR

λ/2 GROUNDED VERTICAL ANTENNA

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL
MEASURED FROM THE HORIZONTAL PLANE
TRANSMISSION LINE FED FROM BASE OF ANTENNA WITHOUT
IMPEDANCE MATCHING NETWORK
RADIATION RESISTANCE ASSUMED 5000 OHMS

ERECTED OVER "POOR" GROUND, $\epsilon = 4, \sigma = 10^{-3}$ MHOS/M

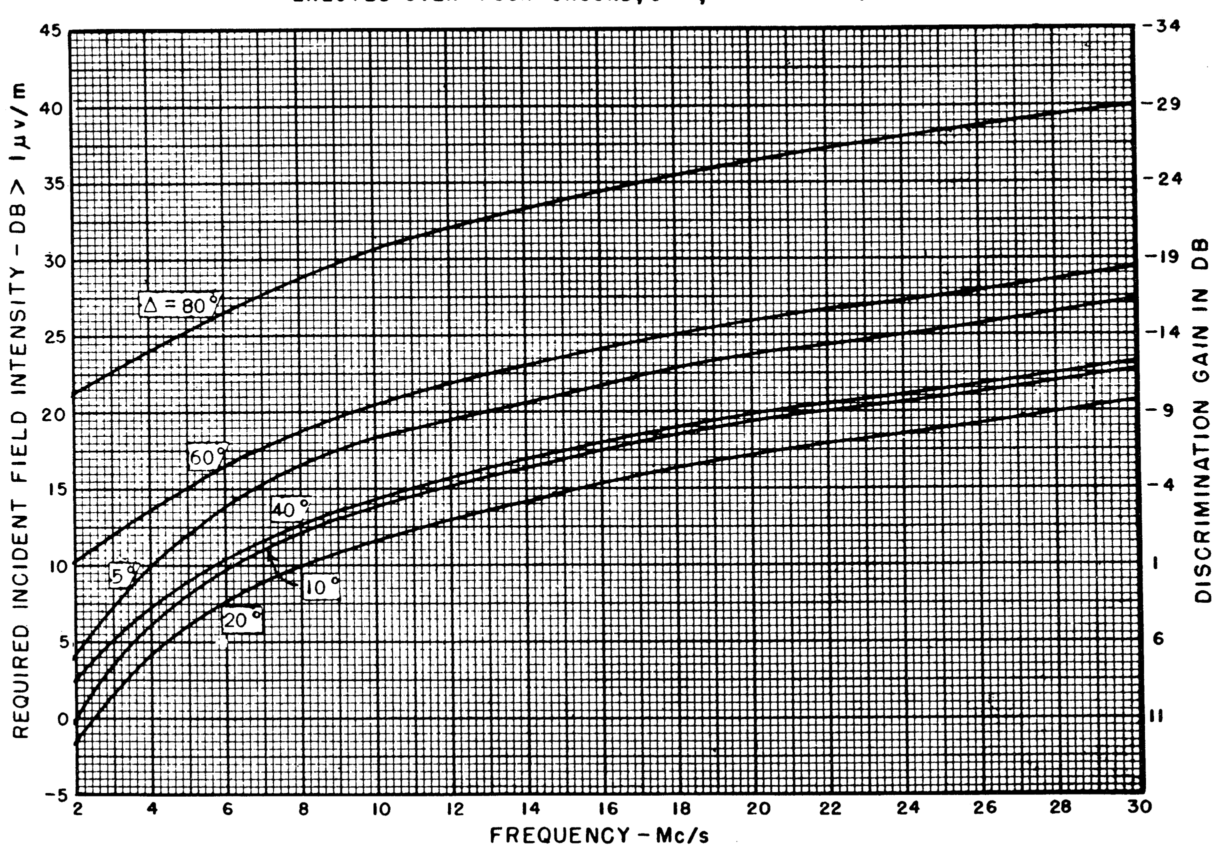


Figure 11-42. Minimum Required Incident Field Intensities and Discrimination Gain, 1/2-Wave Grounded Vertical Antenna, Transmission Line Fed from Base of Antenna

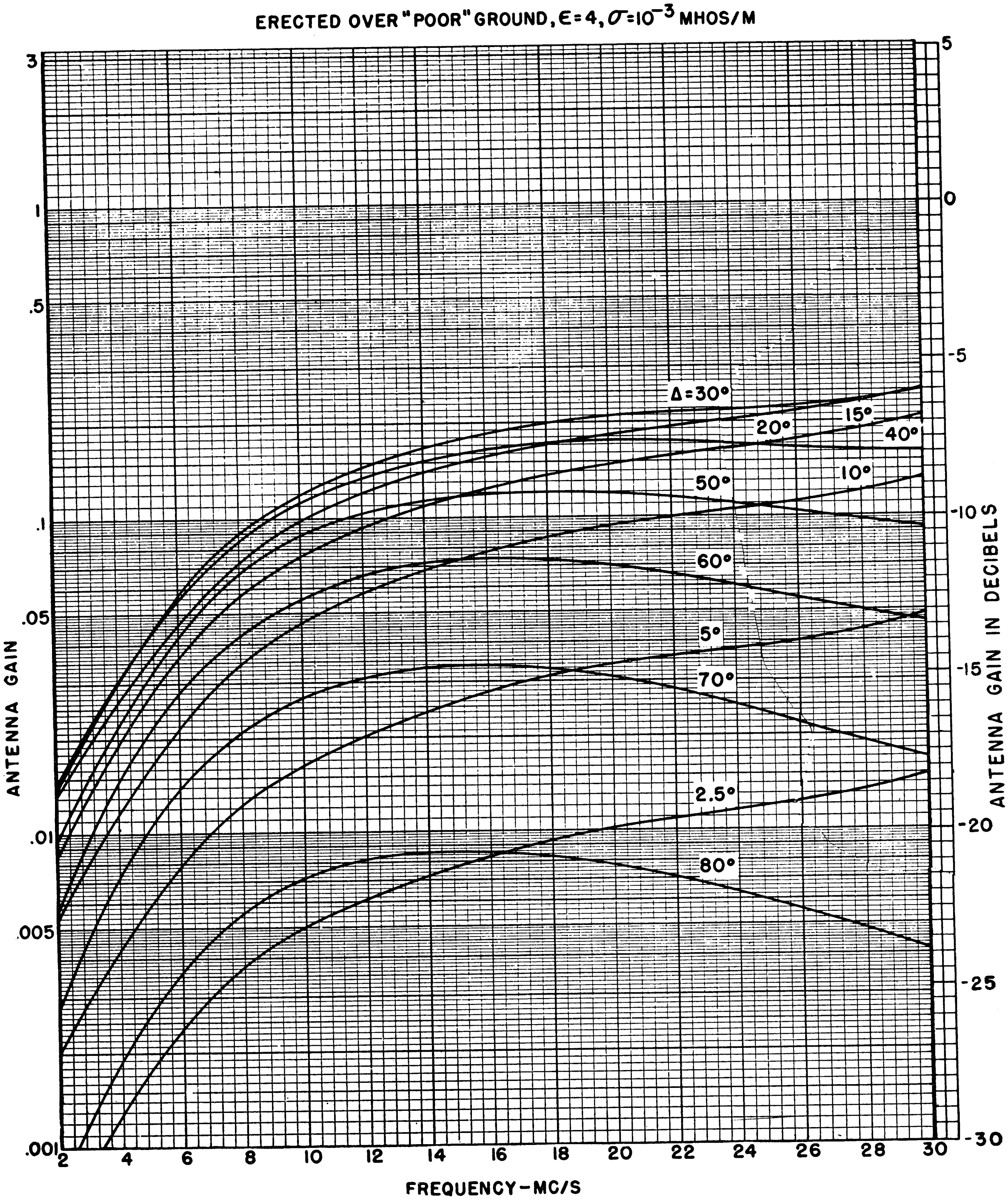


Figure 11-43. Gain Curves, 15-foot Whip Antenna Erected Above Poor Ground

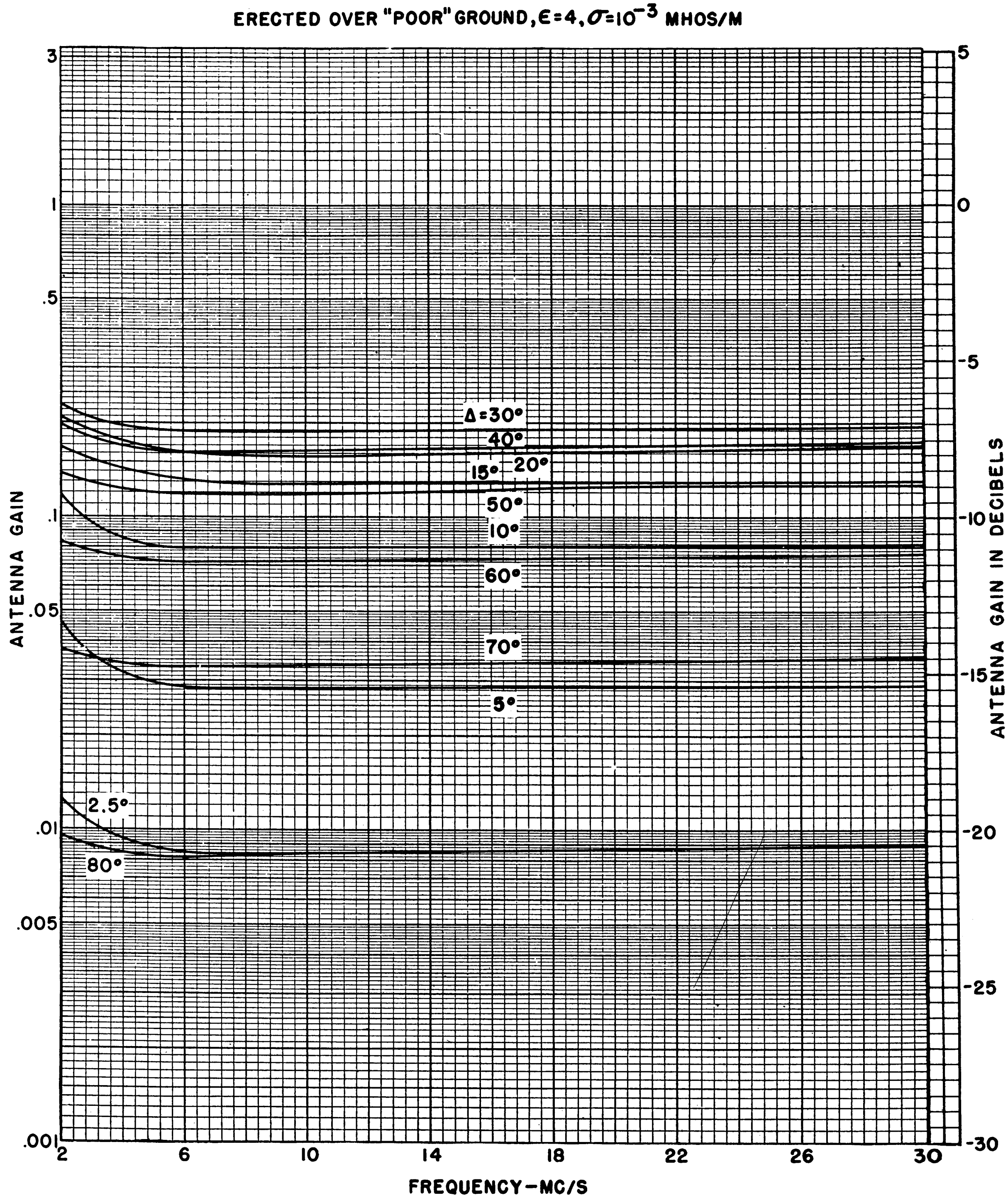


Figure 11-44. Gain Curves, 1/4-Wave Vertical Antenna Erected Above Poor Ground

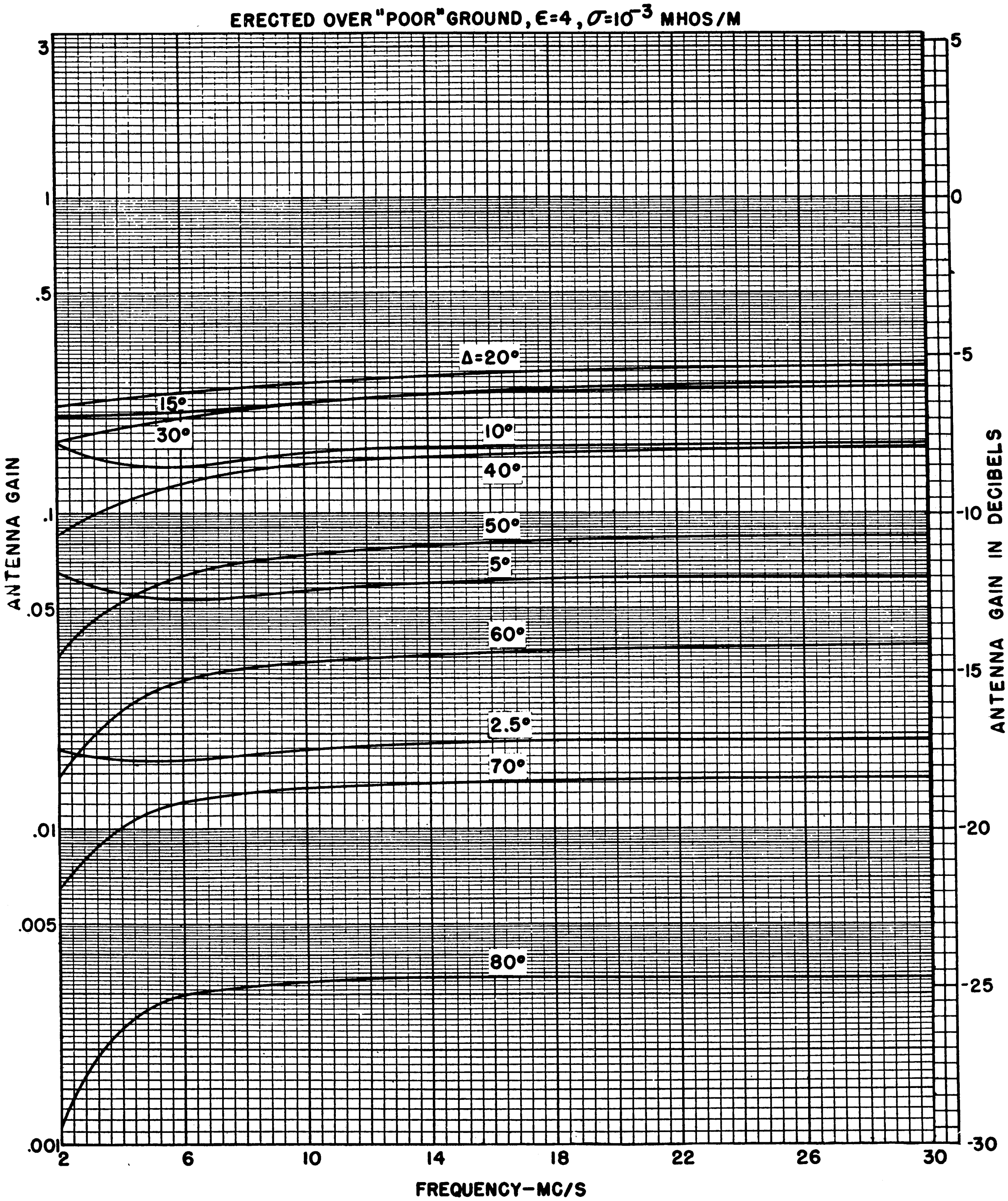


Figure 11-45. Gain Curves, 1/2-Wave Vertical Antenna Erected Above Poor Ground

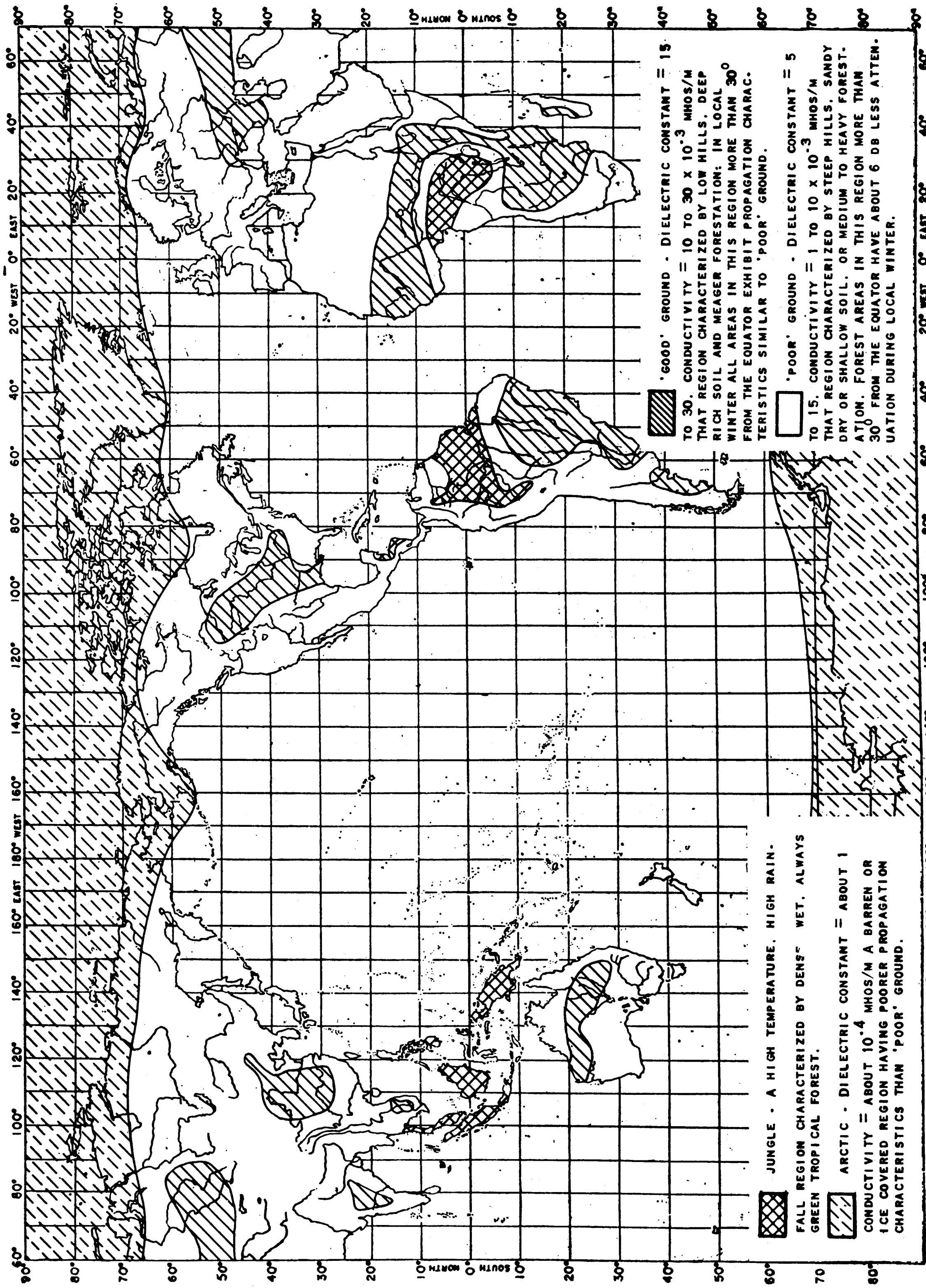


Figure 11-46. World Map Showing Various Types of Terrain

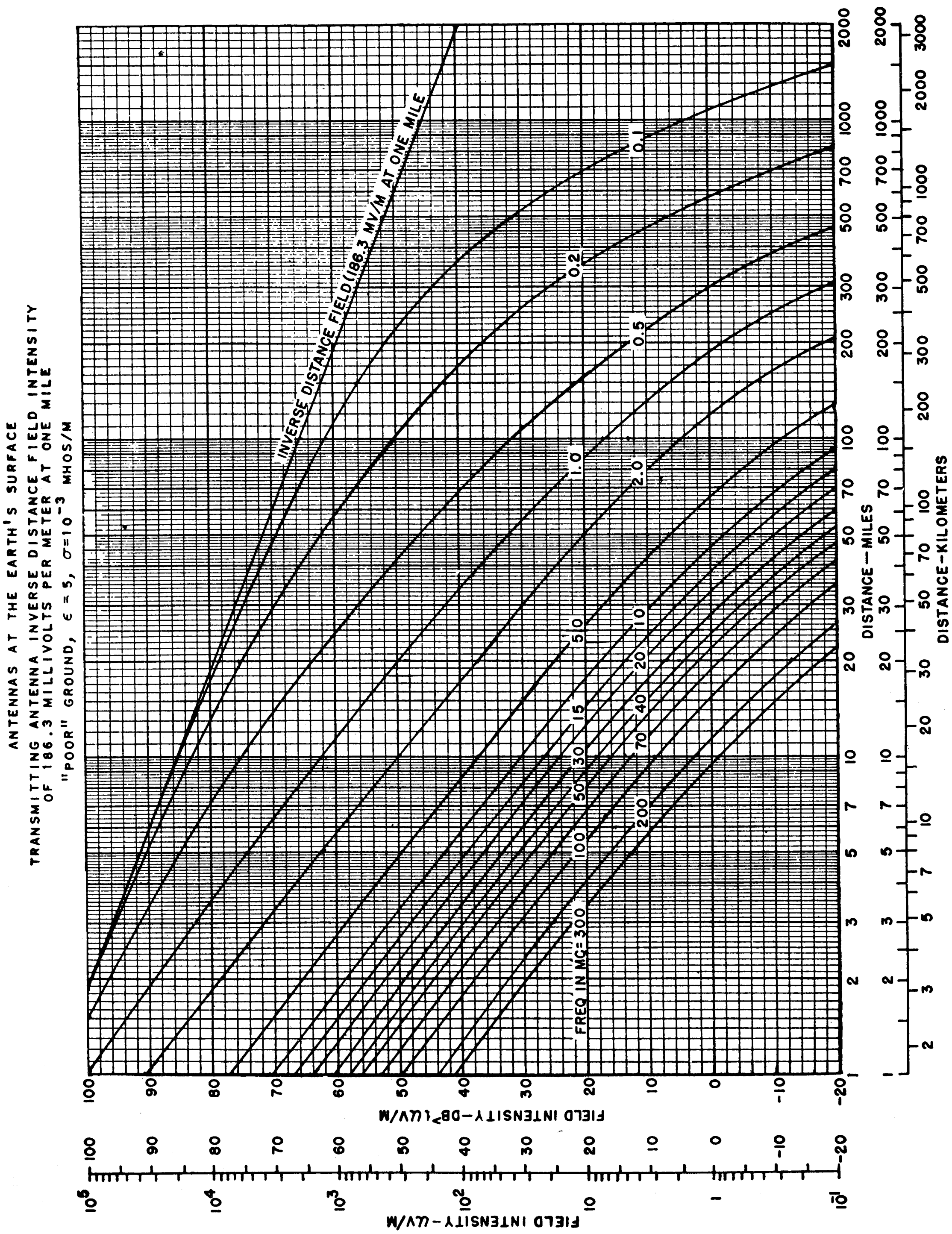


Figure 11-47. Ground-Wave Field Intensity Versus Distance Curves for Various Frequencies in mc, for Vertical Polarization, 1-2,000 miles--Poor Ground

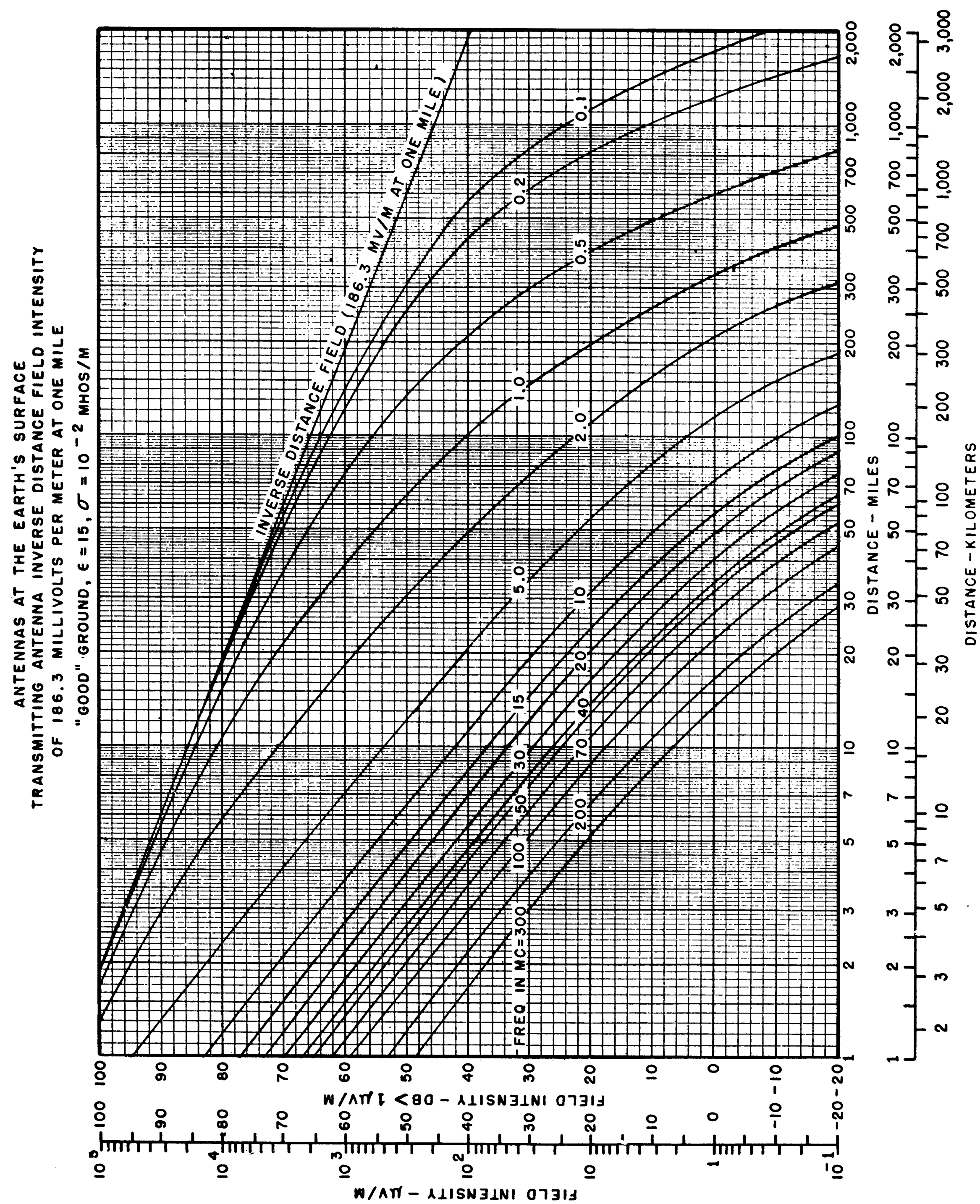


Figure 11-48. Ground-Wave Field Intensity Versus Distance Curves for Various Frequencies in mc, for Vertical Polarization, 1-2,000 miles-Good Ground

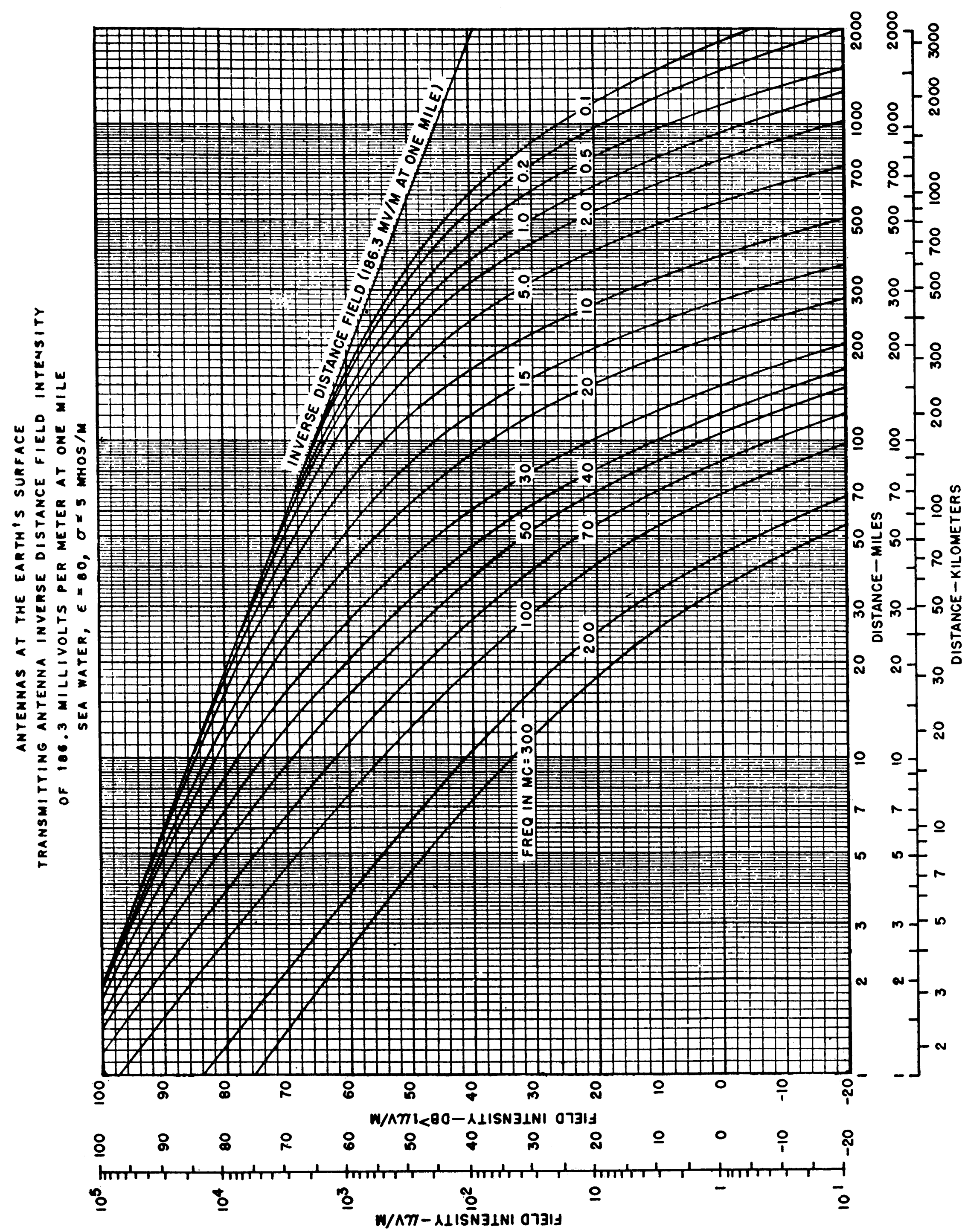


Figure 11-49. Ground-Wave Field Intensity Versus Distance Curves for Various Frequencies in mc, for Vertical Polarization, 1-2,000 miles--Sea Water

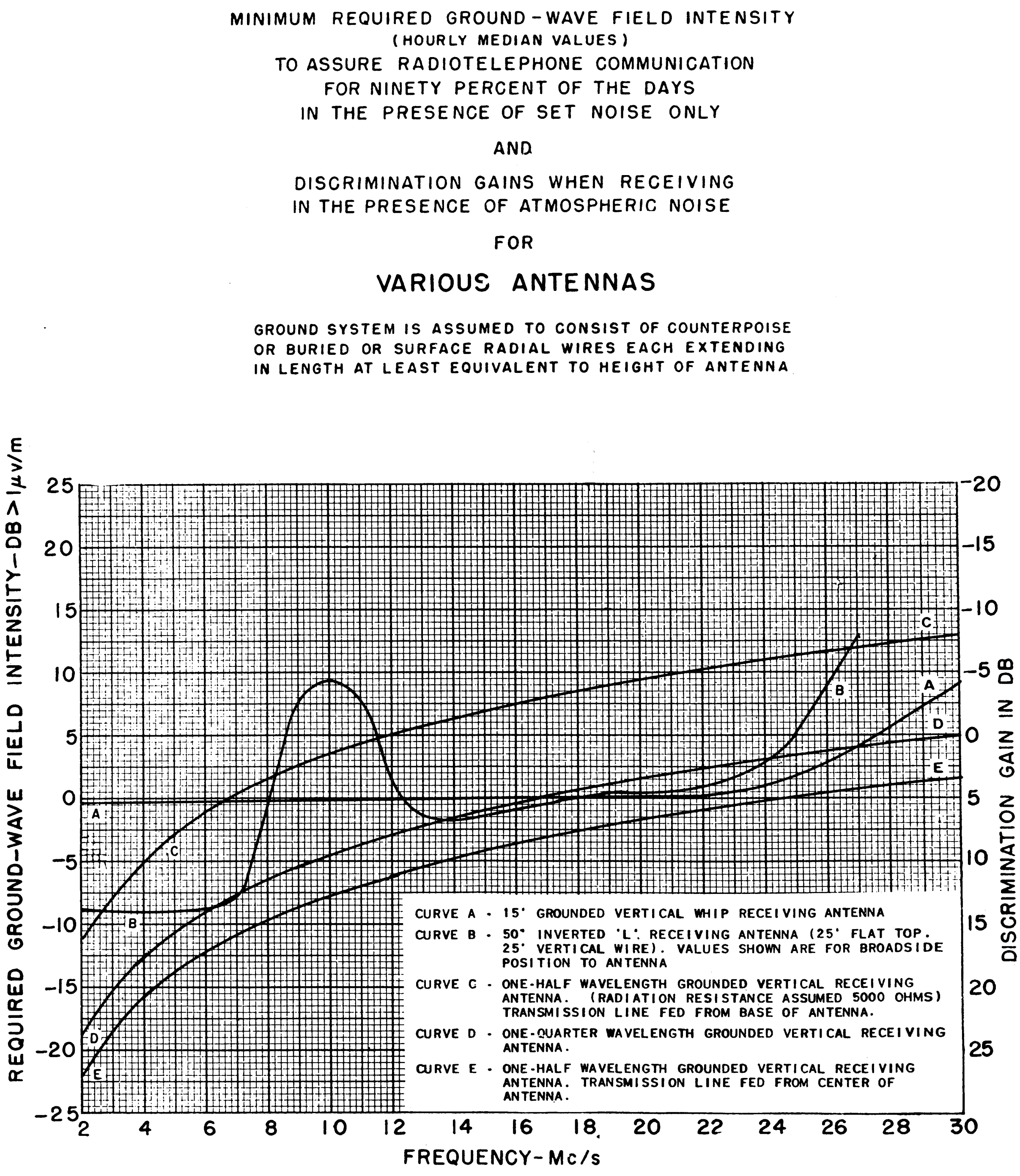


Figure 11-50. Minimum Required Field Intensity in the Presence of Set Noise, and Discrimination Gains in the Presence of Atmospheric Noise, for Various Antennas

Type of Service	Conditions	Bandwidth	Signal Strength in Decibels Above Reference Level
Double sideband radiotelephony	Speech grade quality at 100% modulation	6 kilocycles	0
Double sideband radiotelephony	High quality commercial service	6 kilocycles	25
Standard broadcast	High quality service	10 kilocycles	27
Single sideband radiotelephony	Speech grade quality, carrier suppressed 10 db	3 kilocycles	-9
Single sideband radiotelephony, single channel	High quality, carrier suppressed 10 db	3 kilocycles	16
Single sideband radiotelephony, 2-channel	High quality service	3 kilocycles	18
Manual continuous wave radiotelegraphy	15 words per minute	2 kilocycles	-17
Modulated manual continuous wave radiotelegraphy	30 words per minute	2 kilocycles	-13
Machine speed radiotelegraphy	150 words per minute	1.5 kilocycles	-11
Modulated machine speed radiotelegraphy	150 words per minute	3 kilocycles	-8
Carrier shift radioteletypewriter	150 wpm, 425 cycles shift each side of carrier	1.7 kilocycles	-9
Carrier shift diplex radioteletypewriter	150 wpm, 425 cycles shift each side of carrier, 2 channels operating simultaneously	1.7 kilocycles	-11
Interrupted carrier radioteletypewriter	150 words per minute	3 kilocycles	-6
Single sideband multitone radioteletypewriter	Single channel operation, carrier suppressed 25 db	3 kilocycles	-6
Frequency modulation broadcast service	Broadcast quality	150 kilocycles	2
Facsimile		6 kilocycles	-3

Figure 11-51. Service Gains, Ground-Wave Communication, Nonfading Signal

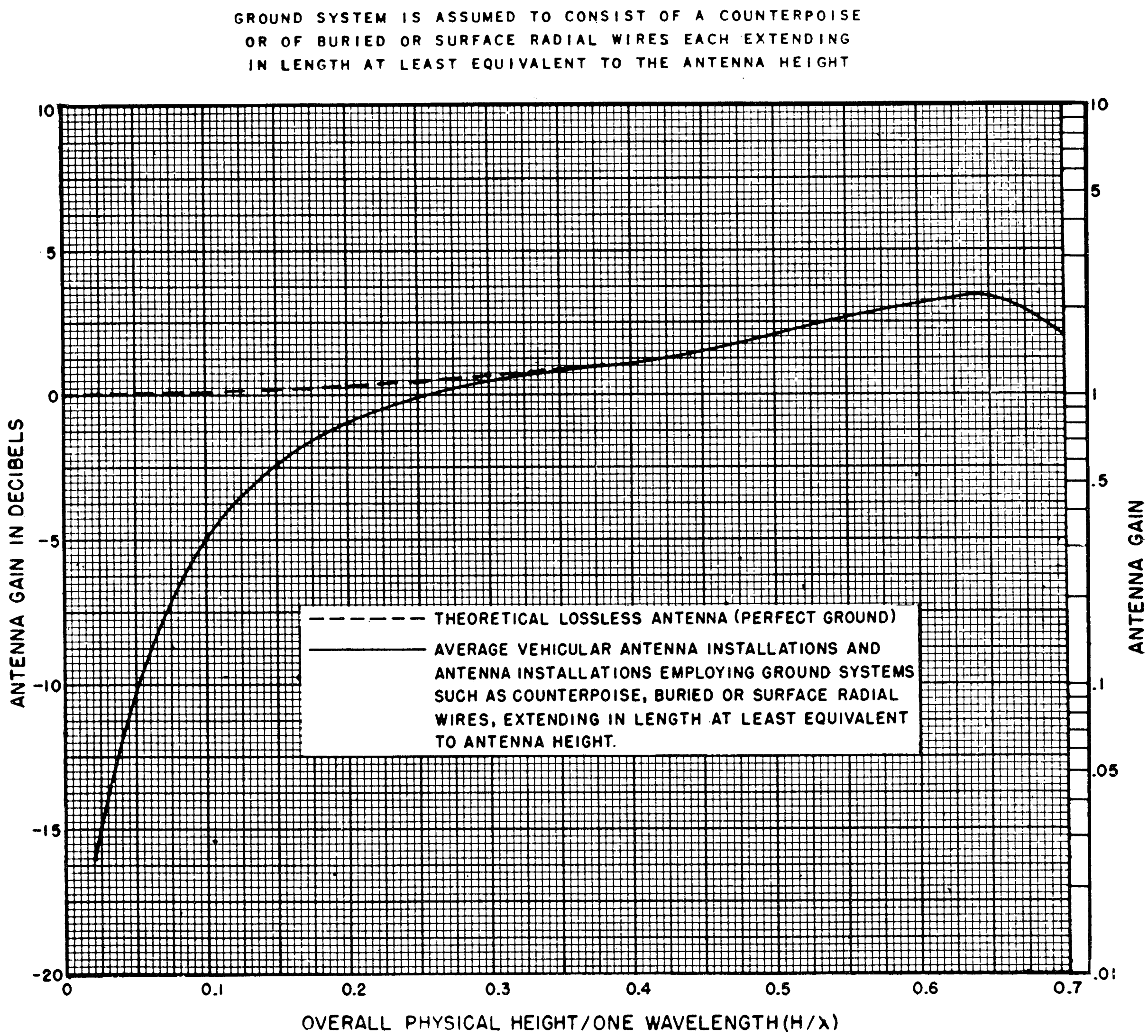


Figure 11-52. Inverse Distance Field Intensity Expressed as an Antenna Gain in Respect to 186.3 Millivolts per Meter at 1 mile, Grounded Vertical Antenna

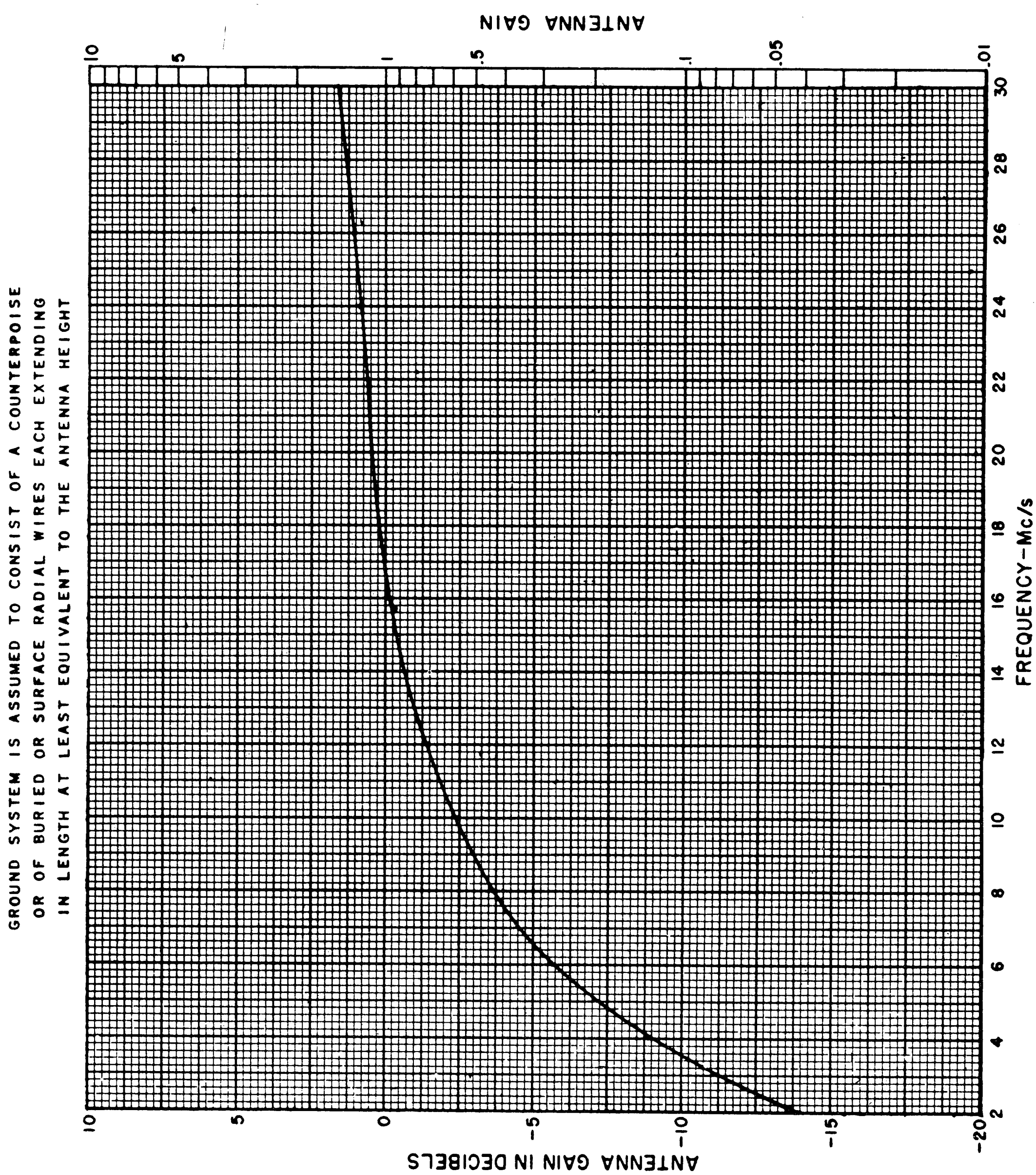


Figure 11-53. Inverse Distance Field Intensity Expressed as an Antenna Gain in Respect to 186.3 Millivolts per Meter at 1 Mile, 15-foot Vertical Whip Antenna

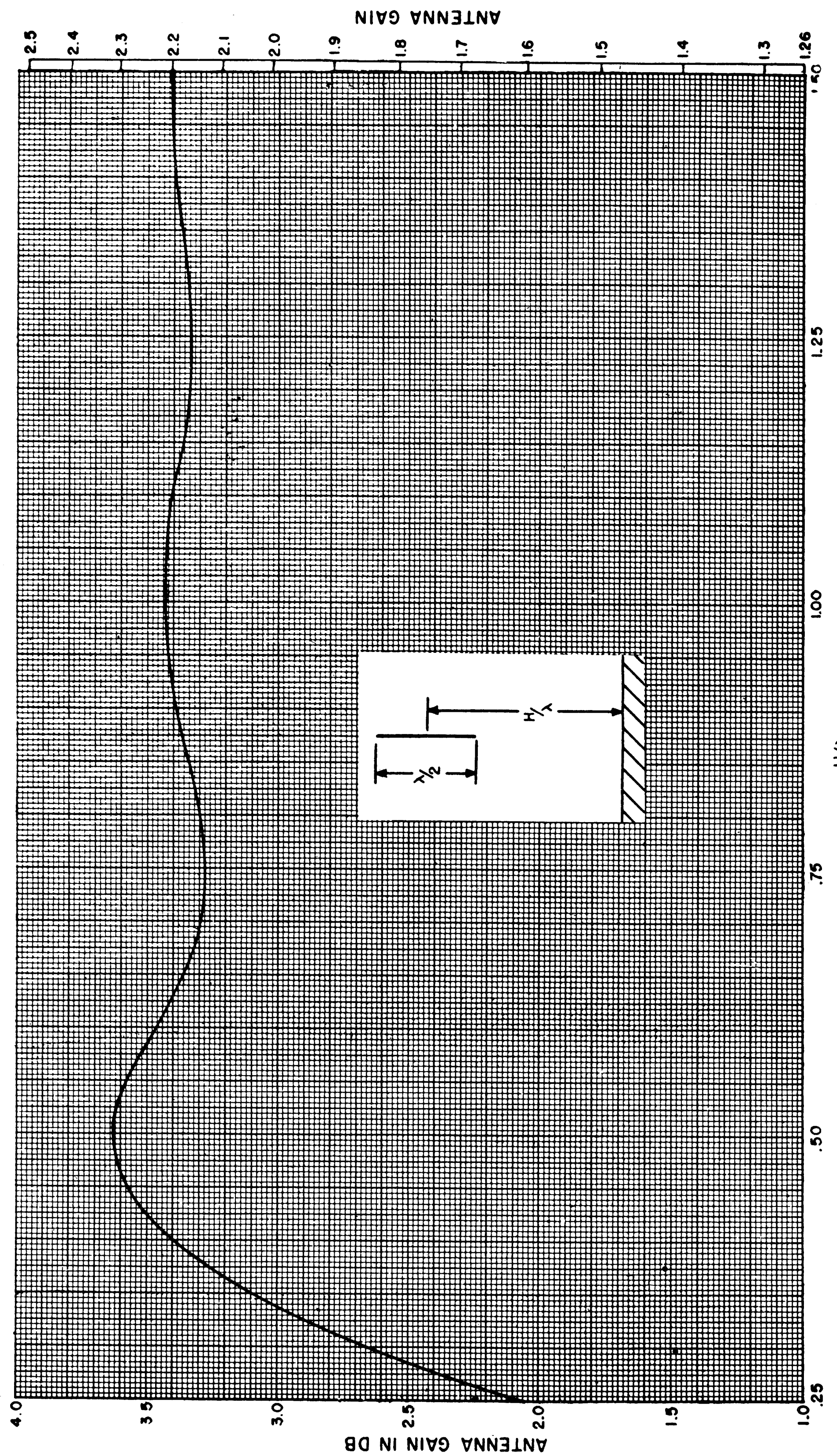


Figure 11-54. Inverse Distance Field Intensity Expressed as an Antenna Gain in Respect to 186.3 Millivolts per Meter at 1 Mile, Half-Wave Vertical Antenna Erected Above Perfect Earth at a Height of H/λ

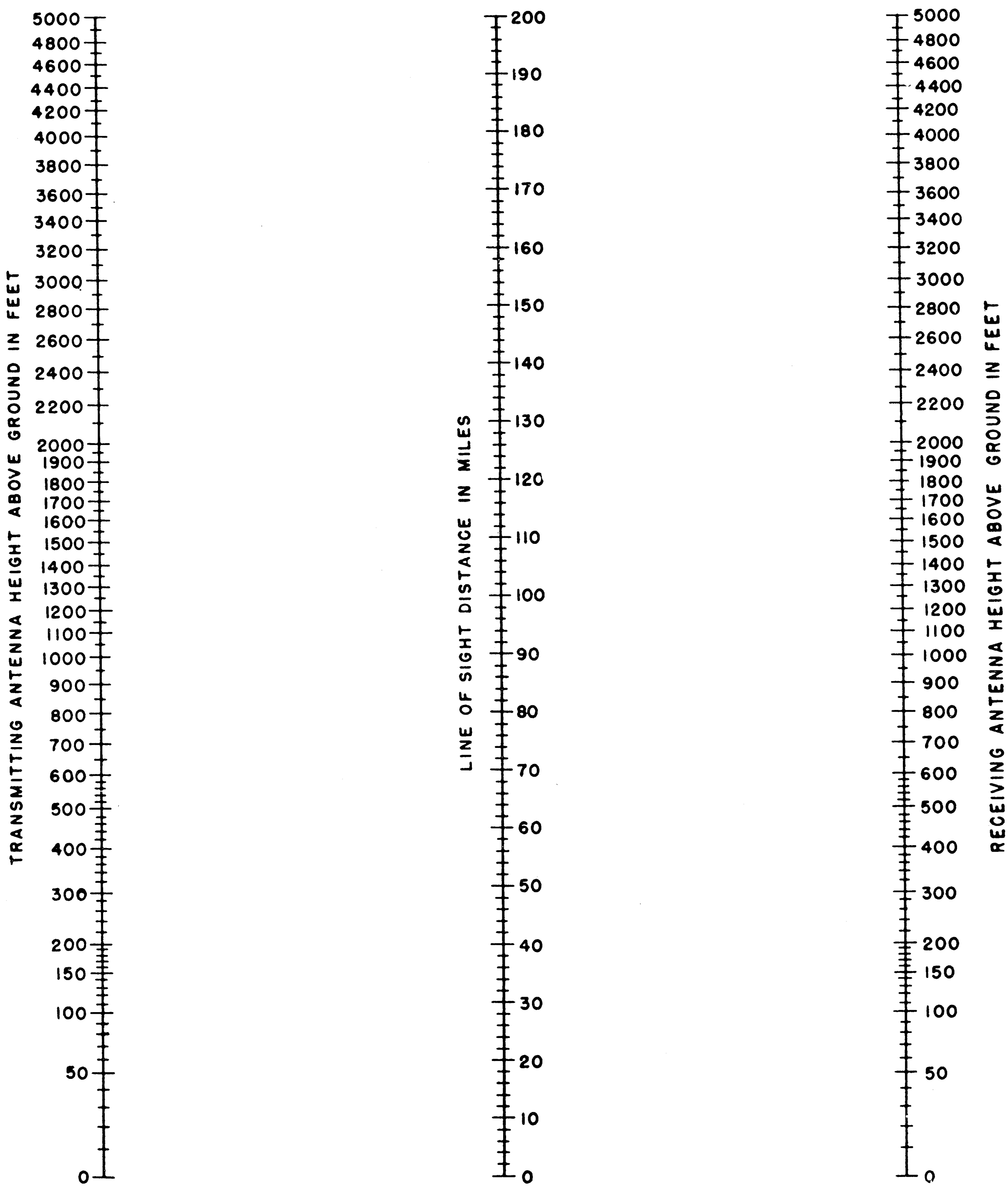


Figure 11-55. Line of Sight Distance for Elevated Antennas (For Smooth Spherical Earth With an Effective Radius of 4/3 the Actual Values), Antenna Heights from 0 to 5,000

9. SAMPLE PROPAGATION ANALYSIS

a. INTRODUCTION

This paragraph illustrates the analysis and solution to a typical propagation problem to determine whether or not satisfactory communication is possible between a given transmitter and a given receiver. The solution of this problem is based on the information given in the first seven paragraphs of this chapter and the typical charts and graphs provided in paragraph 8 of this chapter. Because mathematical procedures are complex and tedious, graphical procedures are employed in a propagation analysis. In the final analysis of the problem, satisfactory communication is possible if the received field intensity is equal to or greater than the required field intensity. For a systematic solution to the problem, the information obtained and derived during the solution of the problem should be entered on a work sheet, a sample of which is provided.

b. SKY WAVE PROPAGATION ANALYSIS

(1) The first step in determining the feasibility of satisfactory communication is to state all the known conditions under which the link will operate. For this sample problem, the known conditions are as follows:

Transmitting station location - Washington, D.C.
Receiving station location - Virginia Beach, Va.
Transmission path distance - 253 km (160 miles)
Month and year - April 1957
Daily period of operation - 0800 to 1600, local time
Transmitter power (KWT-6 xmtr) - 500 watts PEP
Antennas (transmitting and receiving) - 35-ft whips
Type of service - SSB, speech quality voice

(2) The next step is to determine the MUF, using the following procedure. The graphs used in this calculation are published by the Bureau of Standards for each month, three months in advance.

Step 1: Place a piece of tracing paper on the world map, figure 11-8, and draw a horizontal line coinciding with the equator. Then locate the two station locations with dots. Draw a vertical line through the Washington, D.C. station. An example of this overlay operation is shown in figure 11-56, although the transmitter and receiver locations are not Washington, D.C. and Virginia Beach.

Step 2: Place this overlay on the great circle chart, figure 11-9, and align the

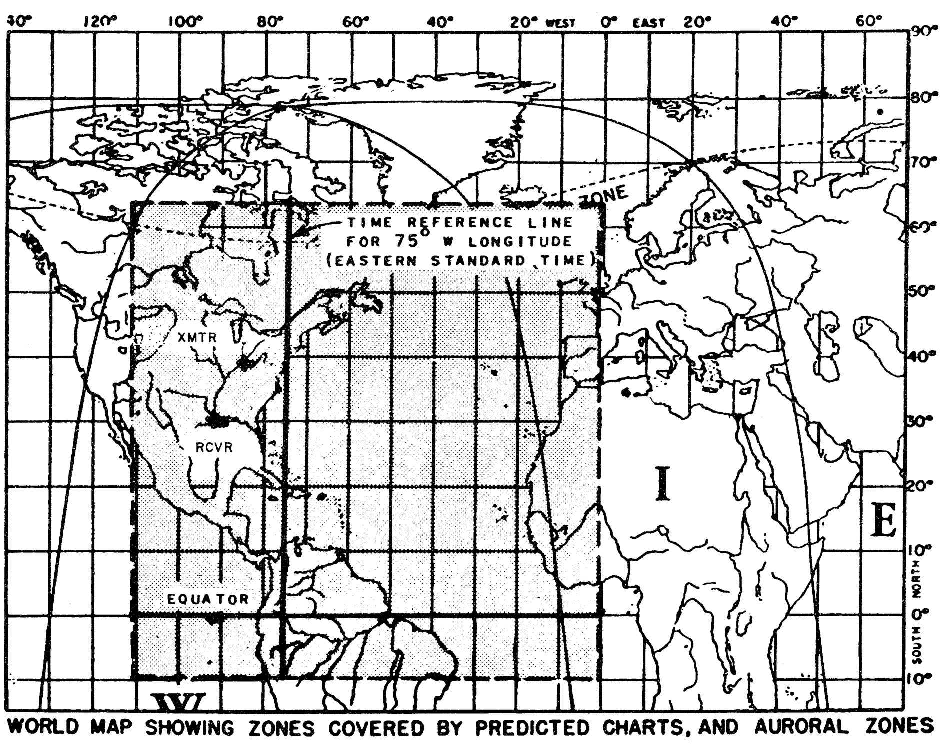


Figure 11-56. Overlay on World Map

equator line of the overlay with the equator line of the great circle chart. Then slide the overlay on the great circle chart until the two stations lie on the same great circle, and draw this transmission path. An example of this operation is shown in figure 11-57. The solid lines represent the great circles, and the dashed lines indicate distance in thousands of kilometers. On the great circle transmission path, locate the midpoint. This is the control point used in determining the MUF. The zone in which the control point lies should be noted from figure 11-8. In this case the control point lies in the W (West) zone.

Step 3: Place the overlay on the F_2-Zero-MUF chart for the W zone, predicted for the month and year of operation, figure 11-10. Align the equator with the zero latitude line and the vertical line with the 0800 local time line. The location of the control point on this F_2-Zero-MUF contour map indicates the zero-MUF in megacycles. To obtain the F_2-Zero-MUF for the other hours of the operating period, slide the overlay horizontally, making the vertical line coincident with the hour of interest. An example of this overlay operation is shown in figure 11-58. The F_2-Zero-MUF information for two-hour increments is entered in column 2 of the work sheet, as shown in figure 11-59.

Step 4: Place the overlay on the F_2-4000 MUF chart for the W zone, predicted for the month and year of operation, figure 11-11, and perform the same operation as in step 3. The F_2-4000-MUF information is entered in column 3 of the work sheet, as shown in figure 11-59.

Step 5: Since the operations of step 3 and step 4 are for the specific distances of zero and 4000 km, it is necessary to interpolate between the two MUF's to obtain the MUF for the particular path length, 253 km. This interpolation is done by the nomogram of figure 11-21. The results of interpolation are entered in column 4 of the work sheet, as shown in figure 11-59. The values entered here are the MUF's for F_2 propagation.

Step 6: The E layer MUF is obtained in a manner similar to the F_2 layer MUF. However, there is only one E layer chart, which is figure 11-12, entitled Median E-2000-MUF. The E-2000-MUF is entered in column 5 of the work sheet. Again, for the particular path length involved, the actual MUF must be interpolated by using the nomogram of figure 11-19. The results of interpolation are entered in column 6 and are the MUF's for E propagation.

Step 7: The sporadic E chart, figure 11-13, should also be analyzed in a manner similar to that for the F_2 and E MUF's. The MUF values obtained from the E_s chart are multiplied by 5 to obtain the E_s-2000-MUF. Then the nomogram of figure 11-19 is used to interpolate the MUF for the particular path distance. Because of the indeterminate nature of E_s, it is not considered in this problem.

The above operations determine the MUF's for the various modes of propagation, i.e., 1-hop E, 1-hop F_2, and 1-hop E_s. For longer paths, 2-hop and 3-hop modes of propagation should also be considered. However, the short communication circuit chosen for this sample problem limits the analysis to a 1-hop sky wave and a ground wave study. This problem was chosen because (1) it is a circuit recently set up in conjunction with the U.S. Navy, and (2) the possibility of ground wave as well as sky wave communication exists because a large portion of the path is over sea water.

(3) Since there is the possibility of propagation by either or both the E layer and the F_2 layer, the minimum frequency that will penetrate the E layer must be determined. If the F_2 MUF is not higher than this E layer penetration frequency, F_2 propagation is impossible. The E layer penetration frequency is determined from the E layer MUF and penetration nomogram, figure 11-20. To do this the frequency strip of the figure must be removed or duplicated. The frequency strip is placed vertically on the nomogram with the E-2000 MUF aligned with the reference line. Then slide the frequency strip horizontally to the point where it corresponds to the path length in kilometers. The points where the curves intersect the frequency strip now indicate (1) the 1-hop E MUF, (2) the 1-hop F_2 penetration frequency, and (3) the 2-hop F_2 penetration frequency, as read from the frequency strip. The value of 1-hop F_2 penetration frequency, of interest in this sample problem, is entered in column 10 of the work sheet, shown in figure 11-59.

(4) The radiation angle for any particular path length and operation mode is obtained from radiation angle curves, figure 11-18. Symmetry is assumed so

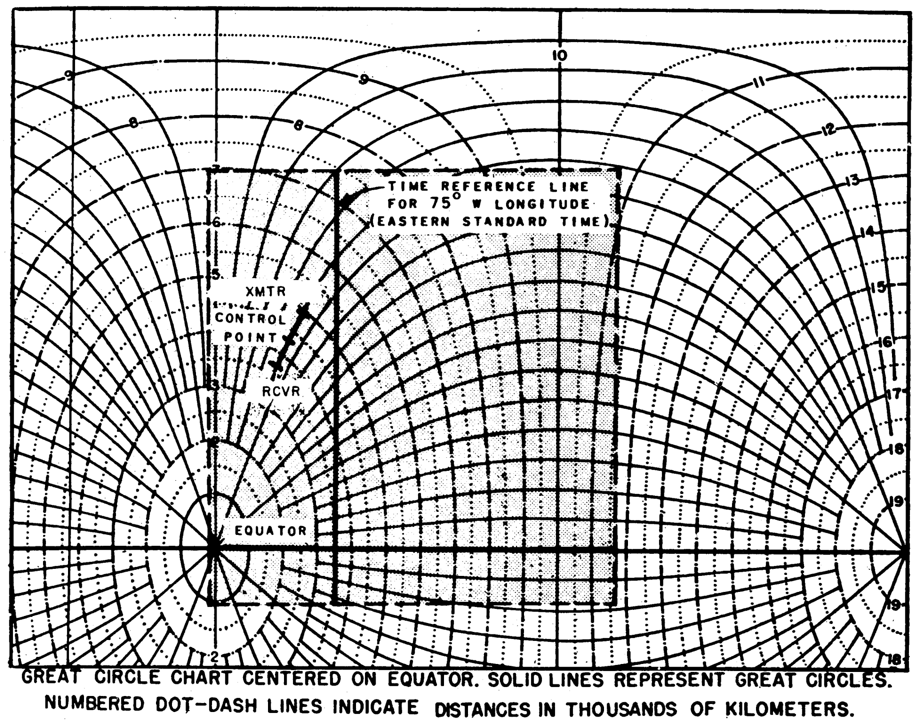


Figure 11-57. Overlay on Great Circle Chart

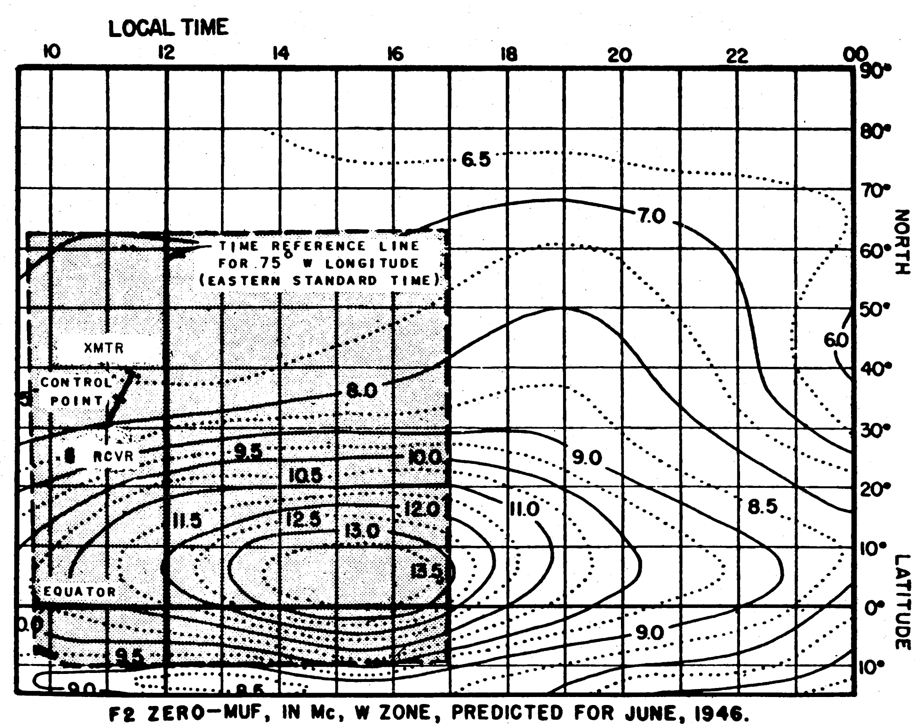


Figure 11-58. Overlay on F_2 Zero MUF, W Zone Chart

that the radiation angle from the transmitting antenna and the angle of reception at the receiving antenna are equal. The radiation angles for the different modes of propagation are obtained from figure 11-18 and entered in column 9 of the work sheet.

(5) Since the received median sky wave field intensity depends upon the total absorption, the absorption must be determined. Auroral absorption K_a, figure 11-23, does not enter into the total absorption because the transmission path is not in the auroral zone. The total absorption is the product, K x M x S. The absorption index K is obtained from the absorption index chart, figure 11-22, in the same manner as the MUF's were obtained, and it is entered in column 7 of the work sheet. Where the path length is greater than 3000 km, the absorption index K must be corrected by using the nomogram of figure 11-24. The sunspot number must be known to determine the solar activity factor S. For the month of April 1957, the sunspot number is 187 and S is found to be 2.0 from the top of figure 11-25. The seasonal correction factor M is read from the table in figure 11-25 for April and is found to be .8. The total correction factor M x S is, therefore 2.0 x .8 which equals 1.6. The corrected absorption index is entered in column 8 of the work sheet, and it is obtained by multiplying the absorption index of column 7 by the correction factor 1.6.

(6) Before the median sky wave field intensity can be determined, it is necessary to choose the operating frequency. For E layer propagation, the frequency of optimum traffic, FOT, is equal to the E layer MUF. For F_2 layer propagation, the FOT is equal to 85 per cent of the F_2 layer MUF. The FOT is chosen as the operating frequency and entered in column 11 of the work sheet.

(7) The received median sky wave field intensity referenced to an inverse distance field of 300 mv/m at 1 km may now be calculated from figures 11-27 through 11-35, the figures used depending upon the mode of propagation and the path length. Where the distance lies between the distances for which these graphs have been made, it is necessary to make a direct-proportion (linear) interpolation between values obtained from two graphs. The values so obtained are entered into column 12 of the work sheet.

(8) The received median field intensity obtained in the operation above is referenced to 300 mv/m at 1 km for 1 kw of radiated power from a short vertical-element antenna over perfect ground, measured in the ground plane. To calculate the actual received field intensity, it is necessary to consider the gain of the transmitting antenna and the actual transmitted power. The gain of the transmitting antenna at different radiation angles is obtained from figures 11-43 through 11-45. The gain of a 15-ft whip antenna is obtained from figure 11-43 and is entered into column 13 of the work sheet. The value obtained is the gain over the reference antenna which is a short vertical element over perfect ground. For the 1-hop E frequencies, the 35-ft whip is less than 1/4 wave length. Therefore, the value obtained for the 15-ft whip is corrected by adding (10 log 35/15) db which is +3.7 db. The value for the 35-ft whip where the radiation angle is 37° is entered in column 14 of the work sheet. For the 1-hop F_2 frequencies, the 35-ft whip is between 1/4 wave length and 1/2 wave length. Therefore, values for the antenna gain are interpolated between the value obtained from figure 11-44 and figure 11-45 for a radiation angle of 66°. This value is entered in column 15 of the work sheet.

(9) The transmitter power output referenced to 1 kw is entered in column 16 of the work sheet. Since the KWT-6 transmitter used in the sample problem is rated at 500 watts PEP, the output referenced to 1 kw is -3 db. The transmitter power output must be referenced to 1 kw because the field intensity entered in column 12 is referenced to 1 kw output.

(10) The effective radiated power is equal to the algebraic sum of the transmitter output, column 16 on the work sheet, and the antenna gain, column 14 or 15. This value is entered in column 22 of the work sheet.

(11) The received field intensity of the median sky wave is the algebraic sum of the effective radiated power, column 22 on the work sheet, and the field intensity in db $>$ 1 uv/m at 1 km, column 12 on the work sheet. This value is entered in column 23 of the work sheet.

(12) Now that the received field intensity is determined, the required field intensity to overcome noise must be determined. Atmospheric noise is determined from a noise distribution chart, figure 11-36, which is drawn from noise level observations and divides the world in various noise grades ranging from 1 to 5. For this problem, the noise grade at the receiving station for April is 2.5. Since the noise level varies with operating frequency and seasons, it is necessary to refer to a curve, such as shown in figures 11-37 through 11-39, to determine the field intensity required to overcome atmospheric noise. Since the operating time is in April, the figure 11-39 is used, and the values obtained are entered in column 17 of the work sheet. The value entered here is the hourly median value of minimum required field intensity that will provide a S/N ratio of 13.8 db 90 per cent of the days for double sideband, radiotelephone communication in the presence of atmospheric noise. Because the required field intensity to overcome atmospheric noise depends upon the location of the receiving station, a separate analysis must be made for a two-way communication circuit whenever the

noise grade for the two stations is different. However, in this sample problem, the two stations are so close together that the same atmospheric noise conditions exist at both stations. Therefore, if successful transmission is possible in one direction, it is also possible in the reverse direction, in this problem.

(13) The field intensity required to overcome set noise is determined from curves such as figures 11-40 through 11-42, in a manner similar to that used for determining the antenna gain for a 35-ft whip antenna. From figure 11-40, the minimum required field intensity to overcome set noise with a 15-ft whip antenna is obtained for the 1-hop E propagation at 37°. From this value, (10 log 35/15) db is subtracted to adjust the figure for the 35-ft whip antenna. The value of (10 log 35/15) is 3.7 db. For 1-hop F_2 propagation at 66°, values are obtained from figures 11-41 and 11-42 for 1/4 and 1/2 wave length antennas. Then the value for the 35-ft whip antenna is logarithmically interpolated between these two values. The values obtained for field intensity to overcome set noise are entered in column 18 of the work sheet. The discrimination gain of the whip antenna is neglected.

(14) The minimum required field intensity for the system to overcome all noise is the greater of the field required to overcome atmospheric noise and the field required to overcome set noise. Therefore, the greater of column 17 and 18 is entered in column 19 on the work sheet.

(15) The required field intensity entered in column 19 is based on a median field intensity with a double sideband voice signal. To adjust this value for single-sideband voice and for a field intensity which exceeds the median 90 per cent of the time, the service gain value is used. The table of service gains for sky wave communication with a fading signal is obtained from figure 11-26. For single-sideband radiotelephony, speech grade quality, the service gain is -1 db. This service gain value, which has been adjusted for a fading signal, is entered in column 20 of the work sheet. The required field intensity for reception, column 21, is then the sum of the required field intensity to overcome noise and the service gain. That is, column 21 is equal to column 19 plus column 20. The value entered in column 21 is the required field intensity to assure satisfactory radiotelephone communication for 90 per cent of the time in the presence of atmospheric noise and set noise for single-sideband radiotelephony.

(16) If the received field intensity, column 23, is greater than or equal to the required field intensity for reception, column 21, satisfactory sky wave communication is possible. The threshold for satisfactory communication is defined as a S/N ratio of 13.8 db. In this sample problem, satisfactory 1-hop E sky wave communication is possible throughout the operation period of 0800 to 1600 during April 1957. This fact is entered in column 24 of the work sheet. Satisfactory 1-hop F_2 communication is not possible.

c. GROUND WAVE PROPAGATION ANALYSIS

(1) For the sample problem, the possibility of ground wave communication exists for the Washington, D.C. to Virginia Beach circuit because the path length is short. This possibility is made evident by an examination of the terrain over the communication path which shows that the greater portion of the path is over sea water. Also, the ability of the transmitter used to operate at frequencies as low as 2 mc increases the possibility of ground wave communication. The transmission path from Washington, D.C. to Virginia Beach, Va. consists of 0 to 50 miles over poor soil, 50 to 75 miles over sea water, 75 to 100 miles over poor soil, 100 to 160 miles over sea water. Figure 11-46 is a world map showing these various types of terrain. Since ground wave propagation over sea water is quite good, compared to propagation over poor ground which greatly attenuates the wave, the 85-mile sea water path increases the possibility of ground wave communication for this circuit.

(2) For ground wave propagation, the choice of operating frequencies is arbitrary, but generally the received field strength increases with a decrease in frequency. The received field intensity is limited only by the power capability of the transmitter and is independent of the time of day. For this sample problem, 2 mc and 4 mc frequencies are chosen for analysis and are entered in column 2 of the work sheet, figure 11-60.

(3) Figures 11-47 through 11-49 are curves which indicate the received field intensity for ground wave propagation versus distance for various types of earth. The received field intensity is referenced to 300 mv/m at 1 km radiated from a short vertical element over perfect ground with an input power of 1 kw. The received field strength over a mixed-earth transmission path is calculated as follows:

Step 1: The field strength for the first 50 miles is determined from figure 11-47 at the operating frequency for poor soil conditions.

Step 2: The field strength for the distance 50 to 75 miles is determined from figure 11-49 by entering the proper frequency curve at the same decibel level as obtained in step 1. From the distance which corresponds with the point of entry, 25 miles is added, and the resulting field strength recorded.

Step 3: The field strength for the distance 75 to 100 miles is determined from figure

11-47 by entering the proper frequency curve at the same decibel level as obtained in step 2. From the distance which corresponds with the point of entry, 25 miles is added, and the resulting field strength recorded.

Step 4: Finally, the field strength for the distance 100 to 160 miles is determined from figure 11-49 by entering the proper frequency curve at the same decibel level as obtained in step 3. From the distance which corresponds with the point of entry, 60 miles is added, and the field strength recorded. This final field strength is the received field strength for the 160 mile mixed-earth transmission path. This value is entered in column 3 of the work sheet, figure 11-60.

(4) The transmitting antenna gain for the 35-ft whip antenna at the operating frequencies is obtained from figure 11-53, which is drawn for a 15-ft whip antenna. Since the operating frequencies are low, the 35-ft whip can be considered equal to the 15-ft whip, because they both are less than 1/8 wave length at the frequencies involved. The antenna gain is entered in column 4 of the work sheet.

(5) Since the field intensity entered in column 3 is referenced to 1-kw input power to the antenna, the input power of the transmitter used must be referenced to 1 kw. The power input of the 500-watt PEP transmitter is -3 db. This value is entered in column 5 of the work sheet.

(6) The received ground wave field intensity can now be determined. It is the sum of the field intensity, the transmitting antenna gain, and the input power, that is, column 3, plus column 4, plus column 5. This value is entered in column 6 of the work sheet.

(7) Having completed the determination of the received ground wave field intensity, the required field intensity for reception must be determined. The required field intensity to overcome atmospheric noise is obtained in exactly the same manner as it is for sky wave propagation, and the same charts and graphs are used. See subparagraph b(12) of this paragraph for this procedure, keeping in mind that the operating frequencies for ground wave propagation are different from those used in the sky wave analysis. The values of field intensity required to overcome atmospheric noise are entered in column 7 of the work sheet.

(8) The field intensity required to overcome set noise is determined from figure 11-50. The curve for the 15-ft grounded vertical whip antenna is used for this calculation, the 15-ft whip being considered equal to the 35-ft whip at the frequencies involved. The values of field intensity required to overcome set noise are entered in column 8 of the work sheet.

(9) The minimum required field intensity to overcome all noise is the greater of the field intensity required to overcome atmospheric noise and the field intensity to overcome set noise. This value is entered in column 9 of the work sheet. That is, column 9 is the greater of column 7 and column 8.

(10) Since the minimum required field to overcome noise is based on a double sideband radiotelephone signal, it must be adjusted by the service gain for single-sideband radiotelephone. The value of service gain for single-sideband radiotelephony for ground wave communication is -9 db, as obtained from figure 11-51. This value is entered in column 10 of the work sheet.

(11) The required field intensity for reception can now be determined. It is the algebraic sum of required field intensity to overcome noise, column 9, and the service gain, column 10. This value is entered in column 11 of the work sheet.

(12) If the received field intensity, column 6, is equal to or greater than the required field intensity for reception, column 11, satisfactory ground wave communication is possible. In this sample problem, ground wave communication is possible for an operating frequency of 2 mc. This fact is entered in column 12. Satisfactory ground wave communication is not possible for an operating frequency of 4 mc.

d. FINAL ANALYSIS

This study of propagating conditions between Washington, D.C. and Virginia Beach, Va. indicates that two modes of propagation may be used during an operating period between 0800 and 1600 in April 1957. Frequencies between 4.6 mc and 5.5 mc may be used for E layer, sky wave propagation, or a frequency of 2.0 mc may be used for ground wave propagation. Of the two possible modes, the strongest signal will result from E layer sky wave propagation because the received field strength is much larger than the required field strength.

Column 1: Operation period logged in 2-hour increments

Column 2: From figure 11-10

Column 3: From figure 11-11

Column 4: Interpolated between column 2 and column 3 using figure 11-21

Column 5: From figure 11-12

Column 6: Interpolated from column 5 using figure 11-19

Column 7: From figure 11-22

Column 8: Column 7 multiplied by correction factor (M x S) which is obtained from 11-25

Column 9: From figure 11-18

Column 10: Interpolated from column 5 using figure 11-20

Column 11: For 1-hop E, taken as column 6; for 1-hop F_2, taken as 85 per cent of column 4

Column 12: From figures 11-27 and 11-30 for 1-hop F_2, using linear interpolation between values obtained; from figures 11-29 and 11-32 for 1-hop E, using linear interpolation between values obtained

Column 13: From figure 11-43

Column 14: Column 13 plus (10 log 35/15) for 1-hop E

Column 15: From figures 11-44 and 11-45 for 1-hop F_2 using logarithmic interpolation between values obtained

Column 16: Transmitter power output of 500 watts referenced to 1 kw equals -3 db

Column 17: From figures 11-36 and 11-39

Column 18: From figure 11-40 less (10 log 35/15) for 1-hop E; from figures 11-41 and 11-42 for 1-hop F_2, using logarithmic interpolation between values obtained

Column 19: The greater of column 17 and column 18

Column 20: From figure 11-26

Column 21: Column 19 plus column 20

Column 22: Column 16 plus column 14 for 1-hop E; column 16 plus column 15 for 1-hop F_2

Column 23: Column 12 plus column 22

Column 24: "Yes" if column 23 is equal to or greater than column 21; "no" if column 23 is less than column 21

SKY WAVE PROPAGATION ANALYSIS

CIRCUIT: Washington, D.C. to Virginia Beach, Va.; 253 km (160 miles)

ANTENNAS: 35-ft whips for both transmitting and receiving

TRANSMITTER: KWT-6 with PEP output of 500 watts

TYPE OF SERVICE: SSB voice

PERIOD OF OPERATION: From 0800 to 1600, April 1957 (local time)

Local Time	F_2 Zero MUF (mc)	F_2 4000 MUF (mc)	F_2 MUF 253 km, 1-hop Path (mc)	E 2000 MUF (mc)	E MUF 253 km, 1-hop Path (mc)	Absorption Index K at Control Point	Corrected K for Seasonal and Solar Factors (Correction factor = 1.6)	Radiation Angle, Δ, for 1-hop E, 1-hop F_2 (degrees)	1-hop F_2 E-layer Penetration Freq (mc)	Operating Freq	Field Intensity for 300 mv/m at 1 km (DB > 1 uv/m)	Antenna Gain with 15-ft whip for Δ = 37° and Δ = 66° (DB)	Antenna Gain with 35-ft Whip for Δ = 37°, (DB)	Antenna Gain with 35-ft Whip for Δ = 66° (DB)	Transmitter Power Output (DB > 1 kw)	Required Field Intensity to Overcome Atmospheric Noise; Noise Grade - 2.5 (DB > 1 uv/m)	Required Field Intensity to Overcome Set Noise (DB > 1 uv/m)	Required Field Intensity to Overcome Noise (DB > 1 uv/m)	Service Gain (DB)	Required Field Intensity For Reception (DB > 1 uv/m)	Effective Radiated Power (DB > 1 uv/m)	Received Field Intensity (DB > 1 uv/m)	Sky Wave Communication Possible
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0800	10.6	31.0	10.8	16.8	4.6	.54	.86	37	--	4.6	37.0	-14.0	-10.3	--	-3.0	-1.0	+3.3	+3.3	-1	2.3	-13.3	23.7	Yes
1000	12.0	33.0	12.3	19.0	5.2	.80	1.28	37	--	5.2	33.0	-13.0	-9.3	--	-3.0	-1.5	+3.3	+3.3	-1	2.3	-12.3	20.7	Yes
1200	12.7	34.0	12.9	19.9	5.5	.90	1.44	1-hop E 37	--	5.5	32.5	-13.0	-9.3	--	-3.0	-2.5	+3.3	+3.3	-1	2.3	-12.3	20.2	1-hop E Yes
1400	12.8	35.5	13.1	19.0	5.2	.80	1.28	37	--	5.2	33.0	-13.0	-9.3	--	-3.0	+1.0	+3.3	+3.3	-1	2.3	-12.3	20.7	Yes
1600	12.5	35.0	12.8	16.6	4.6	.55	.88	37	--	4.6	37.0	-14.0	-10.3	--	-3.0	+3.0	+3.3	+3.3	-1	2.3	-13.3	23.7	Yes
0800	10.6	31.0	10.8	16.8	4.6	.54	.86	66	3.7	9.2	27.0	-15.0	--	-14	-3.0	+8.0	+19.0	+19.0	-1	18.0	-17.0	10.0	No
1000	12.0	33.0	12.3	19.0	5.2	.80	1.28	66	4.2	10.5	26.0	-14.0	--	-14	-3.0	+7.5	+19.0	+19.0	-1	18.0	-17.0	9.0	No
1200	12.7	34.0	12.9	19.9	5.5	.90	1.44	1-hop F_2 66	4.4	11.0	25.0	-14.0	--	-14	-3.0	+8.0	+19.0	+19.0	-1	18.0	-17.0	8.0	1-hop F_2 No
1400	12.8	35.5	13.1	19.0	5.2	.80	1.28	66	4.2	11.1	27.0	-14.0	--	-14	-3.0	+8.0	+19.0	+19.0	-1	18.0	-17.0	10.0	No
1600	12.5	35.0	12.8	16.6	4.6	.55	.88	66	3.6	10.9	30.5	-14.0	--	-14	-3.0	+14.5	+19.0	+19.0	-1	18.0	-17.0	13.5	No

Figure 11-59. Tabulated Sky Wave Propagation Analysis

Column 1: Operation period logged in 2-hour increments

Column 2: Arbitrarily chosen

Column 3: From figures 11-47 and 11-49

Column 4: From figure 11-53

Column 5: Transmitter power output of 500 watts referenced to 1 kw equals -3 db

Column 6: Column 3, plus column 4, plus column 5

Column 7: From figures 11-36 and 11-39

Column 8: From figure 11-50

Column 9: The greater of column 7 and column 8

Column 10: From figure 11-51

Column 11: Column 9 plus column 10

Column 12: "Yes" if column 6 is equal to or greater than column 11; "no" if column 6 is less than column 11

GROUND WAVE PROPAGATION ANALYSIS

CIRCUIT: Washington, D. C. to Virginia Beach, Va.; 160 miles
from 0-50 miles, poor soil
from 50-75 miles, sea water
from 75-100 miles, poor soil
from 100-160 miles, sea water

ANTENNAS: 35-ft whips for both transmitting and receiving
TRANSMITTER: KWT-6 with PEP output of 500 watts
TYPE OF SERVICE: SSB voice
PERIOD OF OPERATION: From 0800 to 1600, April 1957 (local time)

Local Time	Frequency (mc)	Field Intensity (DB > 1 uv/m)	Transmitting Antenna Gain Referred to Short Vertical Element (DB)	Input Power (DB > 1 kw)	Received Field Intensity (DB > 1 uv/m)	Required Field Intensity to Overcome Atmospheric Noise (DB > 1 uv/m)	Required Field Intensity to Overcome Set Noise (DB > 1 uv/m)	Minimum Required Field Intensity to Overcome Noise (DB)	Service Gain (DB)	Required Field Intensity for Reception (DB)	Ground Wave Communication Possible
1	2	3	4	5	6	7	8	9	10	11	12
0800	4	-5	-9.0	-3.0	-17.0	-4.0	-.4	-.4	-9.0	-9.4	No
1000	4	-5	-9.0	-3.0	-17.0	-6.0	-.4	-.4	-9.0	-9.4	No
1200	4	-5	-9.0	-3.0	-17.0	-8.5	-.4	-.4	-9.0	-9.4	No
1400	4	-5	-9.0	-3.0	-17.0	-4.0	-.4	-.4	-9.0	-9.4	No
1600	4	-5	-9.0	-3.0	-17.0	+1.0	-.4	+1.0	-9.0	-8.0	No
0800	2	+8	-14.0	-3.0	-9.0	-10.0	-.4	-.4	-9.0	-9.4	Yes
1000	2	+8	-14.0	-3.0	-9.0	-13.0	-.4	-.4	-9.0	-9.4	Yes
1200	2	+8	-14.0	-3.0	-9.0	-16.5	-.4	-.4	-9.0	-9.4	Yes
1400	2	+8	-14.0	-3.0	-9.0	-11.0	-.4	-.4	-9.0	-9.4	Yes
1600	2	+8	-14.0	-3.0	-9.0	-6.0	-.4	-.4	-9.0	-9.4	Yes

Figure 11-60. Tabulated Ground Wave Propagation Analysis

PROPAGATION ANALYSIS WORK SHEET

CIRCUIT ____________________

ANTENNAS ____________________

TRANSMITTER ____________________

TYPE OF SERVICE ____________________

PERIOD OF OPERATION ____________________

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

16	17	18	19	20	21	22	23	24	25

Sample Work Sheet No. 1

PROPAGATION ANALYSIS WORK SHEET

CIRCUIT ______________________________

ANTENNAS ______________________________

TRANSMITTER ______________________________

TYPE OF SERVICE ______________________________

PERIOD OF OPERATION ______________________________

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

16	17	18	19	20	21	22	23	24	25

Sample Work Sheet No. 2