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DEPARTMENT OF THE ARMY TECHNICAL MANUAL

RADIO PROPAGATION

DEPARTMENT OF THE ARMY · AUGUST 1950

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TM 11-499

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RADIO PROPAGATION

DEPARTMENT OF THE ARMY *AUGUST 1950*

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For explanation of distribution formula, see SR 310–90–1.

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CHAPTER 1

INTRODUCTION

Section I. GENERAL

1. Purpose

The purpose of this manual is to explain the theory of elementary radio propagation and to present methods for the solution of practical radio communication problems.

a. This manual is not intended to be a comprehensive treatise on the theory of wave propagation. Instead, it sets forth in simple form the physical theory underlying the principles of radio propagation and brings the theory into understandable relation with the practical problems of radio communication.

b. This manual is intended to be a practical handbook. It gives complete step-by-step procedures which can be followed when working out the solutions to all kinds of radio propagation problems, such as the determination of expected distance ranges for particular transmitting conditions, the equipment requirements, and the most sitable frequencies for specific communication circuits. Some of the factors which are considered in the solutions of these problems are as follows:

(1) Time of transmission (day, night, season, year).
(2) Frequency of transmission (0.03 to 300 mc (megacycles)).
(3) Geographical locations of the transmitter and receiver.
(4) Types of transmitting and receiving antennas.
(5) Power output capabilities of the transmitter.
(6) Noise output of the radio receiver and the signal strength required to obtain a favorable signal-to-noise ratio.

c. This manual contains numerous charts, curves, and nomograms which eliminate the necessity of solving complex equations involving higher mathematics when working out solutions to radio communication problems. For sky-wave transmission, these charts, curves, and nomograms are supplemented by the ionospheric predictions* published monthly by the Department of the Army.

2. Modes of Transmission

There are two principal ways in which radio waves travel from the transmitter to the receiver: by means of the sky wave which travels up to the ionized layers in the earth's upper atmosphere (called the ionosphere) and which is reflected by them back to earth; and by means of the ground wave which travels directly from the transmitter to the receiver. In this manual, transmission by means of the sky wave is referred to as *sky-wave transmission;* transmission possible without the influence or presence of the ionosphere is referred to as *ground-wave transmission.* Most long-distance radio transmission takes place by means of the sky wave, and most short-distance transmission takes place by means of the ground wave. Some transmissions consist of a combination of both waves.

3. Frequency of Transmission

In this manual, sky-wave transmission at frequencies between 2 and 30 mc is mainly considered. The propagation of vertically polarized ground waves for frequencies between 0.1 and 300 mc also is considered for distances principally beyond the line of sight. In general, the frequencies between 0.03 and 300 mc are used for radio communication as follows:

a. Frequencies from 0.03 to 0.3 mc are used for long-distance ground-wave communication, especially in regions where blackouts are common for sky-wave communication. These blackout periods,

*TB 11–499–( ), Basic Radio Propagation Predictions.

in which sky-wave communication is not possible, occur most frequently in regions at high latitudes where ionospheric conditions often are abnormal.

b. Frequencies from 0.1 to 3 mc are used mainly for ground-wave transmission for moderately long distance over water and moderate to short distances over land.

c. Frequencies from approximately 1 to 3 mc generally are suitable for sky-wave transmission during the night for distances up to about 200 miles; during the daytime, frequencies from about 3 to 8 mc usually are satisfactory for this distance range.

d. Long-distance, sky-wave transmission generally is the most effective for frequencies from 3 to 12 mc during the night and 6 to 25 mc during the day. Frequencies from 3 to 30 mc are used for ground-wave transmission for relatively short distances over land and moderate distances over water.

e. Short-distance, ground-wave communication utilizes frequencies from 30 to 300 mc. The transmission at these frequencies is confined to distances not greatly exceeding the line-of-sight distance.

4. Outline of Chapters

a. This chapter contains an introduction to the subject material of this manual and a review of some of the mathematical concepts of radio propagation theory and practice.

b. Chapter 2 explains the fundamental principles of sky-wave and ground-wave propagation. This chapter is explanatory in nature and does not attempt theoretical proofs of the theories discussed. Mathematical equations are introduced only when they appear to give a clear and concise explanation of the theory.

c. Chapter 3 shows the practical applications of the theory of sky-wave propagation and the solutions of practical sky-wave communication problems. Several practical problems are worked out completely and show the procedures used. Most of the methods are based on the use of nomograms and the direct reading of curves, both of which are included in this chapter. These curves and nomograms have been obtained from the analysis of field intensity recordings.

d. Chapter 4 shows the practical applications of theory of ground-wave propagation and the solutions of practical ground-wave communication problems (for vertically polarized waves). Sample problems are worked out and all necessary curves and nomograms are included. These curves and nomograms are based mainly on theoretical work, primarily the investigations of K. A. Norton (see bibliography, app. II). Experimental data confirm the curves.

e. Appendix I contains a miscellany; appendix II, a glossary and bibliography; and an index to the text material completes the manual.

Section II. MATHEMATICAL INTRODUCTION

5. Use of Mathematics

The main purpose of this manual is to permit rapid evaluation of practical propagation problems; therefore, numerous charts have been included in order to eliminate computations which would involve complicated mathematical formulas. *All necessary calculations can be made by means of simple arithmetic.* Many of the solutions are obtained by the use of nomograms which require only the use of a straightedge. Since many quantities vary in a random fashion, much of the study of propagation is based on statistics. There are curves in this manual which show the statistical variation of field intensities and noise within a given period. All that is required is to read the values from the curves to find the quantities at some specified percentage of time. It is, nevertheless, necessary to explain some of the mathematical theory for those readers who are unfamiliar with the terminology. Many of the mathematical equations are used because it is believed that a simplified equation often gives the best and most concise explanation. If the reader is not familiar with trigonometry and logarithms, he can refer to a standard book on the subject.

6. Decibel

Many quantities used in radio propagation work and in communications engineering are expressed in ratios to some reference quantity. In transmis-

sion line theory, losses are expressed in ratios, since equal portions of power (not equal powers) are lost along each like section of a line. The human ear responds according to ratios, the response to a sound being proportional to the amount of sound already present. The quantities frequently are expressed in db (decibel) units. The db is a unit of power ratio and can be expressed by the equation—

$$db = 10 \log_{10} \frac{P_1}{P_2} \qquad \text{(Eq 1)}$$

where P_1 is the power that is to be expressed in db relative to a power, P_2. This equation can be expressed in terms of voltages and resistances, using the relationship—

$$P = \frac{E^2}{R}$$

where P is the average power,
E is the effective value of the voltage across the load, and
R is the load resistance.
The db then can be written as—

$$db = 10 \log_{10} \frac{P_1}{P_2} = 10 \log_{10} \frac{\frac{E_1^2}{R_1}}{\frac{E_2^2}{R_2}}$$

$$= 10 \log_{10} \frac{E_1^2 R_2}{E_2^2 R_1}$$

$$= 10 \log_{10} \frac{E_1^2}{E_2^2} + 10 \log_{10} \frac{R_2}{R_1}$$

$$= 20 \log_{10} \frac{E_1}{E_2} + 10 \log_{10} \frac{R_2}{R_1}$$

In case the voltage is developed across equal resistances, the expression for the db is—

$$db = 20 \log_{10} \frac{E_1}{E_2} \qquad \text{(Eq 2)}$$

Field intensities in this manual generally are expressed in db referred to 1 microvolt per meter as the base. The inverse distance field intensities of transmitting antennas often are expressed in db referred to a standard value.

7. Arithmetic Mean

Various methods of averaging are used in statistics. An average measures the central tendency of a group of data. The average most commonly used is the arithmetic mean. The arithmetic mean is easy to compute; it is the sum of the values divided by the number of quantities. The arithmetic mean of the group of values 8, 7, 14, 9, and 9 is—

$$\frac{8 + 7 + 14 + 9 + 9}{5} = 9.4$$

8. Median

The median is the middle value of a group of quantities which are arranged according to size. If there is an even number of quantities, the median is taken as the arithmetic average of the two central quantities. The median measures the average of position; the arithmetic mean is the calculated average of values. The median is calculated easily and is not distorted by unusual items. One disadvantage in determining the median is that the items first must be arranged according to size. The group of quantities used in paragraph 7 to illustrate the arithmetic average can be used to show the median. The numbers are arranged according to size, and the middle value is selected as the median, since (in this instance) the number of quantities is an odd number: 7, 8, 9, 9, 14. The middle value, or the median, is equal to 9.

9. Probability of Occurrence

The study of fluctuating phenomena and statistical analysis is based largely on probability theory. In statistics, it often is necessary to work with theoretical values which closely represent the actual observations. In the theory of probability, it is necessary to assign numerical values to probability. It is customary to assign a value of 1 for the probability of an event which is certain to occur. In coin tossing, since there are two possibilities (either the head or the tail), the probability of the head turning up in one toss is 0.50. Although equally likely events such as this one are not frequent in engineering studies, they are useful in explaining the theory. Most quantities in engineering have definitely preferred ranges in value. Although the manufacturer of electrical resistors may desire that the resistors have a certain value (for example, 300 ohms), it is not possible to forecast exactly whether all the resistors will have this value, but it is highly probable that most of them will be approximately 300 ohms. A resistance value of 305 ohms is much more likely to occur than one of 400 ohms. A curve can be drawn show-

ing the chance or probability that a resistor will lie within a certain resistance range. A curve of this nature is known as a frequency distribution or probability curve. These frequency distribution curves can be drawn so that the total area under the curve corresponds to the total number of quantities, and the area within a certain range of values represents the number of quantities that can be expected to fall within this range. Likewise, experimental data follow various distribution laws. These distribution laws can be shown in graphical form.

10. Histogram

Experimental data do not provide a clear description of the facts unless they are condensed and arranged in a systematic manner. Statisticians usually group data into classes showing the number of quantities that fall within a certain group. The arrangement in groups is a frequency distribution, since it indicates the number of quantities of particular magnitudes. The experimental values often are plotted as histograms. The rectangles in figure 1 comprise a histogram. The distribution is drawn in rectangles, the width representing a range of values or a class interval, the height representing the number of values within the class interval. A smooth curve (not shown) can be drawn through the rectangles at the midpoint of the class intervals. If the class intervals are considered as unit quantities, the area under the curve represents the total number of quantities in the data. These experimental frequency curves then can be compared with theoretical distribution curves, such as the normal distribution curve of figure 1, to find what type of distribution function the data appear to follow.

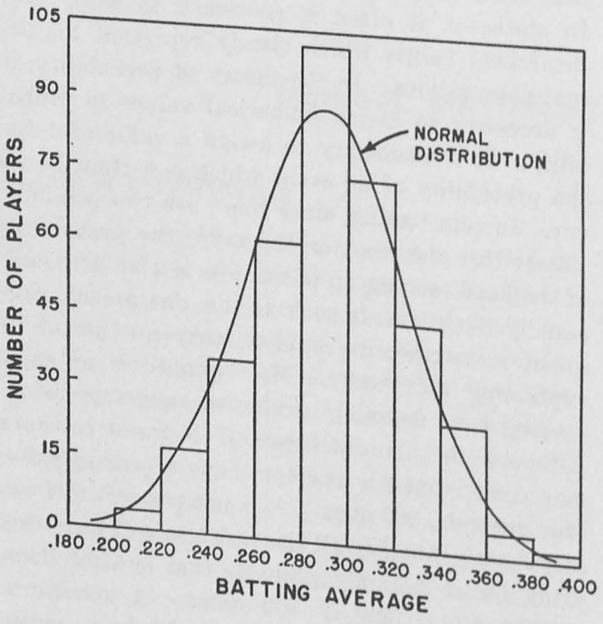


Figure 1. Histogram showing batting averages of major and minor league baseball players.

11. Normal Curve of Error

a. The most commonly used distribution function in statistics is the normal curve of error, also called the normal distribution curve. If numerous measurements are taken of some physical quantity, with all measurements being independent and assumed to be equally reliable, the errors in the measurements from the arithmetic mean can be evaluated. A positive error occurs when the measured quantity is greater than the mean. In performing the measurements, note that all errors are not likely to occur with the same frequency. In general, large errors are less likely to occur than small errors. The probability of positive and negative errors of the same value are equal. An infinitely large error cannot occur. Thus, one can make an approximation of the normal distribution curve by remembering that the most probable value is likely to be the average value, and the probability will decrease as the measured value differs substantially from the mean. This curve extends from minus infinity to plus infinity, with zero probabilities at the infinite points. The probability that a measurement will lie between two values representing a class interval is equal to the area between the class limits.

b. The equation for the error curve can be written as follows:

$$y = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-\left(\frac{\delta^2}{2\sigma^2}\right)} \qquad \text{(Eq 3)}$$

where y is the probability for an error, δ;
δ is an error on measurement expressed as a deviation from the mean;
σ is the standard deviation from the mean and is a parameter arrived at in the mathematical derivation; and
e is 2.71828 (the base of the Naperian logarithms).

c. It can be shown that, for the normal distribution, the sum of the squares of the errors is a mini-

mum. The normal error curve represents errors of observation in physical sciences. The day-to-day variations in sky-wave field intensities approximately follow a normal distribution.

12. Normal Curve Expressed in Standard Deviation Units

The normal curve is shown most often in standard units. The standard deviation indicates the dispersion or spread of the data. For widely spread data, the standard deviation is large. Curve 1 of figure 2 indicates the normal distribution curve, when drawn in standard deviation units.

13. Cumulative Distribution

The probability for a normal distribution that a value will be less than the mean value is 0.5, and the probability that it will be greater than the mean is 0.5 also, since the area under the probability curve is equal to 0.5 on each side of the mean. The probability that a value will be less than some selected value expressed as t, is the area of the curve to the left of t. In mathematical language, such a probability would be equal to the integral of the error curve from minus infinity to t. From probability theory, it is shown that the sum of the probability of a thing occurring and the probability of a thing not occurring is equal to 1. Thus, since a thing either occurs or does not occur, it is evident that the probability that a value will exceed some value t is equal to 1 minus the probability that it will not exceed t. Plots showing probabilities that values will or will not be exceeded are called *cumulative distribution.* Curve 2 of figure 2 is a cumulative distribution of curve 1.

14. Percentage of Values

Statistical studies often are concerned with the percentage of values which are less than or greater than a given value. The percentage is equal to 100 times the probability. The cumulative frequency in percentage is equal to the sum of the percentage of quantities in the class intervals up to the value considered. Thus, if the percentage of values less than some value t is required, the percentage is equal to the sum of the percentages in the class intervals less than t.

15. Probability Paper

The day-to-day and minute-to-minute variations in sky-wave intensities can be plotted on probability paper. Probability paper has scales so arranged that, when the cumulative frequencies of the normal curve are plotted on the paper, the curve be-

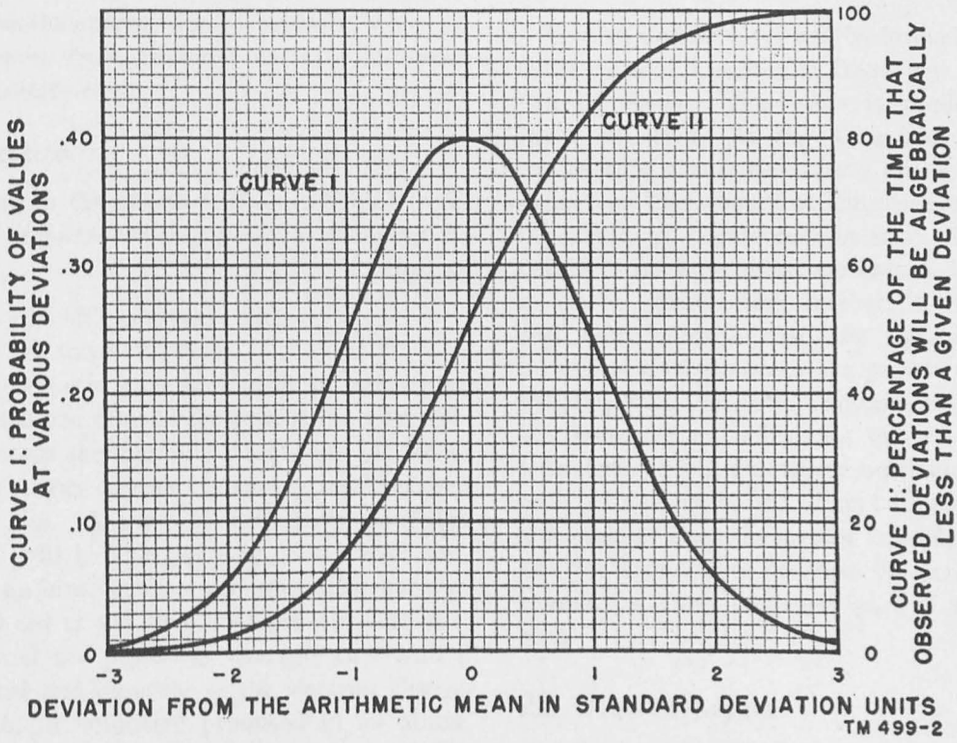


Figure 2. The error or normal curve and its cumulative distribution.

comes a straight line. Thus, if the observed day-to-day values of hourly median field intensities about the monthly median value are plotted on probability paper and the values fall in a straight line, the day-to-day distribution can be said to vary in a normal distribution.

16. Rayleigh Distribution

The minute-to-minute variations or variations that occur in smaller time intervals of sky-wave field intensities, appear to follow the Rayleigh distribution. This distribution shows the total intensity due to a large number of components of equal magnitudes but of arbitrary phases. The mathematical expression for the Rayleigh distribution can be shown by the following equation:

$$y = \frac{2(0.693)E}{Em^2} \; e^{-0.693\left(\frac{E}{Em}\right)^2} \qquad \text{(Eq 4)}$$

where y is the probability for an intensity E;
E is the total or instantaneous intensity due to all the contributing components;
Em is the median intensity; and
$e = 2.71828$.

17. Instantaneous Field Intensity

The percentage of the time that the instantaneous field intensity exceeds a value, E, is obtained by summing up the distribution curve or integrating it from the required value E to ∞. The instantaneous field intensity exceeds the value E for the percentage of time, T, given by the equation—

$$T = 100 \int_E^{\infty} \frac{2(0.693)E}{Em^2} e^{-0.693\left(\frac{E}{Em}\right)^2} dE \qquad \text{(Eq 5)}$$

$$= 100 \; e^{-0.693\left(\frac{E}{Em}\right)^2}$$

CHAPTER 2

ELEMENTARY PROPAGATION THEORY

Section I. FORMATION OF THE IONOSPHERE

18. Electron Orbits

Some of the concepts of modern physics can be used to explain the presence of ionized layers in the earth's upper atmosphere.

a. Bohr explained the structure of atoms as a simple electrical structure. In his theory, electrons are assumed to be traveling in orbits about a positively charged nucleus. The number of electrons at a particular energy level or orbit and the number of orbits occupied by electrons is dependent on the particular element. The number of orbital electrons is equal to the atomic number. The electron is permitted to travel only in certain special orbits called stationary states.

b. The atoms do not radiate or absorb energy when in a stationary state but only when moving from one stationary state to another. When an electron moves from an inner orbit to an outer orbit, it absorbs energy, and, conversely, when an electron moves from an outer orbit to an inner orbit, it radiates energy.

19. Ionization

According to the quantum theory, light is composed of photons each with a quantum of energy, E.

$$E = h\,v \qquad \text{(Eq 6)}$$

where h is Planck's constant; and

v is the wave frequency.

An electromagnetic wave is capable of moving an electron from one orbit to the next if the wave frequency exceeds the minimum frequency for which the photon energy exceeds the energy level between the two orbits. A wave of sufficiently hf (high frequency) will be able not only to move an electron from an inner orbit to an outer orbit but also to knock it out of the atom. Atoms with one electron removed are positively charged ions with a charge equal and opposite to the electron charge. The amount of ionization produced in an atmosphere by ultraviolet waves depends on the intensity and frequency of the waves and the density of the atmosphere.

20. Recombination

Positively charged ions and negatively charged electrons tend to recombine into neutral atoms. As suggested by the kinetic theory of gases, ions are in continual random motion. The rate of recombination is greater in a densely ionized atmosphere since the mean free path of the ions is smaller and ions are more apt to collide with free electrons. As the intensity of radiation increases, both the rate of ionization and recombination increase. With a wave of particular intensity, an equilibrium state is reached. It is assumed that equilibrium is reached with only a fraction of the molecules ionized.

21. Formation of an Ionized Layer

How an ionized layer can be formed by an ultraviolet wave of a particular frequency (Fig. 3) now can be shown. This wave is produced by the sun's radiation. As the ultraviolet wave enters the earth's atmosphere from above, it produces ionization. The amount of ionization increases with the depth of penetration because of the greater density. At first, there are only a few molecules to ionize. Penetrating further, it produces more and more ionization, but the wave is attenuated because it gives up energy in producing ionization. Finally, when the wave penetrates still further into the dense region, it becomes too weak to produce ionization. Thus, ionization is produced in a layer with the density falling off on both sides of a maximum value. Both the greater rate of recombination and the attenuation decrease the extent of ionization in the lower or denser part of an ionized region.

22. Ionized Layers

a. The formation of more than one layer can be

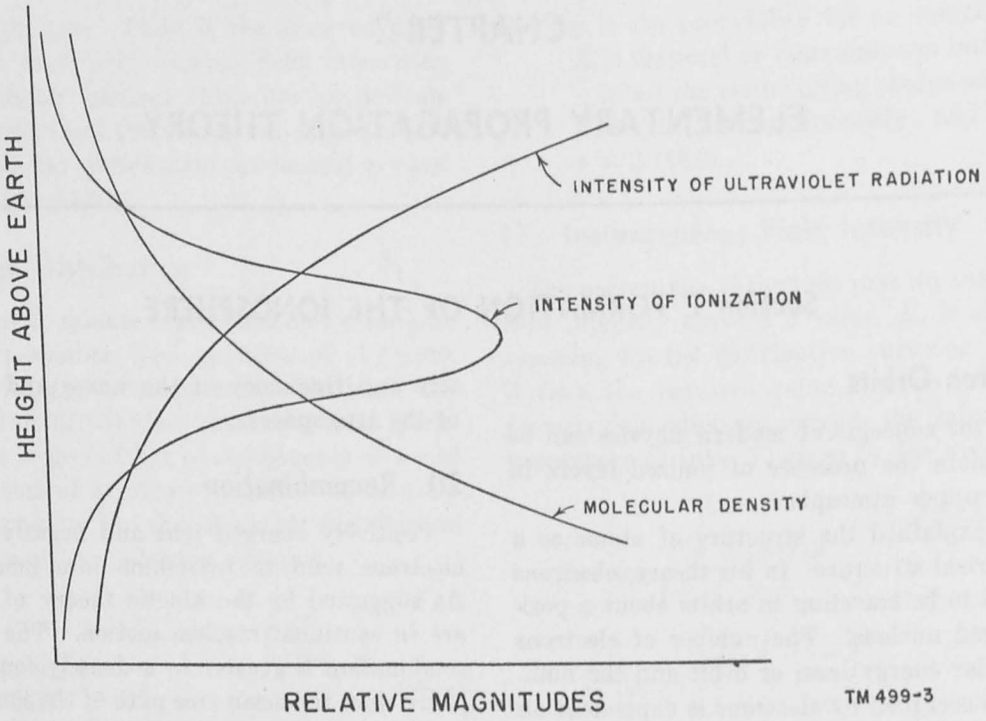


Figure 3. Formation of an ionized layer by a single-frequency ultraviolet wave.

shown if more than a single frequency of ultraviolet light is assumed to be radiated from the sun. Higher frequencies will penetrate further into the atmosphere before producing maximum ionization.* A constant source of radiation thus far has been assumed. Appreciable ionization is not formed immediately when radiation first appears. As the ionization continues, it finally reaches a state of equilibrium governed by the rates of formation and recombination. When the rate of recombination is small, a larger ion density is possible before equilibrium is reached. Then density of ionization follows the changes in radiation and, for rapid changes, there is a time lag between density of ionization and radiation. Thus, the upper layers can be expected to have greater ionization and can be expected to follow changes in radiation intensity less closely.

b. An approximate comparison between two ionospheric layers, the E and F2, is indicated in the following chart.

Layer	Layer heights (kilometers)	Collision frequency per second	Molecule density per cubic centimeter	Electron density per cubic centimeter
E	100	10^6	10^{13}	10^5
F2	320	5×10^3	5×10^{10}	7×10^5

*A mathematical discussion is in chapter XV of Chapmen and Bartel's "Geomagnetism."

23. Effects of Motion of the Sun on Ionization

The daily rotation of the earth about its axis and the annual motion of the earth about the sun in the plane of the ecliptic produce changes of the sun's angle or radiation intensity at particular points in the upper atmosphere. The lower layers in the ionosphere (the ionized portion of the earth's atmosphere) follow closely the changes in the sun's angle. Here, the rate of recombination is large because of high molecular densities. The upper layer follows changes less closely, the rate of recombination being less. The daily ionization maximum lags behind the sun and the ionization is irregular, as based on the simple theory.

24. Other Sources of Ionization

In addition to the source of ionization due to electromagnetic radiation from the sun, ionization also is caused by particle radiation from the sun. The upper layer appears to be affected the most greatly by this particle radiation, although ultraviolet radiation appears to be the predominant ionization source. Other ionization sources are meteors and cosmic rays.

Section II. IONIZATION SOURCE — THE SUN

25. General

a. The sun generates great amounts of energy, probably due to internal atomic fission. Much of this energy is emitted into the surrounding space in the form of heat, particles, and electromagnetic waves. The relative amounts of energy at various high frequencies have been measured on the earth. Measurements indicate that the energy density varies with frequency in a similar manner to the radiation from a theoretically perfect radiator* at an absolute temperature of 6,000° (273° + degrees centigrade). Figure 4 shows the energy distribution plotted against wavelength for a perfect radiator and the measured heat curve of the sun. No ultraviolet is shown at wavelengths less than about 3,000 angstroms (1 angstrom = 10^{-10} meter). Since the ionosphere blankets the earth and probably absorbs higher frequency ultraviolet rays, the amount of ultraviolet radiation in the direction of the earth cannot be determined directly on the earth.

b. There are four regions in the sun that can be distinguished from one another to the differences in temperature, pressure, and chemical composition. These regions, which merge together gradually, are the photosphere, the reversing layer, the chromosphere, and the corona.

(1) The photosphere is the brilliant solar disk. Despite its low pressure, the photosphere appears opaque. It is darker at the edges than at the center. Its brightness is not uniform but patchy. The structure appears granular. The granules come and go with an average life of about 3 minutes. Large irregular bright patches, called faculae, nearly always are present. These, unlike the granules, appear more often near the edges of the disk (limbs) and not nearer to the center than one-half the radius.

(2) Above the photosphere is a layer a few hundred miles thick, called the reversing layer because it absorbs the energy of certain frequencies emitted by the photosphere. In spectrographs, this absorption

*Physicists generally use the term "black body" to denote a body that completely absorbs all radiation incident upon it and acts as a perfect radiator.

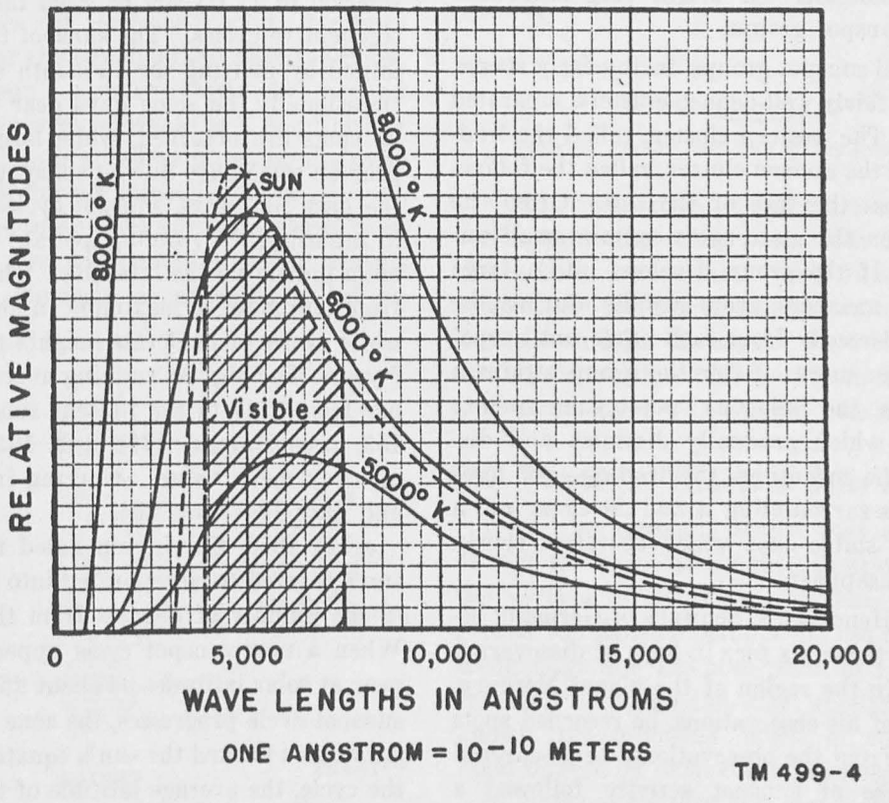


Figure 4. Distribution of energy in the solar spectrum.

causes certain lines which should be bright to appear dark.

(3) The chromosphere lies above the reversing layer. It is a rose-colored flaming ring. The chromosphere appears to be a highly ionized layer of low density. Jet-like prominences often appear in the seething ring.

(4) The solar corona is the most extensive gaseous envelope surrounding the sun. Studies have indicated that the temperature and the extent of ionization of this outer atmosphere is very high. The intensity of lines of a spectrogram due to radiation from the solar corona is related to ionospheric activity.

26. Sunspots

a. Dark areas called sunspots appear on the sun's disk. Sunspots always appear in groups which range in size from small specks to large areas which are visible to the naked eye when viewing the sun through a colored glass. All spots except very small ones appear in two portions which differ in degree of darkness. The central darker area is called the umbra; the surrounding lighter area is called the penumbra. A bright ring surrounds stable large sunspot groups.

b. Nearly all sunspot groups during early stages, consist of two fairly well-defined clusters, separated by 3° or 4°. The western cluster, called the leading spot, leads the eastern cluster, called the following spot, across the face of the sun. Often the regions between the main spots contain small unstable spots. If the group develops into a large one, the two members grow rapidly during the first week and recede from each other until separated by 10° or more. After the group attains a maximum area, the following spot breaks up into smaller spots which gradually diminish and disappear. In the meantime, the leading spot loses the small spots surrounding it and develops into a single, round, stable spot which decreases slowly in area and disappears.

c. In 1825, Hendrick S. Schwabe of Germany began observing the sun's face in hope of discovering a new planet in the region of the planet Mercury. In the course of his observations, he recorded spots on the sun. From the observations, he discovered that the degree of sunspot activity followed a period of about 10 years. In 1849, Rudolf Wolf of Zurich began systematically recording counts of the number of sunspots on the sun's face during individual days. Since that date, there have been continuous recordings of sunspots. Wolf compared sunspot activity by the equation—

$$R = K\,(10\,g + f) \qquad \text{(Eq 7)}$$

where g is the number of individual sunspot groups on the sun's disk;

f is the number of individual spots counted within the groups;

k is a constant depending on the telescope and the observer; and

R is the sunspot number.

d. Sunspot numbers are given as daily, monthly, and 12-month running average values. The daily sunspot number is the number of sunspots recorded near midday according to the formula in equation 7. The monthly average value is the average of the values for the various days of the month. The 12-month running average is the average of the mean values for 6 months in advance and 6 months preceding. The monthly mean values are recorded at the middle of the month and running average sunspot numbers may be recorded at the beginning or middle of the month. Sunspot activity follows a long-term trend in cycles with an average time interval of 11.1 years between the maxima of two consecutive cycles. The sunspot trend curve is obtained by plotting the 12-month average numbers. Occasionally, on some days near sunspot maxima, no spots are observed, while large spots may appear on some days during sunspot minima. During the past 100 years, sunspot cycles have alternated in intensity, the running average number at maximum indicating the intensity. The high cycles rise from minimum to maximum in about 3 to 4 years, while cycles of moderate heights rise in about 4 to 5 years. The highest running average sunspot number from 1749 to the present time had a value of 159, occurring in 1788 and 1947. The highest monthly mean value, occurring in December 1836 and May 1947, was 206.

e. In 1858, Carrington noted that spots on the sun appeared to be separated into groups according to the number of degrees from the sun's equator. When a new sunspot cycle appears, its spots appear at solar latitudes of about 25° to 35°. As the sunspot cycle progresses, the zone of sunspot activity widens toward the sun's equator. At the end of the cycle, the average latitude of the spots is about 8°. About 6 months to a year before an old sun-

spot cycle disappears, spots of the new cycle appear at high latitudes. Sunspot minima usually occur when spots of the new and old cycles are equal in number.

f. From spectroscopic analyses, the splitting of spectral lines (Zeeman effect) indicates that sunspots have magnetic fields. The leading and following spots of a sunspot group have opposite polarity. The polarities alternate with each successive sunspot cycle.

g. The ultraviolet radiation from the sun has been noted previously to be the principal ionization source of the earth's upper atmosphere. Although sunspots themselves appear dark and, thus, would indicate lower temperatures and lower ultraviolet radiation, the sunspots have bright gaseous clouds about them and the processes involved in the production of sunspots probably produce vast amounts of ultraviolet energy. All experimental evidence points out that the sunspot number is a fairly accurate index of ultraviolet radiation. It also is obvious that sunspot numbers cannot give an exact index of ultraviolet radiation. It is reasonable to assume that, when a sunspot group is large and also very active, it will produce considerable ultraviolet radiation.

27. Motion of the Sun

a. The sun does not rotate as a solid; it rotates more rapidly near the equator than near the poles. A point on the sun's equator rotates once around its axis in 27 days with reference to a point on the earth. This rotation is noted by watching the spots on the sun's disk during successive days.

b. Both the earth and the sun spin about fixed axes in space. In addition, the earth travels around the sun annually in an orbit called an ecliptic (fig. 5).

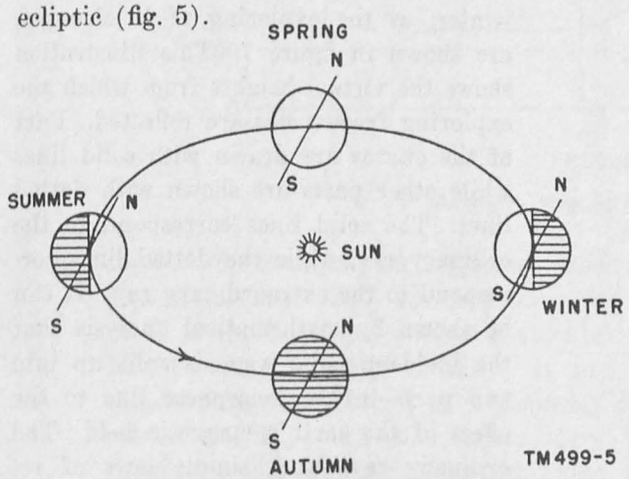


Figure 5. Annual motion of the earth.

c. The earth's axis is shown to be in the same direction in space during all four seasons. This neglects the relatively slow motion, called the precession of the equinoxes. It is noted that the sun shines more directly on the Northern Hemisphere during June, and on the Southern Hemisphere during December.

d. The earth's axis is at an angle of 23.5° from the axis of the earth's orbit, while the sun's axis is at an angle of 7.25° from the axis of the orbit or ecliptic (fig. 6).

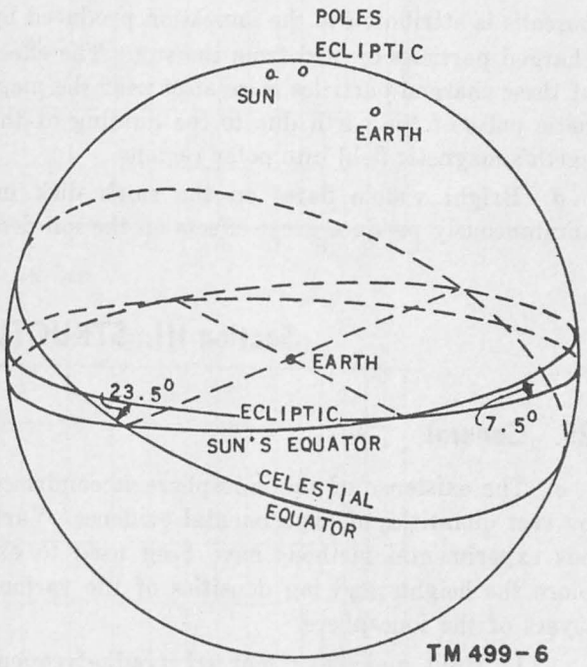


Figure 6. Rotational axes of the earth and the sun.

e. The inclination of the sun's axis causes the sun's pole to dip either away from the observer on the earth or toward him. On 6 June and on 6 December, the sun's equator appears to be a straight line as seen from the earth. On 6 March the sun's north pole is pointed farthest from the earth, while on 8 September, it is pointed nearest the earth.

28. Terrestrial Effects of Solar Activity

It can be generally stated that during periods of high sunspot activity the extent of ionization of the various layers is greater than average. The greater ion density permits the use of higher radio frequencies and the absorption of radio waves increases. Although the exact relationships are not known, the following effects of sunspot activity upon terrestrial phenomena have been observed.

a. Sunspot activity and terrestrial magnetic ac-

tivity appear to be closely related during periods of high sunspot activity. The earth's magnetic field is more disturbed during sunspot maximum than during sunspot minimum.

b. Magnetic storms are related to the presence of large spots on the solar disk. A magnetic storm usually commences about 2 days before the central passage of a large sunspot and extends to 4 days after a sunspot has passed a central meridian.

c. There has been noted a relationship between the frequency of auroras and sunspots. The aurora borealis is attributed to the ionization produced by charged particles ejected from the sun. The effect of these charged particles is greatest near the magnetic poles of the earth due to the guiding of the earth's magnetic field into polar regions.

d. Bright visible flares on the sun's disk instantaneously produce great effects on the ion density of the various ionospheric layers. This effect is known as a SID (sudden ionospheric disturbance) or Dellinger fade. Great increases are noted in the ionization produced at low levels in the ionosphere.

e. The variation on ionization with the 11-year sunspot cycle affects the intensity of ionization of all the layers in the ionosphere.

f. Day-to-day fluctuations in sunspot activity affect the ionization of all the ionospheric layers. There is not an exact correspondence with daily sunspot number and ionization since sunspot numbers are not an exact index of ultraviolet activity. It should be noted that the highest ionospheric layer exhibits greater day-to-day fluctuations in ion density. This layer probably is affected most by partical radiation from the sun. It is quite likely that the extent of particle radiation varies with sunspot activity.

Section III. STRUCTURE OF THE IONOSPHERE

29. General

a. The existence of the ionosphere is confirmed by vast quantities of experimental evidence. Various experimental methods have been used to explore the heights and ion densities of the various layers of the ionosphere.

(1) Breit and Tuve sent r-f (radio-frequency) pulses of very short duration and received them at a short distance from the transmitter. The receiver recorded both the direct ground pulse and the sky-wave pulse. From the time difference between the transmitted and received pulses, the vertical height of a reflecting layer is calculated easily. The radio wave is assumed to travel at the velocity of light for the entire path up to the layer and down again. The simple equation between velocity, time, and distance is used:

$$2\,\delta = ct \qquad \text{(Eq 8)}$$

where $2\,\delta$ is twice the distance from the ground to a point of apparent vertical reflection;
c is the velocity of light; and
t is the measured time between the ground and sky pulses.

(2) The frequency above which layers of particular heights no longer reflect the vertically incident sky-wave pulses is called a critical frequency. The magnitude of the critical frequency indicates the extent of ionization of the layer. Recordings of the apparent vertical heights (called virtual heights) and critical frequencies with a changing exploring r-f wave show that the ionosphere is not one sharp layer but is composed of several regions of high and low ion densities.

(3) Typical daytime records of the virtual heights of the ionosphere for summer and winter, as the exploring rf is changed, are shown in figure 7. This illustration shows the virtual heights from which the exploring frequencies are reflected. Part of the curves are drawn with solid lines while other parts are shown with dotted lines. The solid lines correspond to the ordinary ray, while the dotted lines correspond to the extraordinary ray. It can be shown by mathematical analysis that the incident radio wave is split up into two parts in the ionosphere due to the effect of the earth's magnetic field. The ordinary rays obey simple laws of refraction. All the sections of the curves

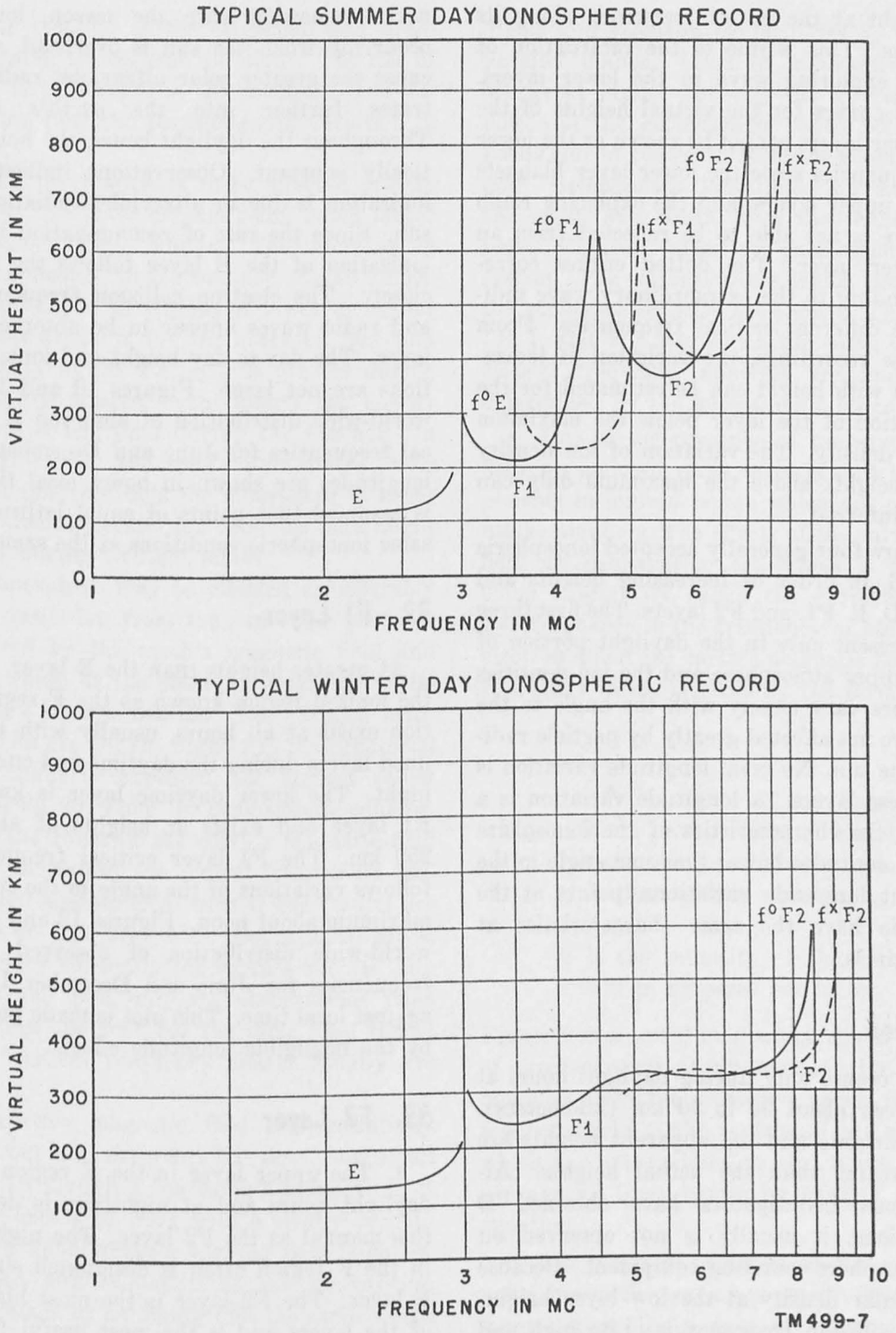


Figure 7. Typical ionospheric records.

show height changes with frequency. The section marked "E," corresponding to the E layer, shows only a slight change in height with frequency initially. It increases abruptly in height at a frequency marked "f°E." All the curves show abrupt increases at their upper end. These rapid increases correspond to the critical frequencies and indicate regions of maximum ion density of the various layers. They correspond to points where the exploring radio wave penetrates the layer. At a critical frequency, the rate of travel of the energy of the incident wave is slow, producing the large virtual heights. The upper layers indicate a high virtual

height at the lowest frequency along its trace. This is due to the retardation of the exploring wave in the lower layers. The curves for the virtual heights of the upper layers cannot be shown at the lower frequencies since the lower layer blankets the upper layers, and the exploring radio wave is not able to be reflected from an upper layer. The dotted curves corresponding to the extraordinary wave indicate different critical frequencies. From these recordings, the variation of ionization with height can be estimated for the portion of the layer below the maximum ion density. The variation of ion density at heights above the maximum only can be inferred.

b. There are four generally accepted ionospheric layers, called, in order of increasing heights and density, the D, E, F1, and F2 layers. The first three layers are present only in the daylight portion of the earth's upper atmosphere and the ion densities of these layers vary closely with the angle to the sun. They are not affected greatly by particle radiation from the sun. No great longitude variation is shown by these layers. A longitude variation is a difference in the characteristics of the ionosphere at different longitudes but at the same angle to the sun. Without longitude variations, points at the same latitude have the same characteristics at equal local times.

30. D Region

This layer occurs only during daylight hours at heights between about 50 to 90 km (kilometers). The virtual heights and the apparent heights are somewhat greater than the actual heights. Although various investigators have obtained D layer reflections, it usually is not observed on standard ionosphere sounding equipment. Because of the molecular density at the low layer height, the electron collision frequency is quite high and radio waves are highly absorbed by the D layer. Ionization probably is caused by the higher and more intense ultraviolet frequencies of solar radiation.

31. E Layer

The E layer occurs during daylight hours at heights between 90 to 140 km. The layer height varies somewhat with the season, lower heights occurring when the sun is overhead, perhaps because the greater solar ultraviolet radiation penetrates further into the earth's atmosphere. Throughout the daylight hours, the height is practically constant. Observations indicate that the ionization is due to ultraviolet radiation from the sun. Since the rate of recombination is large, the ionization of the E layer follows the sun's angle closely. The electron collision frequency is large and radio waves appear to be absorbed in the E layer. The day-to-day height and ionization variations are not large. Figures 10 and 11 show the world-wide distribution of observed E layer critical frequencies for June and December 1946. The longitudes are shown in hours local time since it is assumed that points of equal latitude have the same ionospheric conditions at the same local time.

32. F1 Layer

At greater heights than the E layer, there exists the ionized region known as the F region. Ionization exists at all hours, usually with two well-defined layers during the daytime and one during the night. The lower daytime layer is known as the F1 layer and exists at heights of about 140 to 250 km. The F1 layer critical frequency closely follows variations of the angle to the sun and is at maximum about noon. Figures 12 and 13 show the world-wide distribution of observed F1 critical frequencies for June and December 1946 plotted against local time. This plot is made possible again by the negligible longitude effect.

33. F2 Layer

a. The upper layer in the F region during the daylight hours and at nighttime is designated in this manual as the F2 layer. The nighttime layer in the F region often is designated simply as the F layer. The F2 layer is the most highly ionized of the layers and is the most useful for long-distance communication. The height of this layer ranges from 140 to 250 km in the night for all seasons. During the day, the height varies from 150 to 300 km in winter and 250 to 350 km in summer. The degree of ionization is greatest for this layer and exhibits an appreciable day-to-day variation in comparison with the other layers. There is a decided time lag between maximum radiation and maximum ion density, the degree

of ionization peaking in the afternoon and gradually decreasing throughout the night. The rise of ion density is very rapid in the morning. The low recombination rate also permits rapid variation in ion density.

b. The F2 layer appears to be affected greatly by solar heat, the layer heights being much larger during summer than winter. The increase in height, or expansion, in the summer, causes ionization to be produced in regions of lower molecular density. This accounts for the observed fact that the ion density of the F2 layer is greater during daylight in the winter, even though the energy from the sun is less than during the summer. In the late afternoon, the outer atmosphere cools rapidly and this contracts the ionosphere to lower heights, producing greater ion densities than might be expected during twilight hours.

c. The ionosphere may be affected considerably by particle radiation from the sun. The particles are influenced by the earth's magnetic field and may be the cause of the observed longitude variation in the F2 layer ionization. The F2 layer critical frequencies are not the highest in the equatorial regions as might be expected, the highest values occurring about 20° from the geomagnetic equator. Because of the effect of the earth's magnetic field on F2 layer ionization, the critical frequencies cannot be plotted against local time if the results are expected to be true over wide geographical areas. It is customary to divide the earth's surface into three zones and plot only the observations from stations within one zone for the same local times; thus, three critical frequency charts usually are shown.

d. The earth's magnetic field is substantially constant throughout the years but does show small variations. In studying the earth's magnetism, it often is customary to work with a steady or nonvarying field upon which a varying field is superimposed. An approximation of the nonvarying field can be made by assuming that the earth's field is due to an equivalent magnetic dipole (a very short but powerful magnet) placed at the center of the earth whose axis passes through the point 78.5° north latitude and 69° west longitude. This position is taken as the geomagnetic north pole. Based on this equivalent dipole, a coordinate system can be drawn representing positions with respect to the location of the geomagnetic pole. The geomagnetic equator is determined by the plane at the earth's center at right angles to the equivalent dipole and geomagnetic latitudes by various other parallel planes. Lines of geomagnetic longitude are great circles between the geomagnetic north pole and the geomagnetic south pole on the opposite side of the earth from the geomagnetic north pole. Geomagnetic longitudes are measured from the north and south lines that connect the two poles. Figure 8 shows the geomagnetic coordinate system. The auroral zones which occur 20° from the geomagnetic poles are shown. The three zones (E, I, and W) into which the earth is divided for critical frequency analyses are indicated to be determined by the geomagnetic coordinate system.

e. Due to the presence of the earth's magnetic field, an incident radio wave is split into two components in ionized layers which are propagated in unlike manners. The effects of the earth's magnetic field on propagation conditions is accounted by using a quantity called the gyrofrequency. The gyrofrequency is the frequency of oscillation of an electron about the earth's magnetic field. The gyrofrequency in mc is given by the formula—

$$f_H = \frac{\mu_o \, e \, H}{2 \, \pi \, m} \qquad \text{(Eq 9)}$$

where μ_o is the permeability of free space;
e is the charge of an electron in coulombs;
m is the electron mass in kg (kilograms); and
H is the intensity of the earth's magnetic field in amperes per meter.

Figure 9 is a world map which shows the variation of gyrofrequency at F2 layer heights. This plot is obtained from the measured values of the earth's magnetic field at the surface of the earth in 1945, which are extrapolated to obtain the values at an average F2 layer height by using a mathematical equation.

f. The effect of splitting of the incident radio wave due to the earth's magnetic field generally is more noticeable in case of reflections from the upper layers, particularly the F2 layer. The extraordinary and ordinary waves can be shown to be related by the equation—

$$(f_o)^2 = f_x(f_x - f_H) \qquad \text{(Eq 10)}$$

where f_o is the ordinary ray critical frequency;
f_x is the extraordinary ray critical frequency; and
f_H is the gyrofrequency.

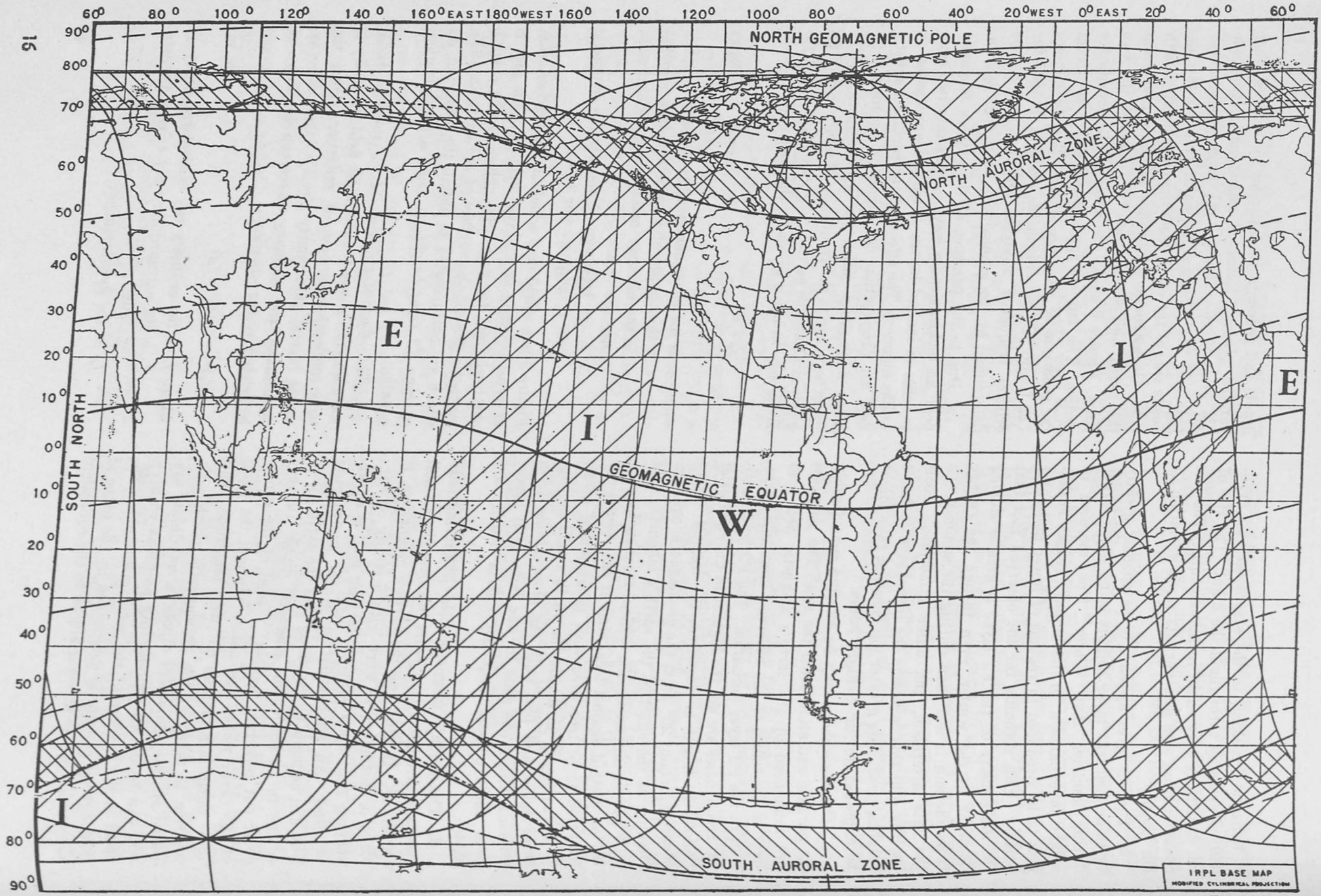


Figure 8. Geomagnetic coordinates as related to east, west, intermediate, and auroral zone.

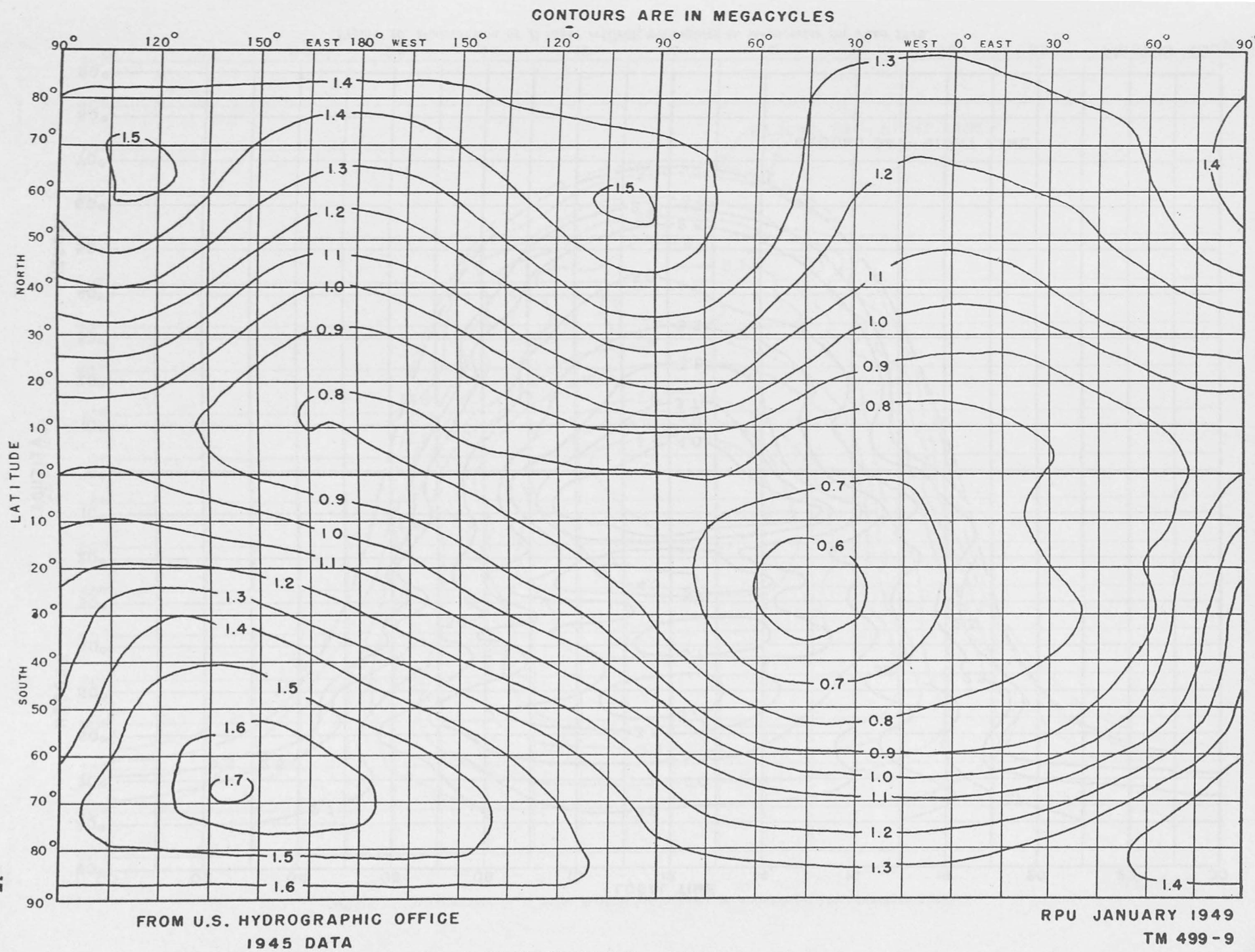
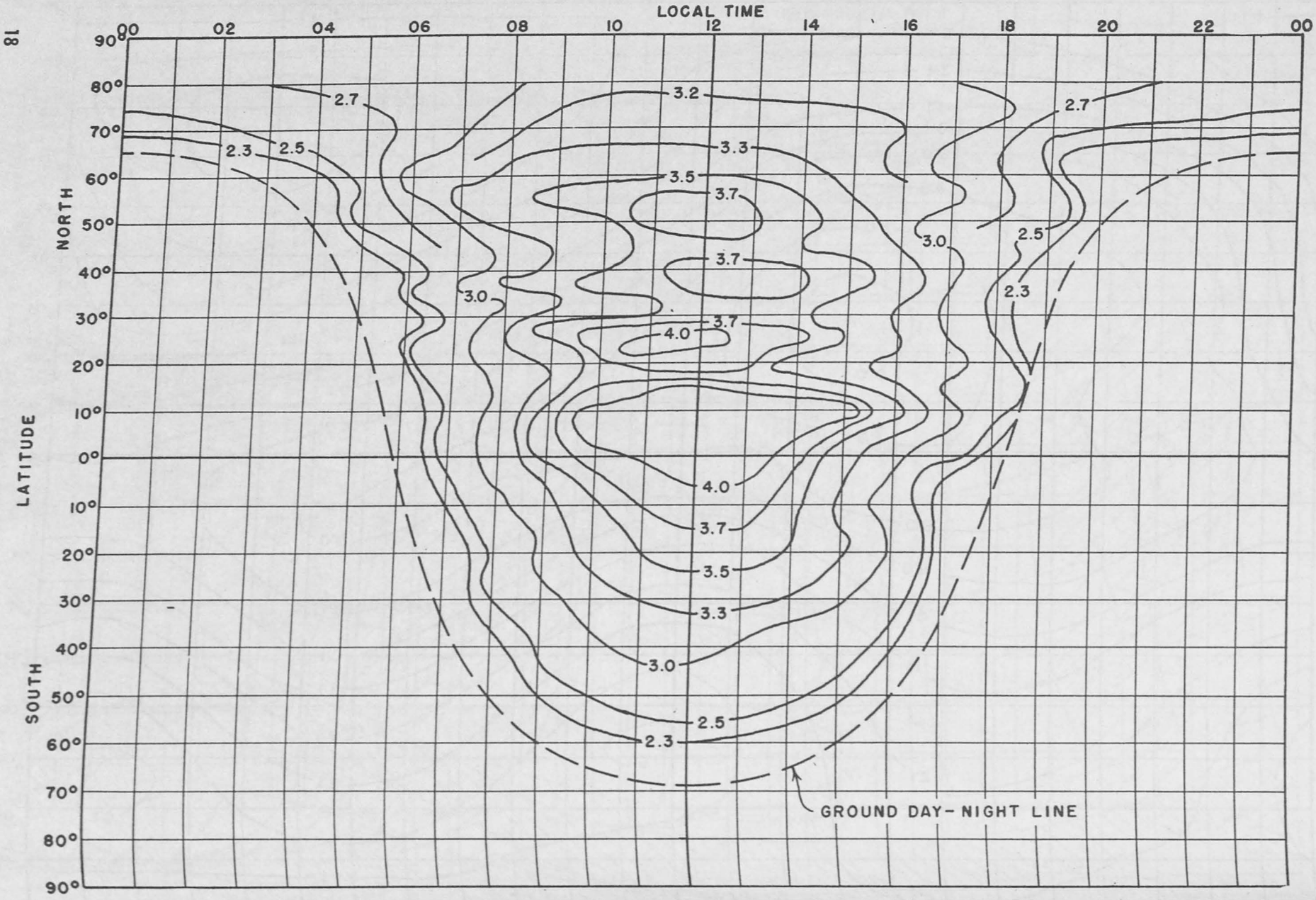


Figure 9. World-wide distribution of F2 layer gyrofrequency.



TM 499-10

Figure 10. Distribution of E layer critical frequencies in megacycles for June 1946.

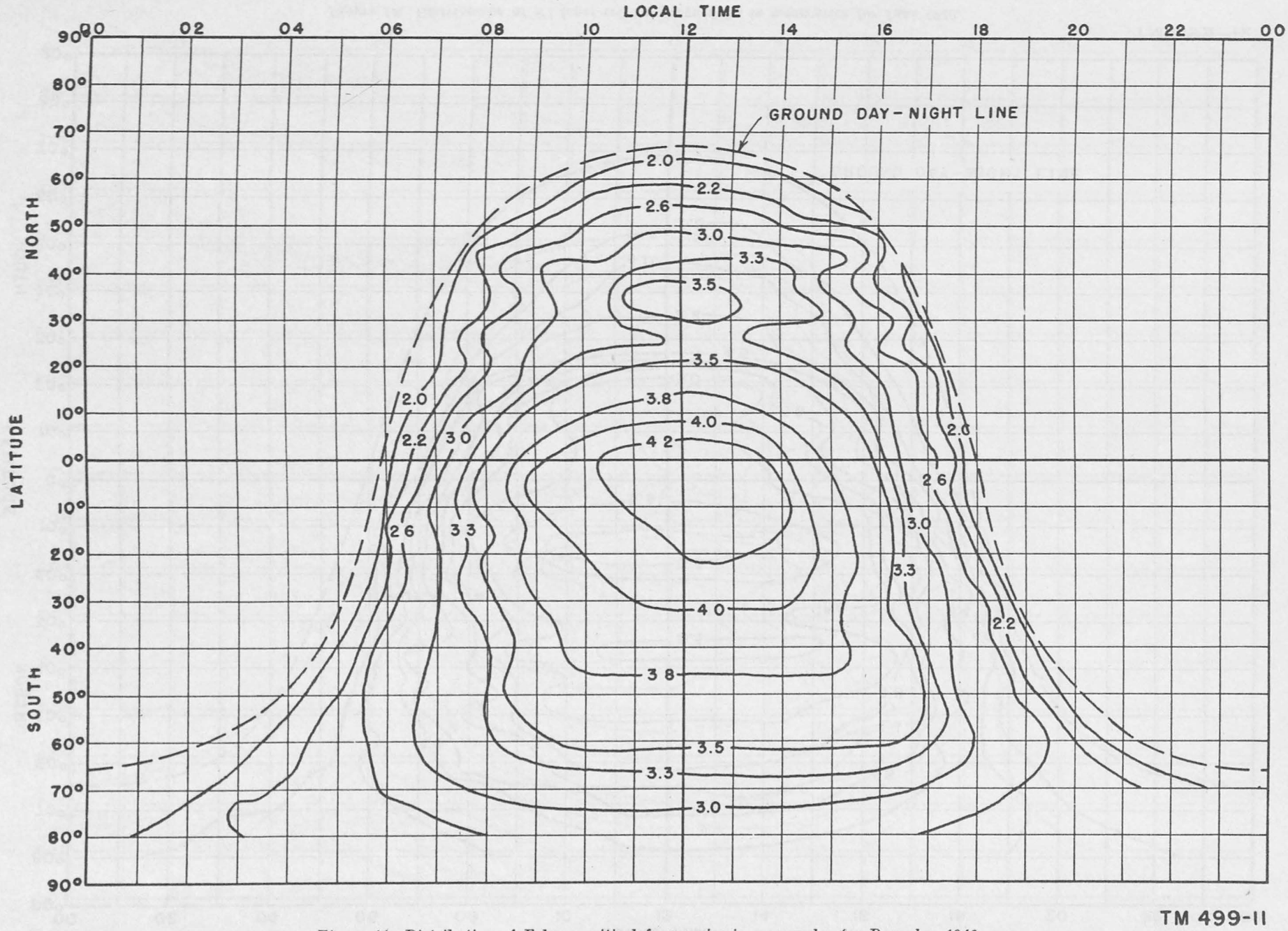
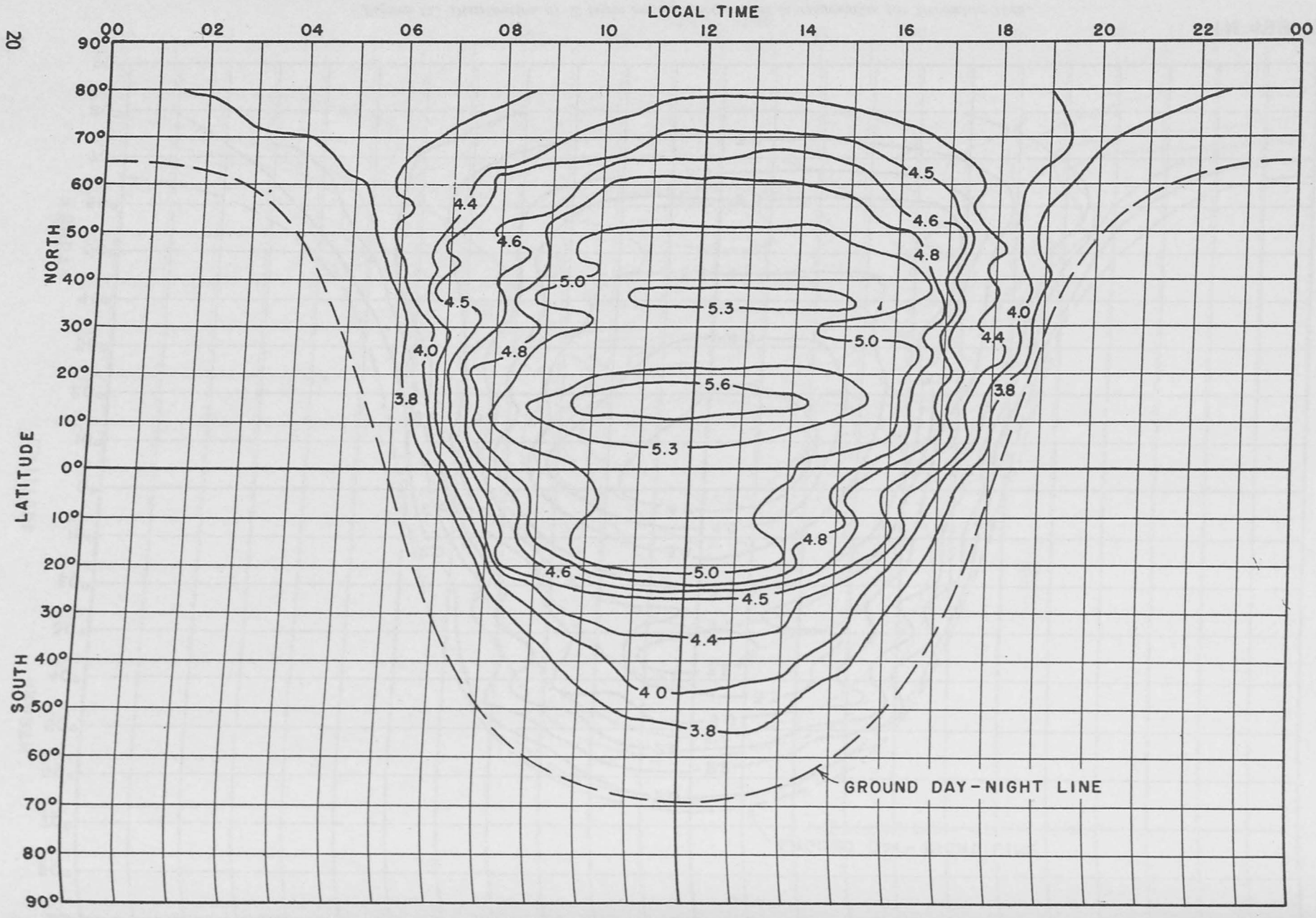


Figure 11. Distribution of E layer critical frequencies in megacycles for December 1946.



TM 499-12

Figure 12. Distribution of F1 layer critical frequencies in megacycles for June 1946.

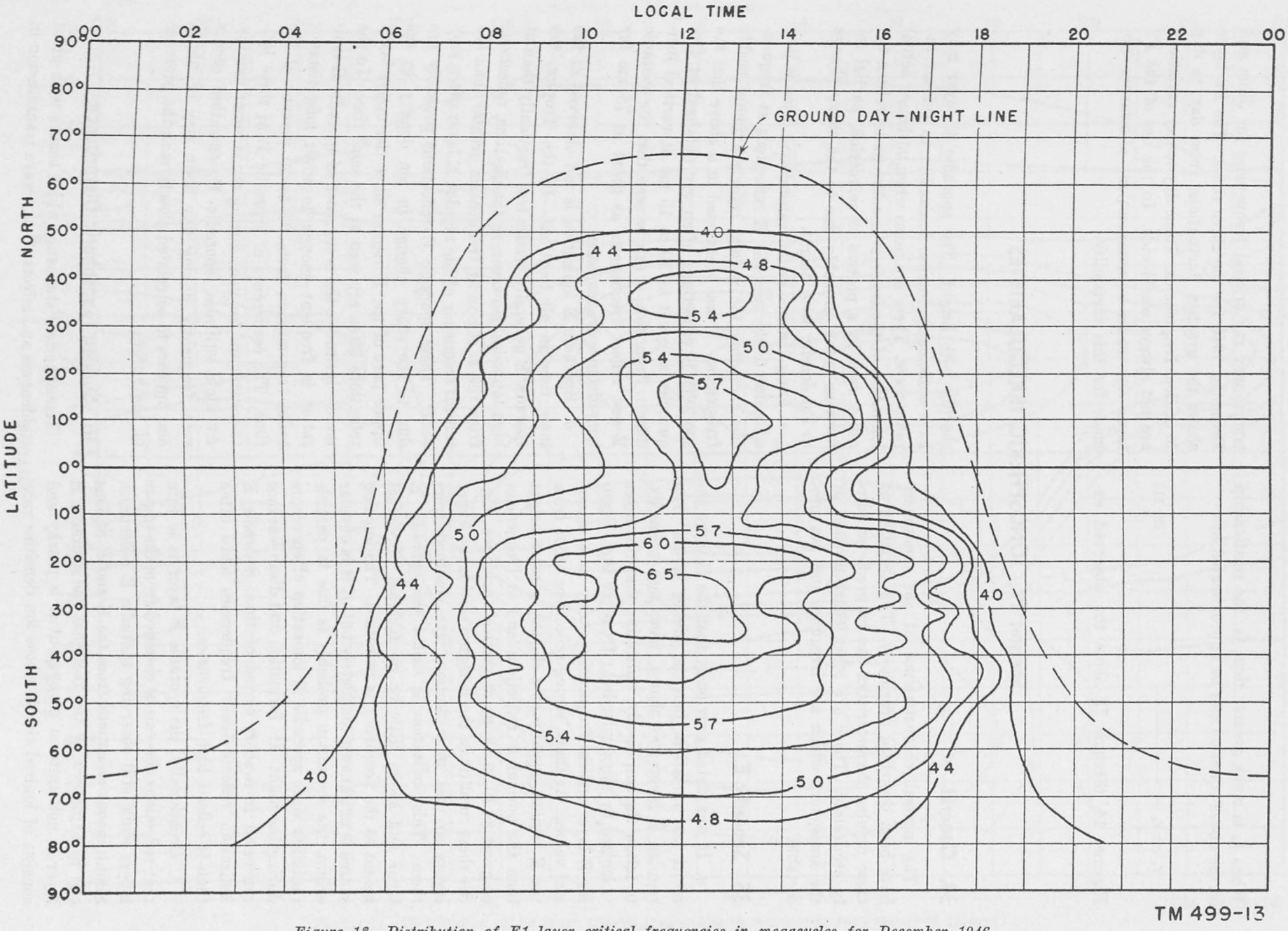


Figure 13. Distribution of F1 layer critical frequencies in megacycles for December 1946.

When f_x is much greater than f_H, the relationship in the above equation can be approximated by—

$$f_o = f_x - \frac{f_H}{2} \qquad \text{(Eq 11)}$$

Figures 14 through 19 show the observed extraordinary ray critical frequencies for June and December 1946 for the three zones. The F2 layer shows the greatest fluctuations from day to day in critical frequencies. These day-to-day variations are not always world-wide. In the use of the F2 layer for radio communication, allowances are made for this variability.

Section IV. IONOSPHERIC IRREGULARITIES

34. General

The normal characteristics of the ionosphere have been described previously. The variation of these regular characteristics can be predicted fairly accurately. There are other characteristics of the ionosphere which are irregular and less predictable.

35. Sporadic E

a. It was stated previously that the E layer exhibits less variation than the higher layers. The regular E layer was shown, from measurements, to follow the sun closely, indicating that this layer is ionized by ultraviolet light from the sun. Regular E layer critical frequencies rarely show abnormal values. At times, strong reflections occur from the E regions, usually at a slightly greater height than the normal E reflections and at frequencies as great as 10 to 15 mc at vertical incidence. Under these conditions, the E region shields the upper layers so that no reflections are obtained from them. This ionization is called the sporadic E layer and shows little or no increase of virtual height as the frequency is increased. The ionizing source is not known completely but, if it is of solar origin, the ionization probably is due to particle radiation since sporadic E ionization often occurs during the night. Its formation and disappearance can occur in a short period of time. Sporadic E ionization reflects lower frequencies more often than it reflects high frequencies.

b. Occasionally, the sporadic E layer is so thin that reflections also can be obtained from the upper layers while still observing sporadic E reflections. Simultaneous reflections from the E and F regions can be explained by the fact that the sporadic E layer is not uniform always but it is patchy and consists of ionized clouds whose ion densities vary sharply with height. The sporadic E layer may have sufficiently intense ionization to refract the radio wave. There are times when, although actual ionization of the layer is insufficient to return the radio wave by a process of refraction, partial reflections occur, probably due to the sharp change in ion density with height.

c. Long-distance radio transmission often is possible due to the sporadic E reflections at frequencies exceeding the normal layer maximum usable frequencies. It was mentioned in *a* above that the sporadic E reflections often are obtained at frequencies as great as 10 to 15 mc at vertical incidence. From this, it can be seen that the sporadic E can reflect frequencies as great as 75 mc for long-distance transmission.

d. Sporadic E ionization is not observed at the same time in all locations. In the Tropics, the sporadic E generally occurs less frequently than at high latitudes. However, in the daytime, reflections from the E region at frequencies greater than the critical frequency of the regular E layer often may occur. These sporadic E reflections probably are due to the sharp change in ion density in the upper part of the E region since the upper layer reflections often are seen at the same time. In the middle latitudes, the occurrence of sporadic E ionization is frequent enough to effect long-distance radio transmission from 25 to 50 percent of the time. The occurrence of sporadic E at these latitudes is more frequent during the summer months. At high latitudes, sporadic E ionization occurs very frequently during any hour, day or night, and appears to be related closely with the presence of the aurora.

36. Sudden Ionospheric Disturbance

Ionospheric disturbance which occurs with great suddenness and affects all sky-wave transmission in

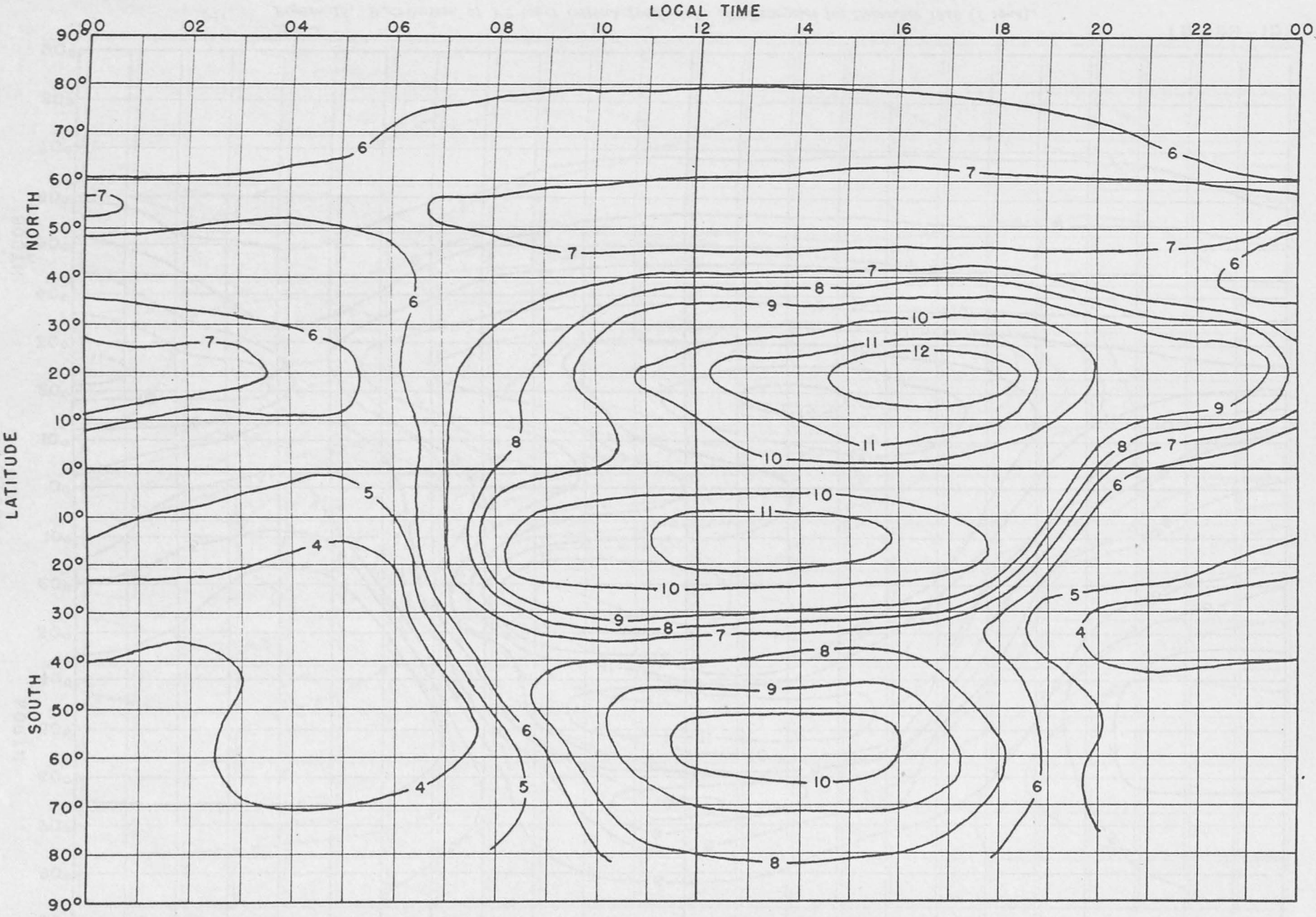


Figure 14. Distribution of F2 layer critical frequencies in megacycles for June 1946 (I zone).

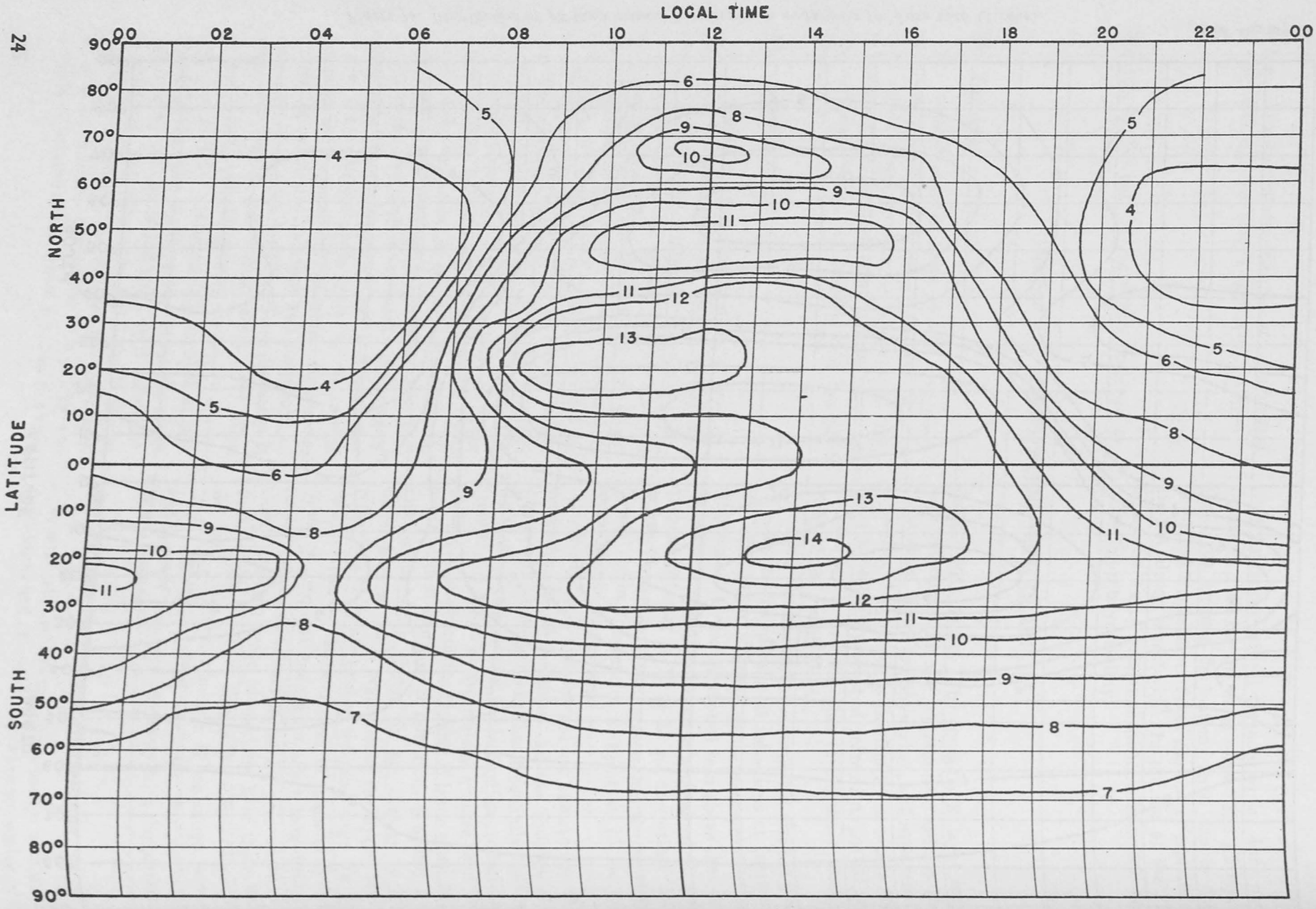


Figure 15. Distribution of F2 layer critical frequencies in megacycles for December 1946 (I zone).

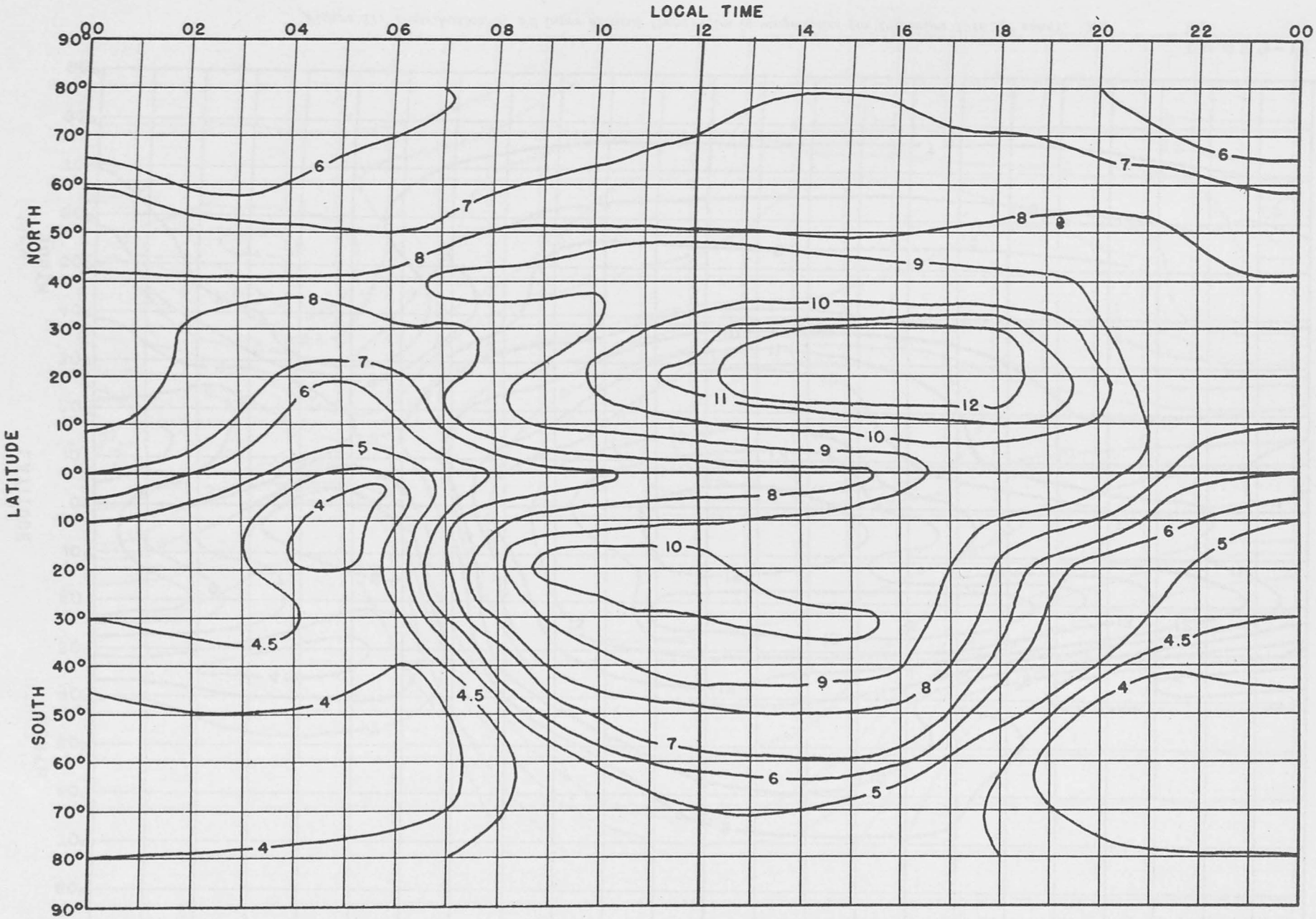


Figure 16. Distribution of F2 layer critical frequencies in megacycles for June 1946 (E zone).

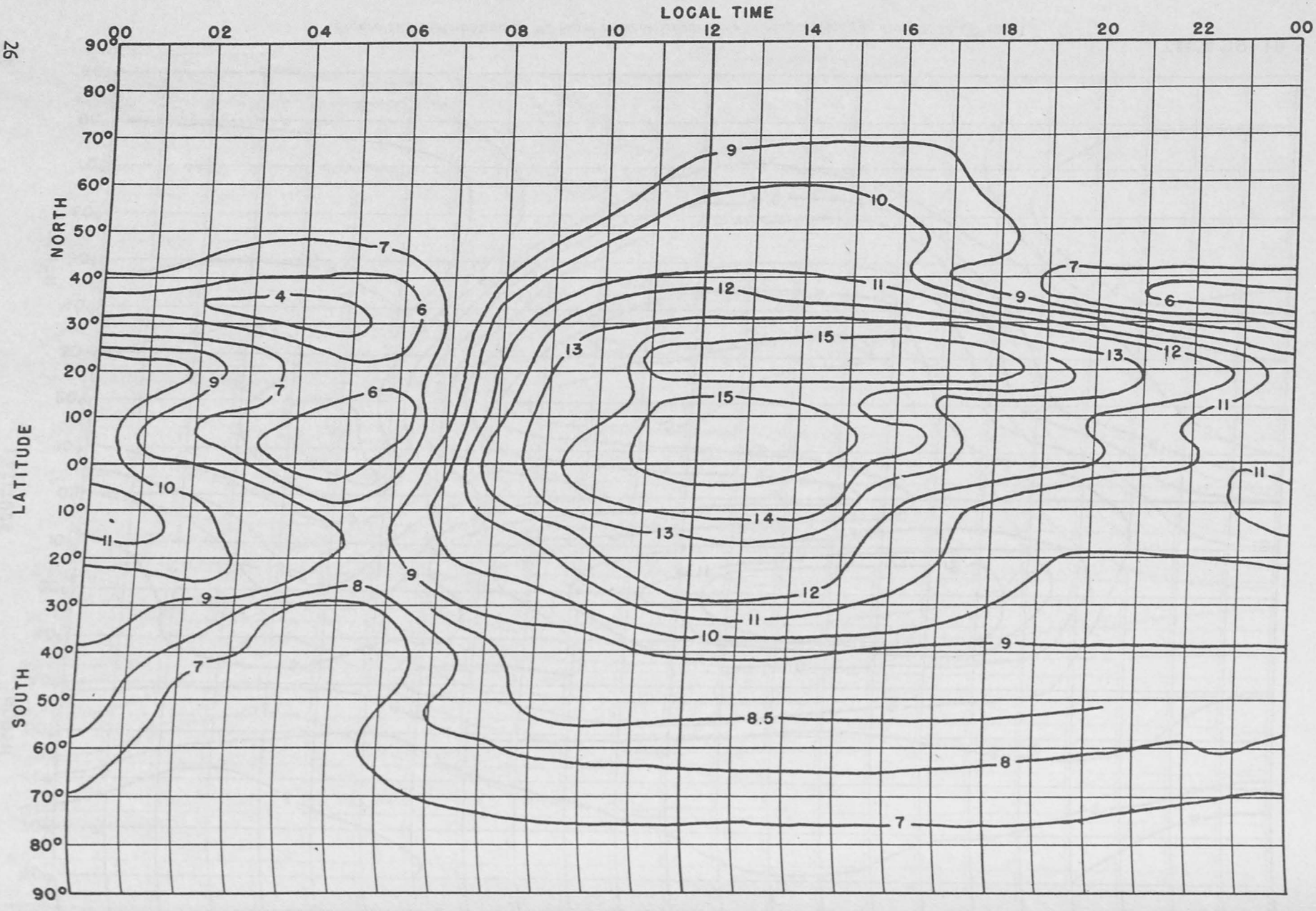


Figure 17. Distribution of F2 layer critical frequencies in megacycles for December 1946 (E zone).

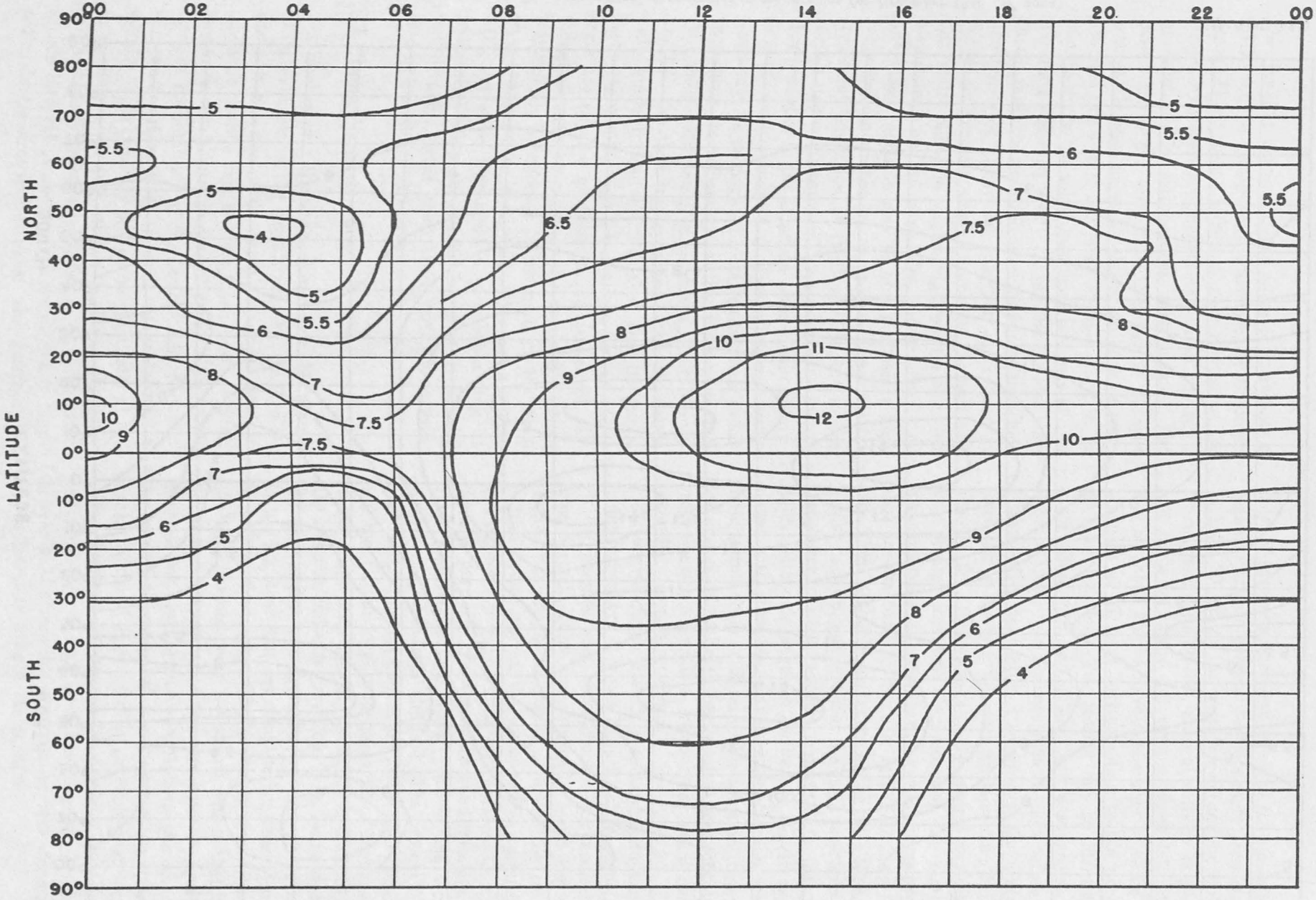


Figure 18. Distribution of F2 layer critical frequencies in megacycles for June 1946 (W zone).

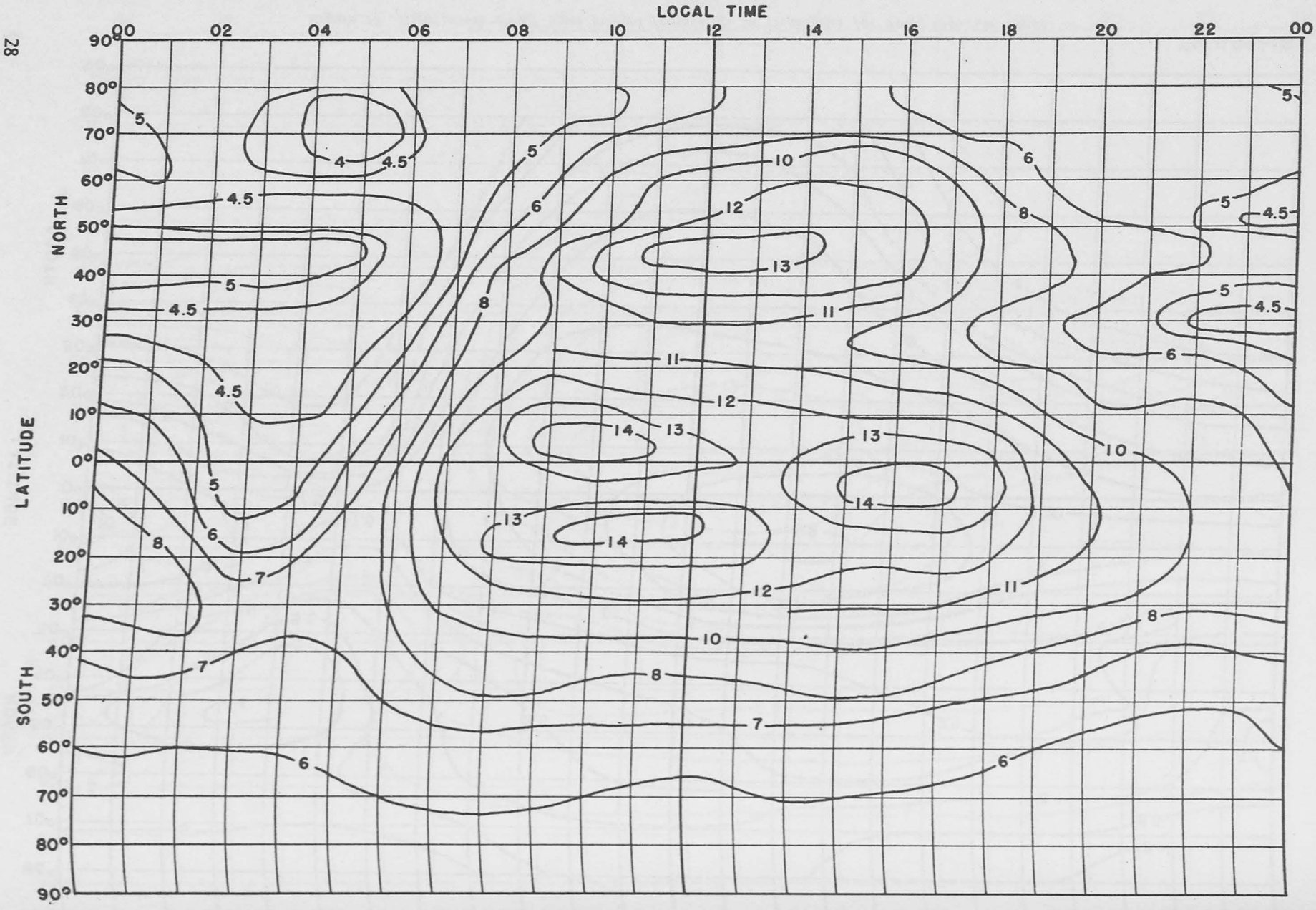


Figure 19. Distribution of F2 layer critical frequencies in megacycles for December 1946 (*W* zone).

the daylight portion of the earth is known as a SID (sudden ionosphere disturbance) or Dellinger fade. This type of fade is closely related to the bright hydrogen eruptions observed on the sun's spectrum with astronomical instruments. The bright flares are seen near large active sunspot groups. Intense flares which last an hour or more are rare. In watching a large sunspot group in its motion across the solar disk, more than one or two flares are observed rarely during the 2 weeks time that it takes the group to cross the sun's face. Sudden bursts of ultraviolet radiation are related to the bright visible hydrogen eruptions, the bursts of ultraviolet radiation originating from the observed disturbance on the sun. The sudden bursts of ultraviolet radiation may be of a sufficiently high frequency and intensity to produce abnormal increases of ionization at the lower heights in the earth's upper atmosphere. This temporary ionization produced in the D region causes great absorption of radio waves. L-f (low-frequency) radio waves may be propagated better under these conditions since the ionization can be sufficient to prevent the penetration of these waves into the layer. The l-f wave thus is propagated in an equivalent wave guide formed by the layer and the earth. Radio circuits through the daylight portion of the earth are affected by these ultraviolet bursts. Although it may be night at the receiving station, transmission is affected if the path of the radio wave is somewhere in daylight. During an intense SID, sky-wave transmission is possible only at frequencies below about 1,500 kc, or at frequencies considerably higher than those normally considered optimum for the circuit.

37. Ionospheric Storms

a. Ionospheric disturbances appear to be related to disturbances in the earth's magnetic field. Disturbed conditions in the earth's magnetic field or magnetic storms can last for periods of varying length (several hours to several days). The variations of the intensity of the earth's field is erratic and can be either great or small. Magnetic storms usually begin suddenly and occur practically at the same time over the earth's surface. Magnetic storms usually follow solar flare-ups or SID's after a time interval of about 18 hours or more. Magnetic storms are severest near the geomagnetic poles of the earth and least severe in the equatorial regions. Aurora generally occurs more frequently in belts 20° from the earth's geomagnetic poles. During magnetic storms, auroral activity is great and tends to extend out toward lower latitudes. The magnetic storms have a tendency to recur in intervals of 27 days corresponding to the period of solar rotation. The storms can be identified quite often with particularly active sunspots. A storm is likely to commence about 2 days before to 4 days after the active spot crosses the central meridian of the sun, the most probable time being about a day after passage of the central meridian. The greater intensity observed near the earth's magnetic poles indicates that magnetic storms probably are the result of particle radiation from the sun. These probably commence at the same time as a solar flare-up, but arrive at the earth later due to the slower particle velocity compared to that of light. Although magnetic storms are closely associated with sunspots, there are times when magnetic storms occur with no visible spots on the sun and no preceding SID. Large active sunspots may cross the sun's meridian without any usual magnetic disturbances occurring.

b. Ionospheric storms are periods of disturbance in the ionosphere in which the critical frequencies, virtual heights, and absorptions differ radically from normal. These storms usually occur concurrently with magnetic storms. During the early part of severe storms, the ionosphere is turbulent and sky-wave propagation is very erratic. During the later part of very severe storms and throughout a moderate storm, the upper part of the ionosphere is expanded and diffused. The critical frequencies throughout storms are lower than normal and the virtual heights much greater. Maximum usable frequencies thus are much lower than usual and communication is possible only at lower working frequencies. An ionospheric storm affects the higher F2 layer first, lessening its ion density and its critical frequency. The lower layers are not affected appreciably by the storms unless the disturbance is very great. Thus, increased absorption is noted only during severe ionospheric storms. In the auroral zones, sporadic ionization often is produced in the E region. It is probable that ionospheric storms are caused by abnormal particle radiation from the sun and, like magnetic storms, are the most severe in the auroral regions, decreasing in intensity toward the equator.

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38. Scattered Reflections

The inspection of ionospheric sounding records indicates that irregularities in the ionosphere are so frequent that they could be considered as the normal conditions in the ionosphere. The ionospheric layers are not ideal but are irregular. The presence of ionized clouds or scattering patches at E layer heights has been mentioned previously. Reflections are obtained from these due to the rapid change of ionization with height. A radio wave can reflect from either the top or bottom of these scattering clouds. Due to reflections from these scattering patches, communication is possible at greater frequencies than the regular layers will reflect. Reflections from these scattering sources cause fading in radio waves. A sky-wave field intensity, being the sum of the contributions of several contributing radio waves of varying phase relationships, fluctuates as these waves vary in phase relationship. The scattering sources themselves fluctuate in height during short intervals of time.

Section V. SKY-WAVE TRANSMISSION

39. General

a. Because of the everyday experience of radio operators, it no longer is a theoretical question whether the sky wave exists. Signals are receivable far beyond the distances expected by ground-wave communication. A practical question in radio propagation engineering is whether the ionosphere will support (reflect) a sky wave of a particular frequency and whether the received signal is strong enough at the receiver to be heard above the noise level present at the receiver.

b. A sky wave gradually is bent from its straight path in passing through an ionized region. At frequencies below a certain critical value, it will be bent back to the earth. Before entering an ionized region, the energy of a sky wave is diminished only because of spreading with distance while, within an ionized layer, some energy is absorbed. Analysis of field intensity recordings shows that sky-wave propagation can be explained by geometric-ray theory. The signal is assumed to arrive at the receiving location along various straight ray paths. These ray paths, or modes, are at various angles to the ground, depending on the transmission distance, the virtual height of the ionized layers, and the number of reflections at the ionosphere. The antenna radiation should be the greatest at the vertical angles corresponding to the modes that have few reflections at the ionosphere and the earth.

40. Sky-Wave Modes

Figure 20 indicates the simple-ray geometry for sky-wave transmission between two locations. Both single reflection (1-hop) and double reflection (2-hop) transmissions are shown. At very long distances, sky-wave transmission is possible only by multiple reflections from the ionosphere. (The angles of incidence and reflection at a layer are assumed to be equal.)

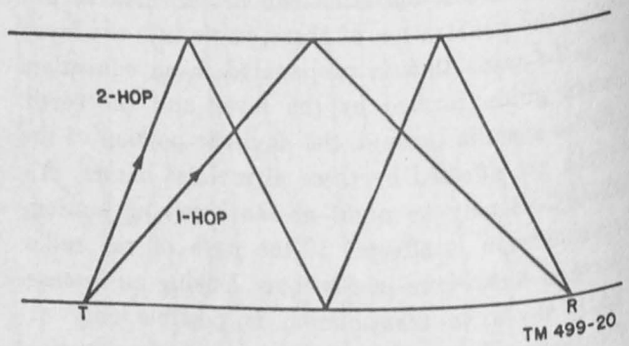


Figure 20. Ray path geometry for sky-wave transmission (plane earth and plane ionosphere).

41. Snell's Law

a. In geometric optics, it is shown that, when a ray of light goes from one medium to another of greater refractive index, it is bent toward the normal (upward). The law of refraction is given by Snell's relationship ratio. For a wave to be bent away from the normal (downward), the wave must be passing from a medium of higher refractive index to a layer of lower refractive index. Figure 21 shows the geometry for Snell's law and figure 22 indicates the bending of a radio wave in an assumed ionosphere with a changing index of refraction.

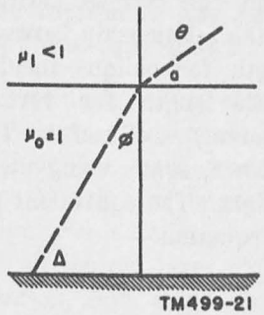


Figure 21. Snell's law geometry.

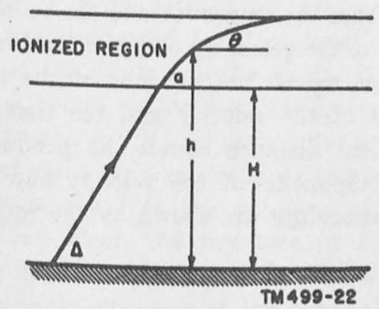


Figure 22. Refraction of a radio wave.

b. Consider a single ionospheric layer with its lower surface at a height, H, above flat earth, and assume a ray that leaves the earth at an angle, Δ; the refractive index is 1.0 where the electron density is zero. As the ray passes into the layer, it approaches regions of increasing electron density and decreasing refractive index. Thus, the ray will be bent further and further away from the vertical as it penetrates the layer more deeply. Snell's law holds for any point along the ray path. Stating the law in terms of the angle of elevation, the law is—

$$\cos \Delta = \text{constant} = \mu \cos \theta \qquad \text{(Eq 12)}$$

where μ is the index of refraction, and

θ is the angle of elevation at height, H.

It can be seen from Snell's equation that the ray is horizontal ($\cos \theta = 1$) when the refractive index, μ, is equal to $\cos \Delta$. Thus, a radio wave, when penetrating an ionized layer of increasing electron density (decreasing refractive index), can reach a point where it is bent over and returned to the earth in a symmetrical path.

42. Index of Refraction for Vertically Incident Radiation

a. In the case of vertically incident radiation, the condition for reflection is that the electron density must be sufficient for the refractive index to be zero for the incident r-f wave. The index of refraction is defined according to ray theory by the equation—

$$\mu = \frac{\text{velocity in free space}}{\text{phase velocity in the ionized medium}} \qquad \text{(Eq 13)}$$

Since the refractive index of an ionized medium must be less than unity, the phase velocity in the medium must be greater than the velocity in free space. This does not indicate that the energy is traveling at a greater rate than the velocity of light, but shows that, for a wave of a constant frequency in an ionized medium, the distance between one wave crest and another is greater than in free space.

b. The mathematical analysis of an electromagnetic wave in a medium, in which the mean free electron paths are extremely large and the earth's magnetic field is neglected, shows that the index of refraction can be given by—

$$\mu^2 = 1 - \frac{N e^2}{m k_o 4 \pi^2 f^2} = 1 - \frac{f_o^2}{f^2} \qquad \text{(Eq 14)}$$

where N is the equivalent electron density per cubic meter;

f_o is the critical frequency;

f is the wave frequency in cycles per second;

e is the electron charge in coulombs;

k_o is the dielectric constant of free space, $\frac{1}{36\pi} \times 10^{-9}$ farad/meter; and

m is the electron mass in kg.

The refractive index depends on the incident radio wave frequency. It can be shown that, in an ionized region, the velocity at which the energy travels (the group velocity) is equal to the velocity of light in free space times the refractive index of the medium. It is stated that, for vertical incidence, a radio wave returns to the earth when the refractive index becomes zero; this implies that the group velocity becomes zero and is similar to the case of a ball thrown into the air. The ball is brought to rest by the earth's gravitational field and returned to the earth. The equation above indicates that a wave will be returned by the ionosphere at the height where the wave frequency equals the critical frequency. It can be seen that the critical frequency is a function of ion density. A particular layer has different critical frequencies at different heights. The usually defined critical

frequency is the critical frequency at the maximum ion density.

c. A vertically incident radio wave does not travel with uniform speed throughout its path to and from the ionosphere. In discussing the structure of the ionosphere, the Breit and Tuve pulse ionosphere sounding method was mentioned. It was stated that the radio wave was assumed to travel uniformly with the speed of light, and the distance to the ionosphere was obtained from the time interval required for the path and the assumed uniform speed. Thus, the path length obtained is an equivalent path; the half-path length is known as the virtual height. Exploring radio waves have been indicated previously to be reflected from progressively higher heights with increases in frequency. Near the critical frequency of an ionized layer, the equivalent path becomes large. The great apparent height is due to the fact that the radio wave has to travel through a considerable distance in regions of low group velocity, in addition to the fact that the wave is reflected from a greater height.

43. Index of Refraction for Obliquely Incident Radiation

a. It is convenient to show the relationship between obliquely incident transmission and vertically incident transmission by the aid of the equivalent paths. Figure 23 shows both the actual ray path and the equivalent path for an obliquely incident sky wave. The reflection is assumed to be at a height, h, above plane earth.

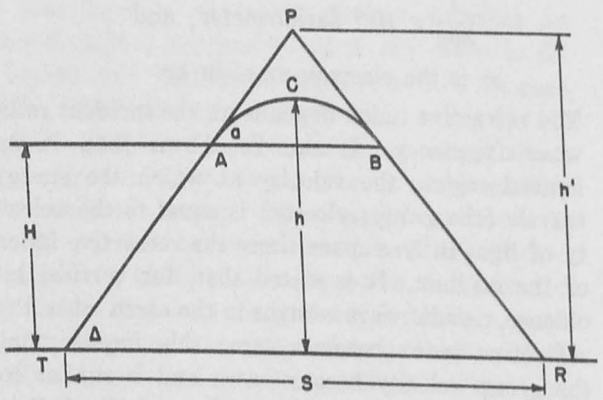


Figure 23. Oblique incident transmission.

b. In discussing oblique incident paths, the relationship between the equivalent path length (TPR) and the horizontal distance(s) between the transmitter and the receiver (Breit and Tuve theorem) and the relationship between the equivalent path length for oblique incidence and the equivalent path length for vertical incidence (Martyn's theorem) are useful. These relationships can be shown, again, using the example of a projectile in flight. The equivalent path length is defined by the equation—

$$P_{eq} = ct \qquad \text{(Eq 15)}$$

where c is the velocity of light, and

t is the time required for the wave to travel from the transmitter to the receiver.

Referring to the geometry of figure 23, the horizontal distance equals the product of the horizontal component of the velocity and the time, and the total vertical distance equals the product of the vertical components of the velocity and the time. These relationships are shown by the equations—

$$(c \cos \Delta)\ t = S \qquad \text{(Eq 16)}$$

$$(c \sin \Delta)\ t = 2h' \qquad \text{(Eq 17)}$$

Using the above equations, Breit and Tuve's and Martyn's theorems can be written directly—

$$P_{eq} = S \sec \Delta \text{ (Breit and Tuve's theorem)} \qquad \text{(Eq 18)}$$

$$P_{eq} = 2h' \csc \Delta = P' \csc \Delta \text{ (Martyn's theorem)} \qquad \text{(Eq 19)}$$

where P' is equal to the equivalent vertical path.

c. The relationship between the critical frequencies at vertical and oblique incidence can be approximated. Previously, in discussing an obliquely incident wave, it was shown that the ray becomes horizontal at the height where the refractive index is equal to the cos Δ and the refractive index was given by the equation—

$$\mu^2 = 1 - \frac{f_o^2}{f^2} \qquad \text{(Eq 14)}$$

Substituting the cos Δ for μ in the above equation and writing f as f', a relationship can be obtained between the critical frequency at oblique incidence, f', and the critical frequency at vertical incidence, f_o.

$$f' = fo \csc \Delta \qquad \text{(Eq 20)}$$

Thus, it can be seen from the above that a radio wave at a frequency, f, is equivalent to a vertically incident wave at a wave frequency, $f \sin \Delta$. These vertically and obliquely incident radio waves are reflected at the same height or ion density.

44. Oblique Incidence Ray Paths for a Plane Earth and a Plane Ionosphere

Using the simplified picture of a plane earth and a plane ionosphere, an account of the characteristics of oblique incidence transmission can be given. Figure 24 indicates the ray paths at various vertical angles. For a radio wave of a particular frequency in an ionized layer of a particular extent of ionization, rays at greater vertical angles than a critical angle are not returned from the layer but escape into space. At the critical angle, the wave is propagated horizontally within the layer. For angles of smaller elevation, the ray returns to the earth. As the angle of elevation is decreased below the critical angle, the ray is returned to the earth at shorter distances until a minimum distance is reached. At smaller elevation angles than that for the minimum distance, the distance at which the ray returns to the earth tends to increase due to greater distances traveled in the straight portions of the path, although the distance in the ionosphere becomes smaller. The minimum distance at which a ray of a particular frequency can be returned is known as the skip distance and the frequency is known as the maximum usable frequency for that distance. At distances greater than this, two ray paths are possible. One ray path has a vertical angle slightly greater than the vertical angle for the ray at the skip distance but less than the vertical angle for the critical ray. The outer ray path starts off at a lower vertical angle than the angle for the skip distance. At large distances, since the angle between the critical angle and the high ray angle is small, very little energy leaves the transmitting antenna to supply the high-angle rays and, thus, the low-angle ray, alone, predominates.

45. Transmission Characteristics at Oblique Incidence

Transmission characteristics at oblique incidence can be found from the vertical incident curves with the aid of graphical methods based on the equivalence theorem, stating that the behavior of a radio wave at a frequency, f, at an elevation angle, $\triangle$, is the same as the behavior of a vertically incident wave at a frequency, $f \sin \triangle$. From the Breit and Tuve theorem, and Martyn's theorem, a relationship can be formed between the horizontal distance, the virtual height, and the angle, $\triangle$. The equation is—

$$h' = \frac{S \tan \triangle}{2} \qquad \text{(Eq 21)}$$

where S is the horizontal distance.

Plots of the relationship between virtual heights and a geometric angle are called transmission curves. Instead of plotting against the tangent of the elevation angle, $\triangle$, the curves usually are drawn relating the virtual heights and the secant of the angle that the equivalent triangular path makes with the line through the earth's center and the equivalent reflection point.

46. Ray Path for Curved Earth and Curved Ionosphere

In discussing oblique incident transmission, the curvature of the earth and the ionosphere and the effects of the magnetic fields have been ignored.

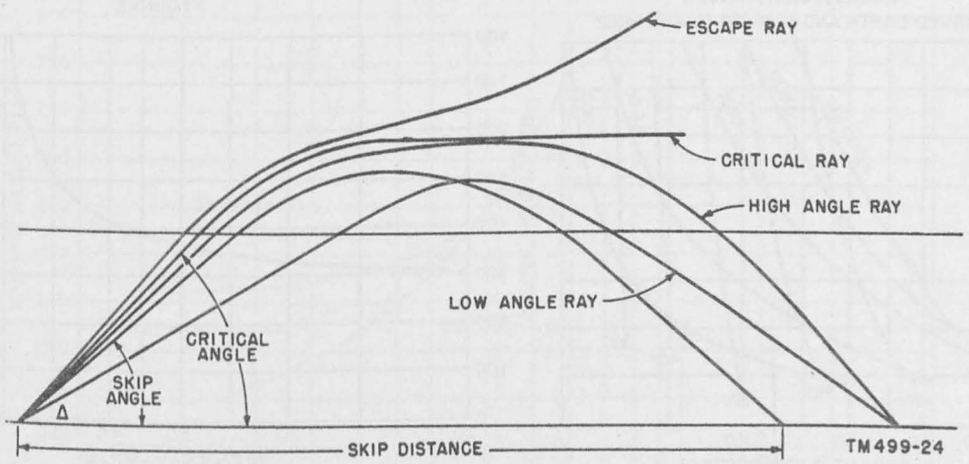


Figure 24. Oblique incident ray paths for a plane earth and a plane ionosphere.

Practical transmission curves are drawn with corrections for these factors. The equivalence theorem does not hold exactly for the spherical earth and ionosphere case. It can be shown that Snell's law for spherical earth can be written by the following equation—

$$\mu\ (r_o + h)\ \cos\theta = (r_o + H)\ \cos a_o = r_o \cos \triangle \qquad \text{(Eq 22)}$$

where $\triangle$ is the angle of elevation at the ground;
a_o is the angle of elevation at height, H;
θ is the angle of elevation at height, h; and
r_o is the radius of the earth.

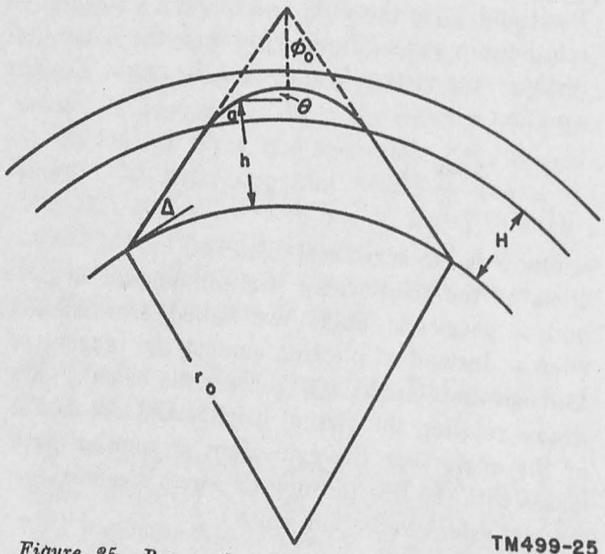


Figure 25. Ray path for a curved earth and a curved ionosphere.

The point where the ray path becomes horizontal is not given by μ equal to cos $\triangle$ but depends upon the way the refractive index varies with height. The critical escape ray does not become horizontal at the level of maximum density of the layer but at a point slightly below this.

47. Relationship Between Wave and Critical Frequencies

The relationship between the wave frequency and the critical frequency can be given for the corrected conditions by the equation—

$$f = k f_o \sec \phi_o \qquad \text{(Eq 23)}$$

where k sec ϕ_o is referred to as the corrected secant.

The value of k depends on distance and ion density and is difficult to calculate. Transmission curves are drawn for the corrected secant with the correction factor obtained from experimental observations. At short distances, since plane earth is approximated, the factor, k, approaches 1.

48. Transmission Curves

a. Curves of the relationship between the virtual heights and the corrected secants of the angle, ϕ_o, generally are drawn on semilog paper for transmission distances of 100 to 4,000 km. The secant scale is logarithmic and runs from right to left. This set of transmission curves can be used to obtain oblique incidence characteristics when used in conjunction with a virtual height-frequency curve also plotted to the same scale on semilog paper with a logarithmic frequency scale running from left to right. The virtual heights must satisfy both the geometric relationship with angle and the measured relationship with frequency. Figure 26 shows a set of transmission curves and a typical virtual height-frequency curve.

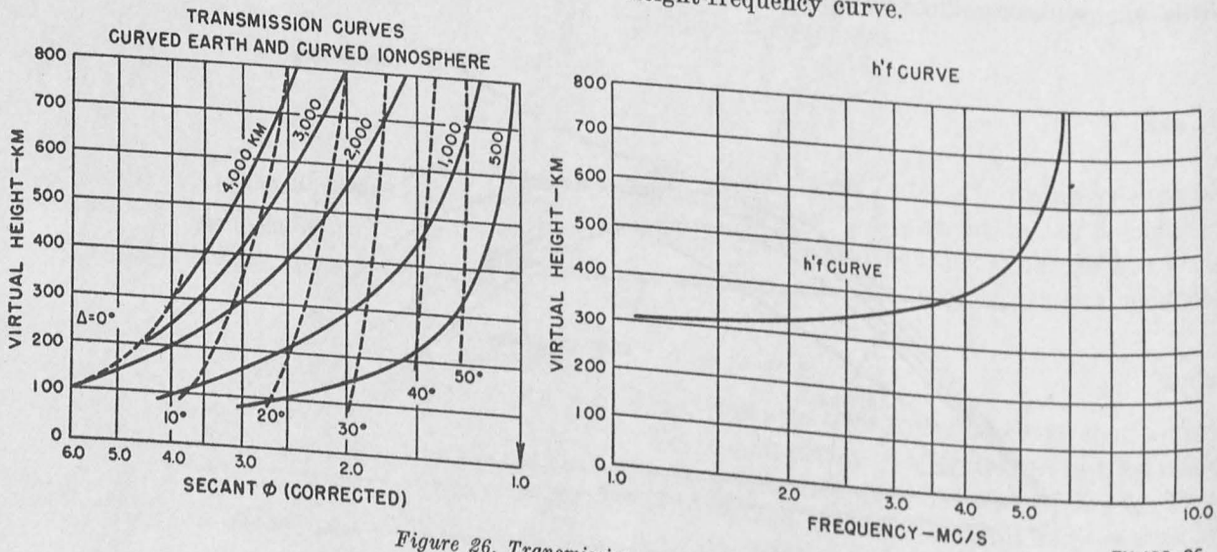


Figure 26. Transmission curves and h'f curve.

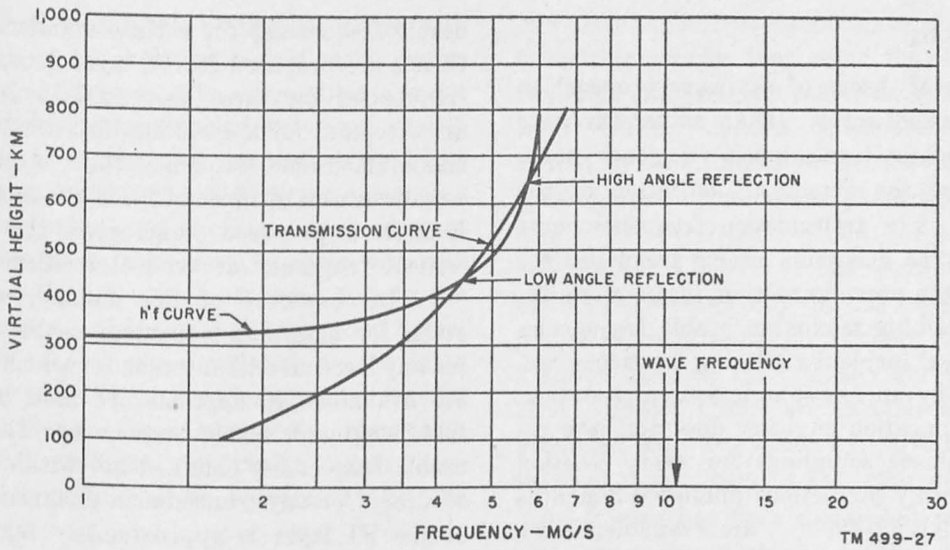


Figure 27. Virtual height calculation.

b. If a transparency with a semilogarithmic transmission curve for a particular distance is laid over an $h'f$ curve with the abscissa, sec $\phi_o = 1$, overlaying the wave frequency, the virtual height can be obtained. The intersection of the transmission curve and the $h'f$ curve give the virtual height at which the wave frequency, f, is reflected. At wave frequencies which are greater than the critical frequency for the layer, two reflecting heights are observable corresponding to the low- and high-angle rays. Figure 27 indicates the process of finding the virtual height at a known wave frequency (or vice versa) for an assumed circuit for which the $h'f$ curve is known at the control point. The $h'f$ curves are, of course, different with season, location, time of day, and sunspot cycle.

49. Graphical Calculation of Usable Frequency

This method can be used to find the maximum usable frequency for any given distance from the vertical-incident measurements. The transmission curve is set so that it is tangent to the $h'f$ curve. The maximum usable frequency is the frequency that lies underneath the abscissa, sec $\phi_o = 1$. If the transmission overlay has sets of curves for the various distances, maximum usable frequencies can be obtained quickly by sliding the particular curve until it is tangent to the $h'f$ curve. Figure 28 shows the graphical calculation of maximum usable frequency.

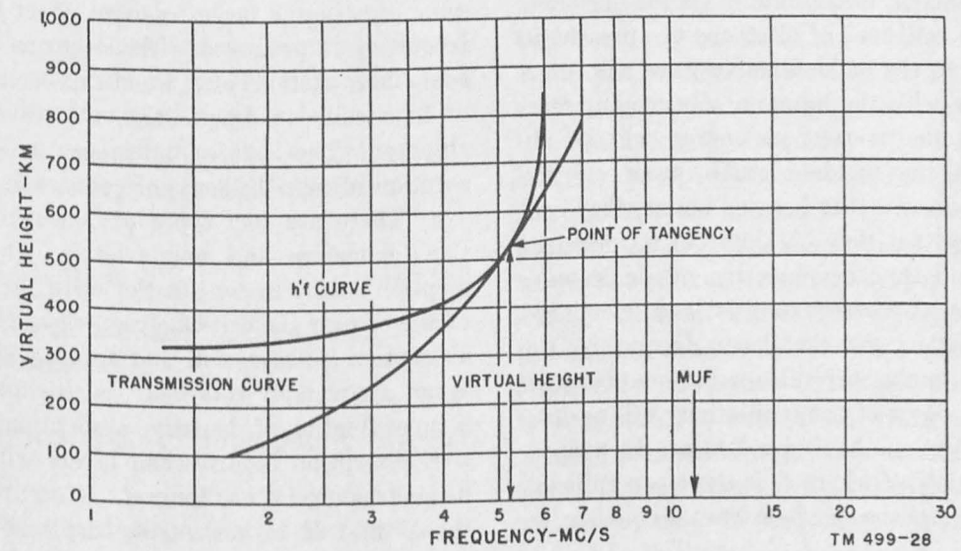


Figure 28. Graphical solution of maximum usable frequency.

50. Predictions

a. The general theory of sky-wave propagation has been discussed above. In an actual sky-wave circuit, the highest transmission frequency possible depends on the extent of ionization of the ionized layers. The transmission frequency must be lower than the maximum usable frequency for the route. In the previous section, means were discussed for obtaining maximum usable frequencies from the vertical incident exploring frequency records obtained by an ionospheric sounding station. The radio propagation engineer does not have access to ionospheric soundings for every location and time. Monthly predictions published 3 months in advance in TB 11–499–( ) are available. These predictions, compiled by the Central Radio Propagation Laboratory of the National Bureau of Standards, are based on actual ionospheric soundings and analysis of past records. Transmission curve methods are used to calculate the maximum usable frequencies for certain standard distances. Charts are prepared for F2 layer maximum usable frequencies for three geographic zones, for zero distance, and for a 4,000 km distance. An E layer maximum usable frequency chart is prepared for a transmission distance of 2,000 km, and a sporadic E chart is prepared which gives the sporadic E critical frequency at vertical incidence.

b. In chapter 3 of this manual, methods are given for obtaining maximum usable frequencies for any location and any time for which predictions are available. Nomograms are used in obtaining these maximum usable frequencies. The maximum usable frequencies obtained are within 10 percent accuracy for any transmission distance. The effect of the F1 layer is approximately taken into account in the E layer nomogram by the assumption that the F1 layer controls propagation at distances between 2,000 and 4,000 km, the MUF (maximum usable frequency) being a few percent above the E layer MUF.

Section VI. IONOSPHERIC ABSORPTION

51. Absorption Produced Regularly in Ionosphere

a. Ionization not only can cause a radio wave to bend but can absorb energy from the radio wave as well. Observations indicate that the greatest absorption occurs in regions of large molecular densities in which the statistical mean collision frequency is high. The incident radio wave causes electrons in an ionized region to oscillate in simple harmonic motion. If no collisions of electrons are present in an ionized layer, the incident radio wave will interchange energy with the harmonically moving electrons, and on the average no energy will be abstracted from the incident radio wave. If the electrons collide with the heavier atoms, they will give up energy that they obtain from the incident radio wave and thus decrease the available wave energy. If the wave frequency is large compared with the statistical mean collision frequency, the electrons will make several oscillations between each collision. Most of the oscillations will be lossless. The oscillations having a loss are in proportion to the ratio f_c/f where f_c is the mean collision frequency and f is the incident wave frequency.

b. The effect of the magnetic field is considerable on the wave absorption. When a radio wave is traveling in the direction of the earth's magnetic field, it is broken up into circularly polarized components. The magnetic field makes the free electrons rotate in a plane perpendicular to the direction of the wave travel. The earth's field tends to produce maximum rotations (at the gyrofrequency). When both the earth's field and the wave's electrical field tend to produce rotations in the same direction, a large resonant effect at the gyrofrequency is produced. The electrons tend to execute large motions and, when this occurs at a level of high collision frequencies, the wave is greatly absorbed. The gyrofrequency can reduce the absorption in case the sense of rotation is opposite.

c. There are two types of ionospheric absorption: deviative and nondeviative. Deviative absorption occurs in conjunction with the slowing up of waves near the critical frequency. Nondeviative absorption is absorption that occurs when the wave is not appreciably retarded. In this manual, there is no evaluation of deviative absorption. Nondeviative absorption occurs when layers with high collision frequencies are ionized. It occurs mainly in the D and E layers during daylight hours and varies approximately inversely with the wave fre-

quency squared. Since this absorption varies with the intensity of lower layer ionization, it varies with the angle of the sun. The attenuation is greater for long-distance transmission, becoming smaller the more nearly vertical the incident wave. Since the lower layer ionization is a function of sunspot activity, absorption also increases with sunspot number. Absorption also seems to vary with season in a manner not alone accounted for by the angle of the sun. This seasonal absorption variation appears to be due to variation in the ionospheric heights. The greater heights for the F2 layer in the summer tend to decrease absorption for radio paths reflected by the F2 layer. Nondeviative absorption can be represented by the equation—

$$A = \frac{C F(\psi) \sec \phi_o (M \cdot S)}{(f + f_H)^2} \quad \text{(Eq 24)}$$

where M is the seasonal correction factors;
S is the solar activity correction factor;
ϕ_o is the equivalent angle of incidence at the ionosphere;
$F(\psi)$ is a function of the angle between the reflection point in the ionosphere and the sun;
C is a constant;
f is the wave frequency; and
f_H is the component of the gyrofrequency in the direction of the radio wave.

Analysis of field intensity recordings show that the absorption can be related to a function, K, of the angle of the sun.

$$K = 0.142 - 0.858 \cos \psi \quad \text{(Eq 25)}$$

where ψ is the angle between the perpendicular to the ionosphere at the reflection point and the direction to the sun.

The angular relationships at the ionosphere can be given by the absorption index, K, multiplied by the distance.

$$Kd = c' f(\psi) \sec \phi_o \quad \text{(Eq 26)}$$

where d is the transmission distance, and
c' is a constant.

52. Absorption Due to Ionospheric Irregularities

a. In addition to absorption produced regularly in the ionosphere, there are additional absorptions due to ionospheric irregularities. It has been mentioned previously that solar flares and particle radiation from the sun can cause abnormal absorption. During sudden ionospheric disturbances caused by solar flares or bursts, the lower ionospheric layers often become abnormally ionized and can cause severe absorptions for all frequencies above about 1.5 mc. It has been stated that the disturbances occur only during daylight hours and generally are of short duration not exceeding about 2 hours. Because the intensity and time of occurrence of solar bursts are variable and cannot be predicted with any accuracy, no attempt is made to account for them in this manual.

b. It also has been mentioned previously that sky-wave communication is less reliable for circuits passing through regions at high latitudes. Absorption appears to be much greater in these circuits, particularly during certain seasons of the year. In the northern latitudes, the radio circuits are disturbed most during the months from midsummer through fall. The high absorptions very likely are due to ionization occurring during periods of auroral activity. The same cause which produces the aurorae probably produces the increases in absorptions and other irregularities in these high latitude radio circuits. The aurorae are caused by particles radiated from the sun that are guided into the polar regions by the earth's magnetic field. Auroral activity extends from heights greater than about 600 km to about 100 km. Observations of the visible aurora indicate that the auroral activity does not simply increase toward the poles, but there is a circular zone of maximum auroral activity. The auroral zones shown in this manual are based on observations of the visible aurorae. These zones, as mentioned before, lie about 20° from the earth's geomagnetic poles. Observations indicate that the maximum frequency (the number of days of auroral activity) occur near the equinox months. Auroral activity is most likely to occur at certain hours of the day. The auroral activity also appears to vary with the relative sunspot number. The number of occurrences per year appear to follow the 11-year sunspot cycle. Since the available experimntal information is limited, auroral activity is accounted for only on an average basis in this manual. Auroral absorption is determined by using an equivalent absorption index, K_a, which is assumed constant throughout the year, the sunspot cycle, and the day.

Section VII. SKY-WAVE FIELD INTENSITIES

53. General

a. Sky-wave communication is possible at a particular frequency if the ionosphere is sufficiently ionized to reflect radio waves of that frequency. Methods of chapter 3 show how to determine when the ionosphere will support communication between a transmitter and a receiver that are located at any geographical points for any particular time.

b. For useful communication, the signal strength at the receiver must be sufficient to override the effects of noise. In this manual, the field intensity of the downcoming sky wave at the receiving location is found by using methods requiring as parameters the transmitting antenna radiation, the absorption function (K) for the circuit, the transmission distance, and the wave frequency. The absorption function is corrected for variations in sunspot activity and season. The field intensity methods give the downcoming sky-wave field intensity by subtracting the absorption from the unabsorbing field intensity, the median downcoming sky-wave field intensity that would have been observed had no ionospheric absorption occurred in the ray path.

54. Antennas

a. In radio propagation, energy is transmitted between the transmitter and the receiver by electromagnetic waves. Variable currents in a conductor produce electromagnetic waves in the space surrounding the conductor, in addition to an induction field. Energy is transferred alternately to and from the conductor to the near or induction field as the current alternates, with no energy lost permanently in the induction field. At high frequencies, all the energy fed into the conductor does not remain there or in the induction field but much is radiated into space in electromagnetic waves. The amount of radiated energy is proportional to the frequency of the current, being greater at higher frequencies. These electromagnetic waves travel away from the wire with the velocity of light. Electromagnetic waves have moving electric and magnetic fields which always are associated with each other. The electric and magnetic fields are at right angles to each other and perpendicular to the direction of wave travel. These fields follow the current variations in the conductor but occur at a later time due to the time required for wave travel. The fields oscillate at the frequency of the antenna current. The wave frequency, velocity of propagation, and the wavelength are related by the equation—

$$\lambda = \frac{C}{f\ 10^6} = \frac{300}{f} \qquad \text{(Eq 27)}$$

where λ = wavelength in meters;
f = frequency in mc; and
$C = 3 \times 10^8$ meters per second.

b. The intensity of an electromagnetic wave usually is obtained by measuring the electric intensity. Radio engineers measure the intensity in microvolts per meter. A field intensity is an electromotive force per unit length. The electric and magnetic intensities of a plane wave in free space are related by the impedance of free space or 377 ohms.

c. Transmitting antennas are designed for high efficiency in radiating energy and receiving antennas are designed for the efficient pick-up of energy. On many radio circuits, transmission is required between a transmitter and only one receiving location. In these cases, it is desirable to radiate as much energy as possible in the desired direction since radiated energy is useful only in that direction. Directional characteristics in a receiving antenna increase the energy pick-up in the favored direction and reduce the reception of unwanted noise and signals from any other direction. The general requirements for receiving and transmitting antennas are that they have small energy losses and that they be efficient as receptors or radiators.

55. Transmitting Antennas

a. Transmitting antennas are designed to be efficient radiators of energy. Electromagnetic waves are radiated by each part of a circuit in which h-f currents flow. The greatest radiation is from those in which the current is the greatest. An antenna may be described as a circuit arranged in such a manner that the radiation from each part of the circuit does not cancel the radiation from other parts. The circuit is spread or opened into space in order to make the radiation appreciable. By connecting the output of a transmitter into an open-ended circuit of sufficient length, it is possible to

obtain standing waves along this open end or antenna. The electrical impulses from the transmitter travel to the open end of the wire and are reflected backward. The incident and reflected impulses produce a standing wave of current along the wire. Practical resonant antennas, such as the half-wave antenna, have large standing wave current distributions along the wires. Nonresonant antennas, like rhombic antennas, have traveling waves of current in the wires. The currents are in proper phase relationship to produce large radiations.

b. Often it is convenient to express the radiation from the antenna in terms of its radiation resistance. This resistance is such that if it were substituted for the antenna it would consume the same amount of power as is actually radiated from the antenna. The magnitude of the resistance depends upon the point at which the resistance is considered to be inserted since current varies along the antenna and the power is assumed to be equal to the current squared times the radiation resistance. The efficiency of an antenna is the ratio at the feed point of the radiation resistance to the sum of the radiation resistance plus the loss resistance. Antennas, in which the ratio between the length of the antenna and the wavelength is 0.25 wavelength or more, usually have an efficiency of 75 percent or greater. Antenna reactances do not affect the antenna efficiency but do affect the matching problem between the transmitter and the antenna. All perfectly efficient antennas radiate all the power that is delivered to them.

c. The directivity gain of an antenna in some particular direction is the relation between the power per unit area radiated in that direction to the average power per unit area. An omnidirectional antenna radiates average power in all directions.

d. At frequencies below 2 mc, vertical antennas generally are used since communication occurs principally on ground waves. A vertical radiator of a length of 0.625 wavelength gives the greatest radiation at the ground plane. At these lower frequencies, due to the large required physical height, it is necessary from practical considerations to limit the height-wave length ratios to values less than a quarter-wave although radiation is not as good as it would be for longer height-wave length ratios. The sky-wave radiation varies approximately as the cosine of the angle above the ground plane and the radiation in a horizontal plane is equal in all directions or omnidirectional. Directivity in the horizontal plane can be obtained by using two or more spaced radiators. The concentration of the energy at low radiation angle (angles above the ground plane) increases as the antenna length approaches a half wave length. If the vertical antenna is longer than a half wave length, high angle radiation occurs due to the radiation from secondary lobes in the antenna pattern. Because of ground losses, the ground system should be made as efficient as possible. In many Army uses, it is recommended to use radial ground wires laid on the surface of the ground radiating at a point below the vertical antenna.

e. In the frequency range from 2 to 30 mc, vertical half-wave antennas are used when omnidirectional radiation in the horizontal plane is required. Horizontal half-wave antennas are very good radiators of sky waves at short and intermediate distances. Maximum radiation occurs at right angles to the antenna, while there is minimum radiation in the direction of the antenna. Since the low angle radiation increases with the height that the horizontal antenna is placed above ground, the antenna should be at a height of a half wave length or more if it is to be used for long-distance routes. At short distances, the optimum height above ground is about a quarter wave length. When directivity is required, several half-wave radiators can be used in an antenna array. It is customary, in routes of very long distance, to use very directive antennas in order to obtain sufficient field intensities with moderate transmitter powers. In most of these installations, rhombic or V antennas are used.

f. At frequencies above 30 mc, many types of antennas commonly are used. Some of these are loops, half-wave radiators, cone antennas, and various types of antenna arrays. Communication at these frequencies is by groundwaves. Broadcast work usually is done with horizontally polarized waves.

g. All the basic field intensity curves and nomograms of this manual are worked out for an antenna which radiates a field of 300 millivolts per meter when measured at a distance of 1 km (186.3 millivolts per meter at 1 mile). The radiation characteristics of practical antennas such as used in Army circuits are given in curves of chapter 3. The field intensity produced by an antenna is inversely proportional to the distance from the antenna if no absorption losses are present. The value of this inverse distance field produced at a standard distance by a transmitting antenna with a standard

input power measures the effectiveness of the antenna as a radiator. The antenna curves are given in ratios squared of the inverse distance field intensity (in the ratios of power radiated per square meter) for the actual antenna at 1 mile to 186.3 millivolts per meter. The reference field intensity value of 186.3 millivolts per meter is the value that a short, lossless, vertical antenna erected over perfectly conducting earth will produce at 1 mile with 1 kw (kilowatt) of input power when the measurements are made in the ground plane. The antenna curves show the antenna gain under actual operating conditions with respect to the short theoretical antenna. This is illustrated by the equation—

$$\text{Gain} = \left(\frac{\text{field intensity in millivolts per meter at 1 mile produced in the required direction by the actual antenna with 1 kw of input power}}{\text{186.3 millivolts per meter}} \right)^2 \quad \text{(Eq 28)}$$

The antenna curves generally give the radiation in the direction of the maximum radiation in the horizontal plane. Curves are drawn for various angles with respect to the ground plane. As shown in chapter 3, the received sky-wave field intensities can be adjusted for the actual antenna gain and input power by using the values of the antenna curves. The antenna curves account for ground reflections and antenna losses, giving a good index of the antenna radiation under actual operating conditions. The curves, mainly based on theory, closely check with measurements taken under field conditions.

56. Receiving Antennas

a. A receiving antenna should be designed for the efficient reception of electromagnetic waves. Directional receiving antennas abstract more energy out of a passing radio wave than a nondirectional antenna and pick up less atmospheric noise from directions other than that in which the antenna is pointing. At frequencies below 2 mc, simple antennas pick up sufficient energy and directional antennas are not required to increase the receivable energy. At these low frequencies, the receiving antennas should be vertical to receive the vertically polarized radiation from the transmitting antennas. Loop antennas commonly are used with broadcast receivers because they do not pick up much of the electric induction fields produced by electric appliances. At frequencies above 2 mc, increased antenna directivity is important, although, oftentimes, only short pieces of wire are used as receiving antennas up to 30 mc. At frequencies above 30 mc, directive antennas are required for good reception.

b. The characteristics of a receiving antenna usually are described in its effective height. The effective height of a receiving antenna is the quantity which, when multiplied by the incident field intensity, gives the voltage induced across the antenna terminals. The effective height is given in meters so that, when it is multiplied by the incident field intensity in microvolts per meter, the induced voltage is in microvolts. A receiving antenna picks up energy for the reason a wire placed in a varying field has a voltage induced in it. Remembering motor theory, the voltage induced in a wire is equal to the intensity of the magnetic field at right angles to the wire multiplied by the length of the wire and the velocity at which the wire is moved. The induced voltage across a wire in an electromagnetic field is equal to the magnetic intensity multiplied by the length of the wire and the impedance of free space or is equal to the electric intensity in the direction of the wire multiplied by the wire length. Since the impedance of space is related to the velocity of the electromagnetic wave, the case for the motor and for the receiving antenna is similar. Although it has been a practice in the past to define effective height for electric intensities in the direction of the wire, recently, the effective heights have been defined for plane waves incident to the antenna at any angle with the directional characteristics of the antenna included. It is a practice to calculate receiving characteristics from the transmitting characteristics. It has been shown that the effective heights, radiation resistances, and directional patterns of an antenna are the same whether it is receiving or transmitting.

57. Diversity Reception

It has been stated previously that the sky-wave field intensities present both slow and rapid variations with time. An effective way of reducing rapid variations or fading is to use more than one receiving antenna. It has been shown experimentally that the signals induced in each antenna fade independently, provided the antennas are about five wavelengths apart. The downcoming sky-wave field intensity is due to the combination of more

than one wave and the contributing waves do not combine exactly alike at all locations at the receiver. Generally, the output of each antenna is fed to separate receivers and the receiver outputs are combined after detection. The strongest signal usually dominates the situation in practical installations, since the receivers have a common age (automatic gain control). Thus, the strongest signal regulates the stages of the other receivers. Diversity systems generally are used on high-speed automatic telegraph systems. In these systems, it is desirable for satisfactory service to have very little fading. In case the fading occurs over even a brief time interval, the intelligence can be lost. Figure 29 shows the diversity gain for 2-, 3-, and 4-stage diversity reception. The gains are given for various percentages of time.

58. Discrimination Gains

a. Since directional antennas pick up little atmospheric noise except from the direction which the antenna favors, their use improves the signal-to-noise ratio at the receiver. It can be shown that the improvement in signal-to-noise ratio at the receiver input is equal to the antenna directivity gain in case of omnidirectional atmospheric noise. The nature of atmospheric noise is discussed in Radio Propagation Technical Report No. 5* when the noise limitations for reception are given. It is pointed out that atmospheric noise occurs principally due to thunderstorm activity. The principal sources of atmospheric noise occur over tropical land masses during the daytime hours. Throughout the day, noise centers vary in activity and in location. An antenna will not pick up the same amount of noise at all hours of the day. From the present knowledge, it is extremely difficult to determine in advance the directional characteristics of atmospheric noise. The amount of noise pick-up differs with receiver frequency and hour of the day. Considering that noise centers shift in location, it has been shown by limited experimentation that even though an antenna is pointed at a distant average center of thunderstorm activity, as a daily average, it discriminates against atmospheric noise as well as if it were not directed at a noise center. Thus, a practical estimate of the discrimination gain against atmospheric noise can be based on an assumed omnidirectional noise.

b. There are curves in this manual which show the required signal strength necessary to override the effects of atmospheric noise. The measured noise voltages were converted into equivalent incident field intensities by using the ground plane effective heights of the vertical antennas that were used during the noise measurements. Useful communication is possible when the received sky-wave field intensity is equal to the required incident field intensity, in case the receiving antenna effective heights are alike for both signal and noise. Based on the assumption that all antennas received the same amount of omnidirectional noise, the signal-to-noise ratio at the receiver input is increased by directional receiving antennas. The amount of signal power increases while the noise power remains the same. The discrimination gain or the improvement in signal-to-noise ratio due to the antenna directivity can be obtained from the ratios of the effective height for the signal to the effective height for the noise. The signal-to-noise ratio at the receiver input can be written by the following equation:

$$S/N = 20 \log_{10} \frac{E_s}{E_n} \qquad \text{(Eq 29)}$$

where S/N is the signal to noise ratio at the receiver input, in decibels;
E_s is the signal voltage; and
E_n is the noise voltage.

The signal voltage at the receiver input is equal to the received incident field intensity multiplied by the effective height for the receiving antenna in the direction of wave arrival, and the noise voltage at the input is equal to the required incident field intensity (equivalent omnidirectional incident field intensity) multiplied by the ground plane effective height of the noise-measuring antenna. The signal-to-noise ratio can be written by the following equation:

$$S/N = 20 \log_{10} \frac{e_s h_s}{e_n h_{gp}} = 20 \log_{10} \frac{e_s}{h_s} + 20 \log_{10} \frac{h_s}{h_{gp}} \qquad \text{(Eq 30)}$$

where e_s is the incident field intensity of the signal to the receiving antenna;
e_n is the incident field intensity of the noise at the receiving antenna;
h_s is the effective height of the receiving antenna; and
h_{gp} is the effective height of the noise-measuring antennas.

*See item No. 33 in bibliography in appendix II.

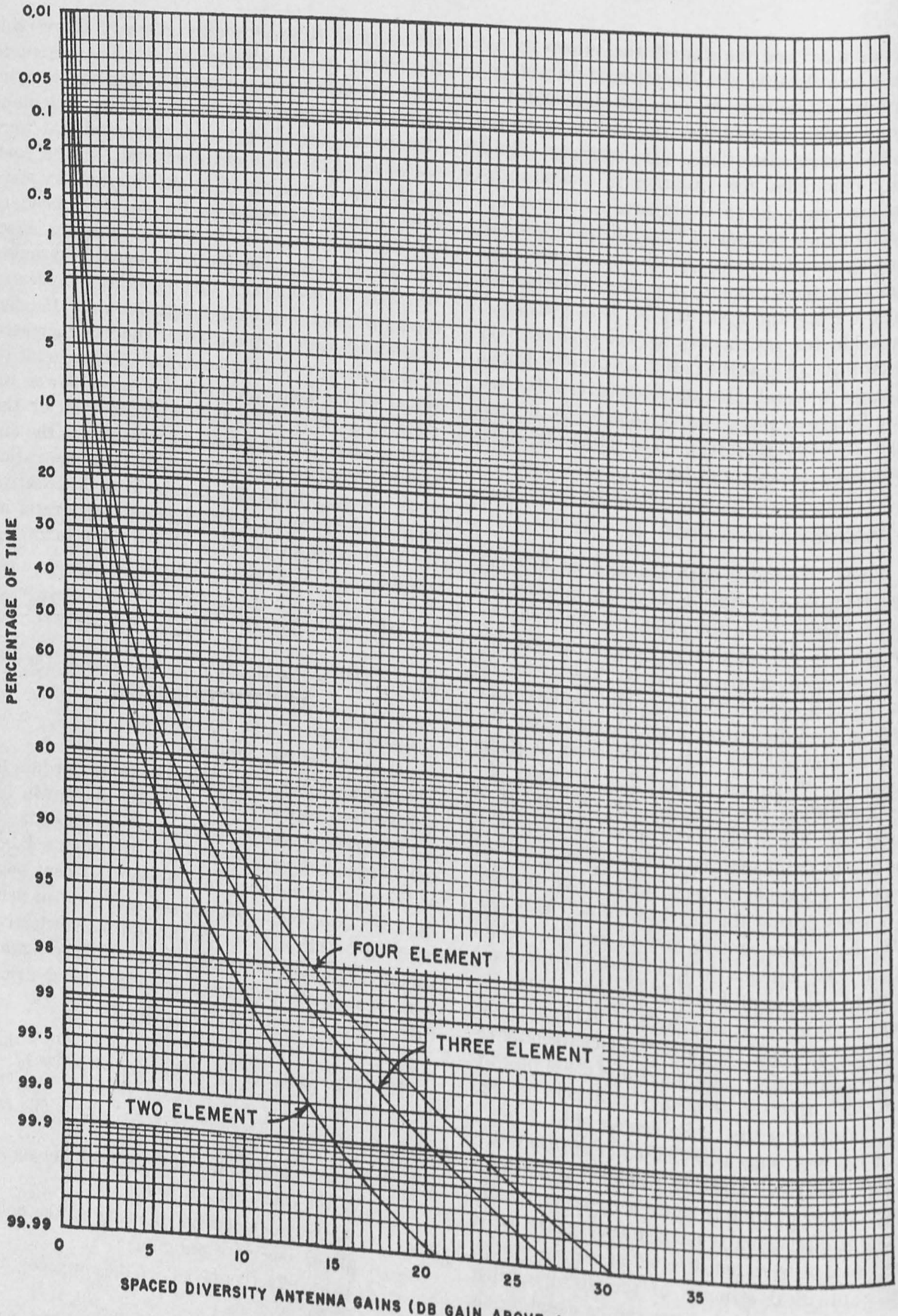


Figure 29. Gains of spaced diversity receiving antennas for rapidly fading signals.

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Thus, the discrimination gain or the improvement in the signal-to-noise ratio is equal to the ratio of the effective height of a receiving antenna at the wave arrival angle to the effective height of the noise-measuring antenna at the ground plane. Transmission line losses are included in the effective heights.

c. In chapter 3 of this manual, there are receiving antenna curves which show, in addition to the discrimination gains at various vertical angles in the optimum horizontal direction, the required incident signal strengths to overcome random noises generated in the receiving set. Discrimination gains are applied only in the case of atmospheric noise in this manual.

59. Fading

Received sky-wave field intensities vary with time because of fluctuations in ionospheric conditions. In this manual, field intensity values are given for any hour of the day as a monthly median. From day to day and minute to minute within the hour, the values are not steady but fluctuate in a statistical manner. These slow and fast variations are accounted for by a method based on the analysis of the records of sky-wave field intensities from distant stations. It appears best to account for the slow variations and the fast variations separately, as shown in paragraphs 63 and 64, on the evaluation of fading effects. Rapid fluctuations that occur from minute to minute or in smaller time intervals generally are referred to as *fading*. In addition to producing a varying amplitude, fading can produce distortion. There are four general types of variations: interference, polarization, absorption, and skip fading. The first two are responsible for the majority of rapid changes that occur from minute to minute while the other two are responsible for slower changes.

60. Interference Fading

a. Interference fading is caused by the interference effect produced by different wave components arriving from the same source that have traveled along slightly different paths in the ionosphere. A sky wave is not one simple wave, but is composed of a large number of component waves, each of which is reflected at a slightly different place. The differences in path lengths cause phase differences between the wave components. Thus, the received sky-wave field intensity fluctuates as the phase relationship between the component waves changes with time. The sky-wave field intensity actually is the sum of the contributions of a large number of waves of random relative phase. The field intensity fluctuates about the value it would have had if the reflecting layer had been an ideal instead of an irregular layer.

b. In addition to interference fading due to layer irregularities, there are several other types of interference fading. The combination of sky waves that arrive at the receiving location over different ray paths also can produce severe fading when the different sky-wave modes are comparable in magnitude. A sky wave may arrive at the receiving location after either single or multiple reflections from any of the ionospheric layers. The combination of the randomly varying sky wave and the ground wave produces very bad interference fading when the sky and ground waves are comparable in magnitude. *Flutter* fading, which is characterized by very rapid fluctuations in intensity, is due to the combination of a large number of waves which differ appreciably in path length. Scattered reflections from localized ionospheric cloud patches can produce flutter fading. Flutter fading usually is noted on paths passing in or near the auroral zone. Interference fading also can be produced by rapid variations in ionospheric layer heights at sunrise and sunset. This type of fading, which is experienced primarily at low frequencies, occurs when the sky wave combines with the ground wave. The fading usually has a relatively long period.

61. Polarization Fading

a. Polarization fading is caused by the changes produced in the state of polarization of the sky wave by the ionosphere. In discussing the radiation of electromagnetic waves, the most elementary wave type considered is one in which the wave front is plane. In such a wave, the electric and magnetic field are at right angles to one another and lie within the wave front perpendicular to the direction of propagation. Radio engineers, when discussing the polarization of the plane waves, refer to the direction of the electric intensity. A vertically polarized downcoming sky wave is one in which the electric intensity lies within a plane perpendicular to the earth. The sense of polarization is in the direction of the electric vector. A horizontally polarized downcoming sky wave is one in which the

electric intensity lies in the plane horizontal to the earth. Any downcoming uniform plane wave can be broken up into two components, one in which the electric intensity is in the horizontal plane and one in which the electric intensity is in the vertical plane. This wave can be considered as two plane waves, one vertically polarized and one horizontally polarized. Two uniform plane waves of the same frequency but of different phases, magnitudes, and orientations of the field vectors, result in an elliptically polarized wave. Remembering elementary alternating current theory, it is noted that two electric fields of equal magnitudes at 90° in space and at 90° in phase difference produce a resultant rotating electric field. Elliptically and circularly polarized fields rotate in the plane of polarization at right angles to the direction of propagation. Generally, it is possible to consider any plane wave as the combination of two waves rotating in opposite directions. In free space or any ionized medium without a magnetic field, a wave of any type of polarization can be propagated. The polarization ellipse of any elliptically polarized wave can have any eccentricity or position parallel to the wave front. In a magnetic field, polarization no longer is arbitrary and for a given direction of propagation relative to the field, the polarization ellipse is fixed. It is useful to discuss special cases, one in which the direction of propagation is in the direction of the magnetic field and the other in which it is at right angles to the magnetic field of the earth. In the longitudinal case, if a uniform plane wave is assumed, this plane wave can be considered to be two oppositely rotating circular waves. The two circularly polarized waves are affected dissimilarly in the propagation through the ionized layer because of the effects of the earth's field. The indices of refraction and the amounts of wave attenuation are different for the two components. In case the electromagnetic wave is at right angles to the earth's magnetic field, only plane wave propagation is present.

b. If the downcoming sky wave is plane-polarized, the signal induced into a linear receiving antenna depends upon the angle between the direction of the electric intensity and the wire. If the downcoming sky wave is considered to be randomly polarized, the median effective field intensity is $\frac{\sqrt{2}}{2}$, times the intensity, had no polarization fading occurred. The polarization of a downcoming skywave is changing constantly due to the random combination of the two components of the original electromagnetic radiation that has been split by the earth's magnetic field. The downcoming sky wave usually is elliptically polarized with the direction of rotation in either direction and the orientation and dimensions of the ellipse changing constantly with respect to the receiving antenna. Polarization changes are more rapid at high frequencies.

62. Skip Fading

Skip fading occurs when operating at frequencies near the maximum usable frequency. Near sunset and sunrise, the ion density of the ionosphere changes rapidly and the maximum usable frequency for the transmission path may vary about the wave frequency.

63. Evaluation of Rapid Variations

a. Short-time variations in sky-wave field intensities during a period of time (usually an hour or less), when the over-all ionospheric absorption can be considered to be constant, is evaluated by the Rayleigh distribution function. This distribution agrees well with measurements of the instantaneous sky-wave field intensities. It was noted previously that all sky waves consist of the combination of energy reflected from various points of an uneven ionospheric layer. Since the lengths of the transmission paths for the wave components are very alike, although substantially different in phase relationship, the sky wave can be considered to be the sum of a large number of waves of equal intensity but random phase. The time distribution of the sky-wave field intensity, as it varies from minute to minute, is given by the Rayleigh distribution. The percent of time that the instantaneous field intensity, E, exceeds the median field intensity is given by the following equation:

$$T = 100\, e^{-0.693 \left(\frac{E}{E_m}\right)^2} \qquad \text{(Eq 31)}$$

where E is the instantaneous field intensity;
E_m is the median field intensity; and
e is the base of the natural logarithms, 2.718281828.

For a Rayleigh distribution, the median field intensity is equal to the square root of 0.693 times the homogeneous field (the value that the field would have had, were no fading present). Figure 30

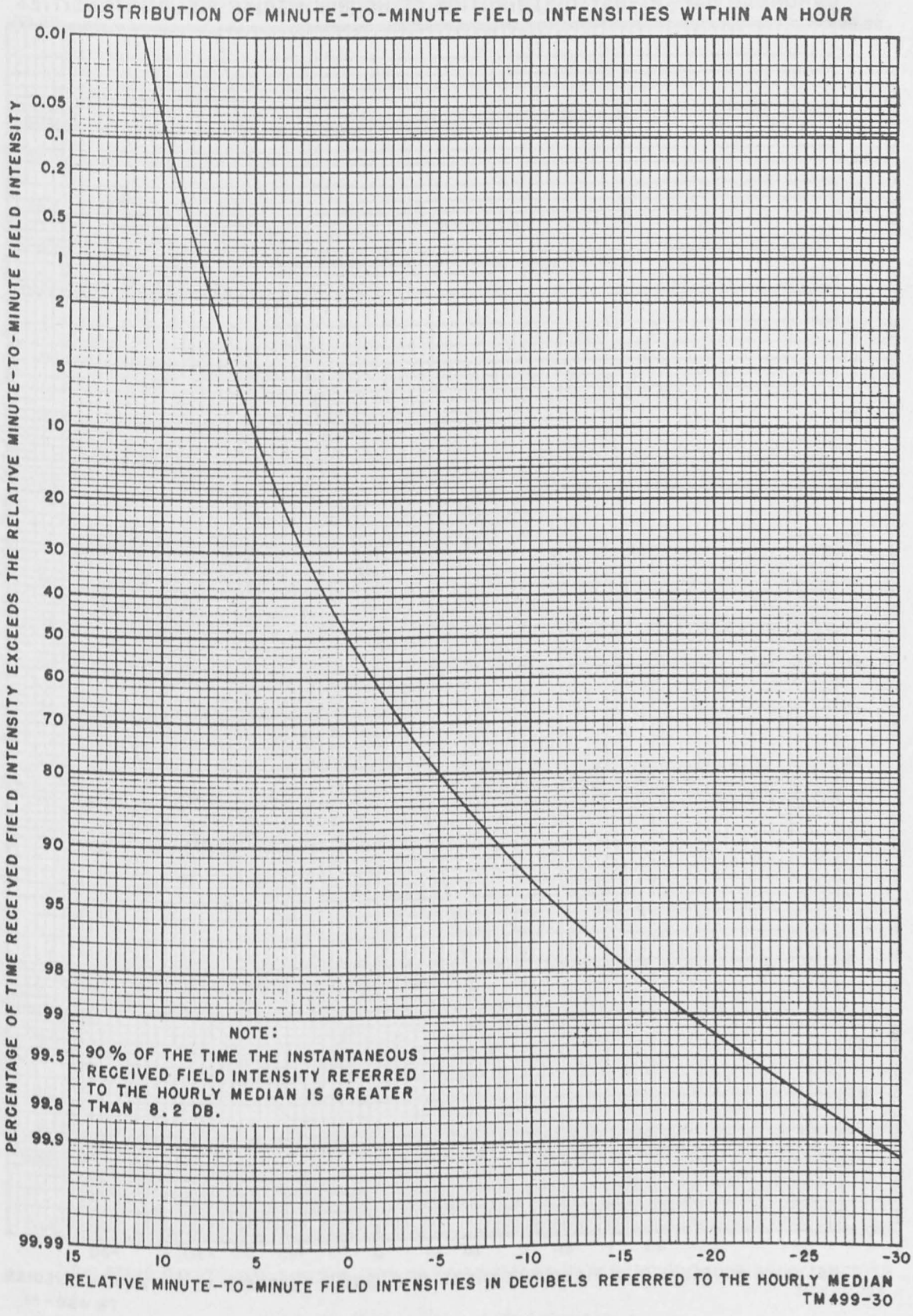


Figure 30. Rapid variation of sky-wave field intensity.

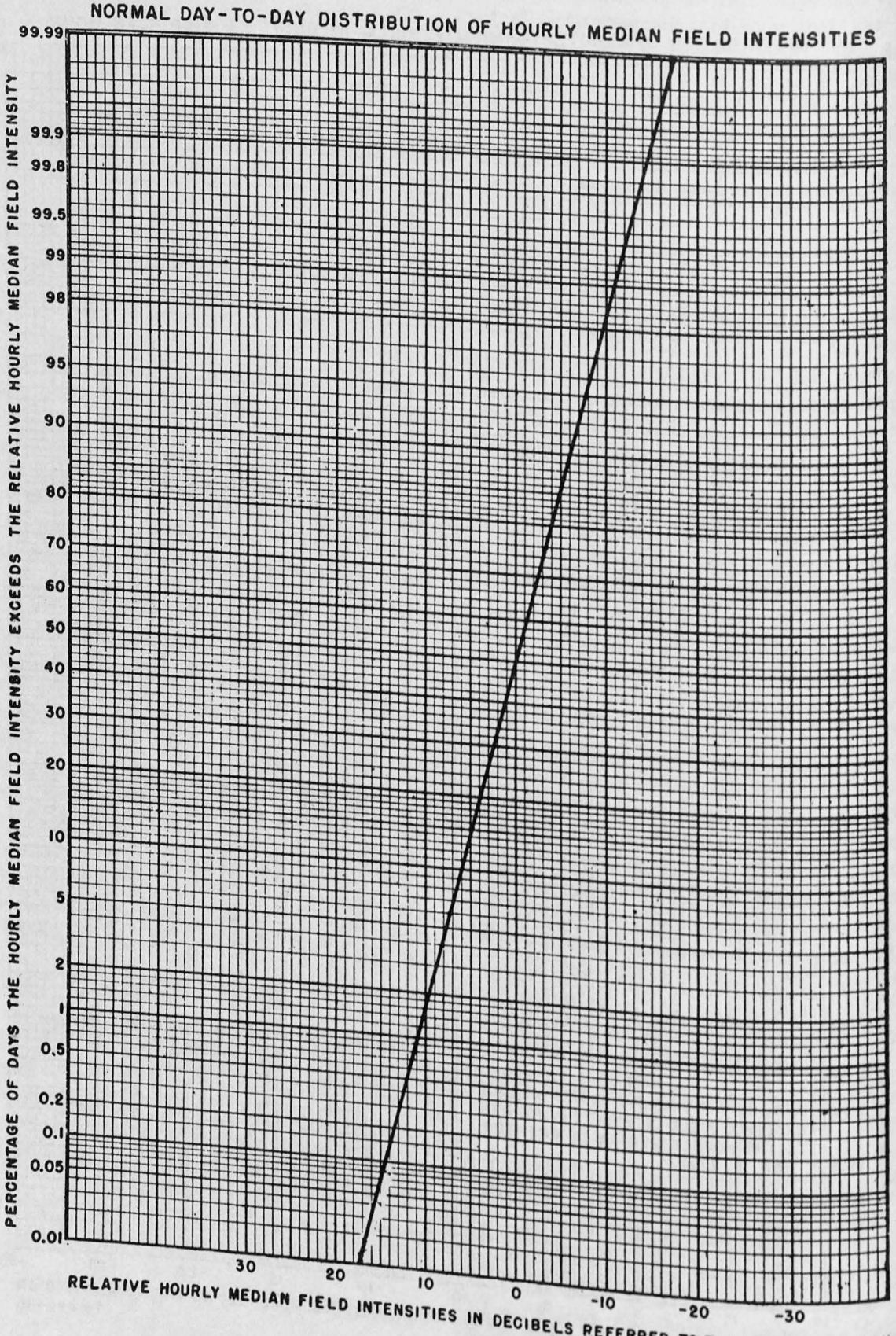


Figure 31. Slow variation of sky-wave field intensity.

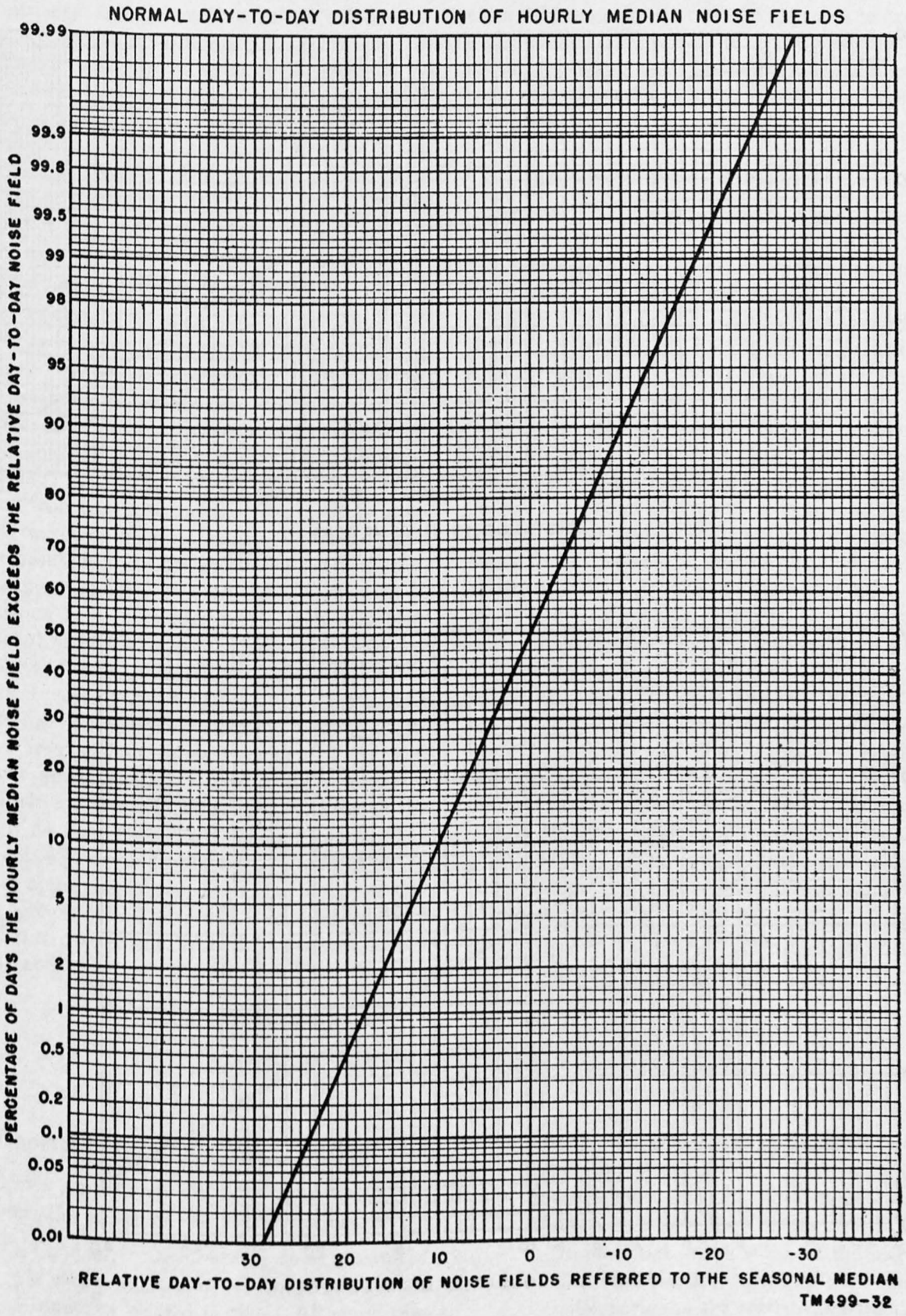
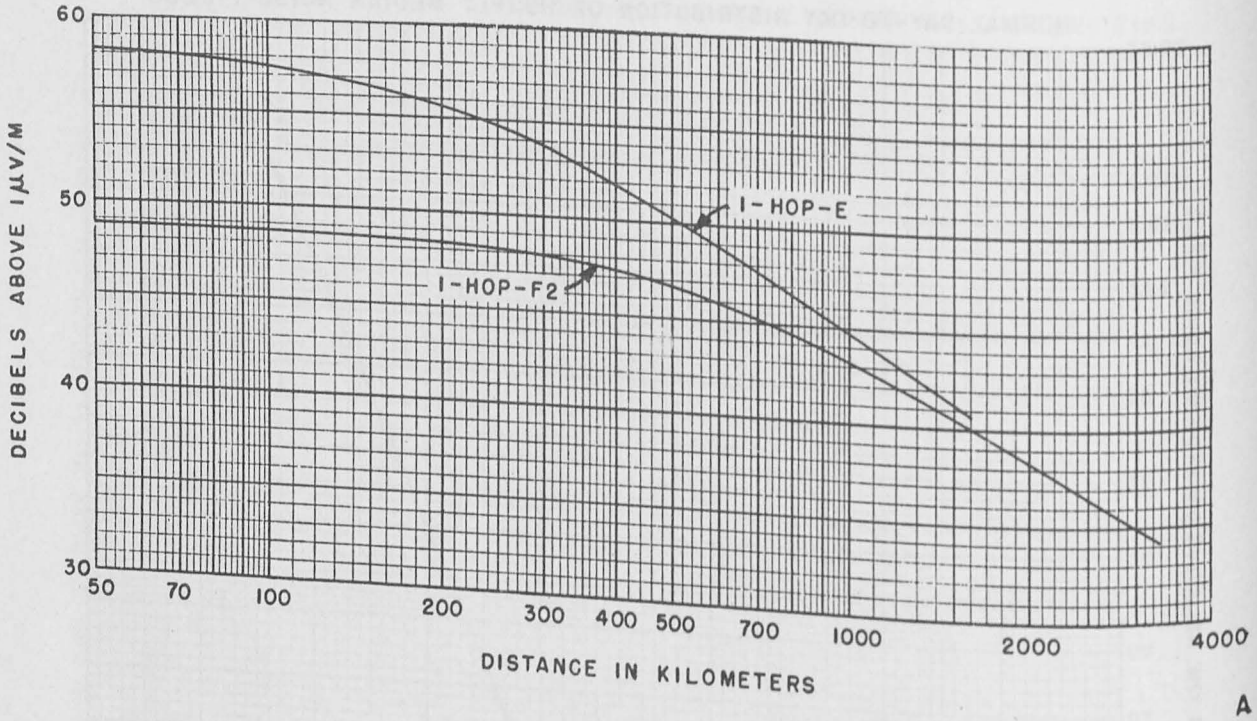
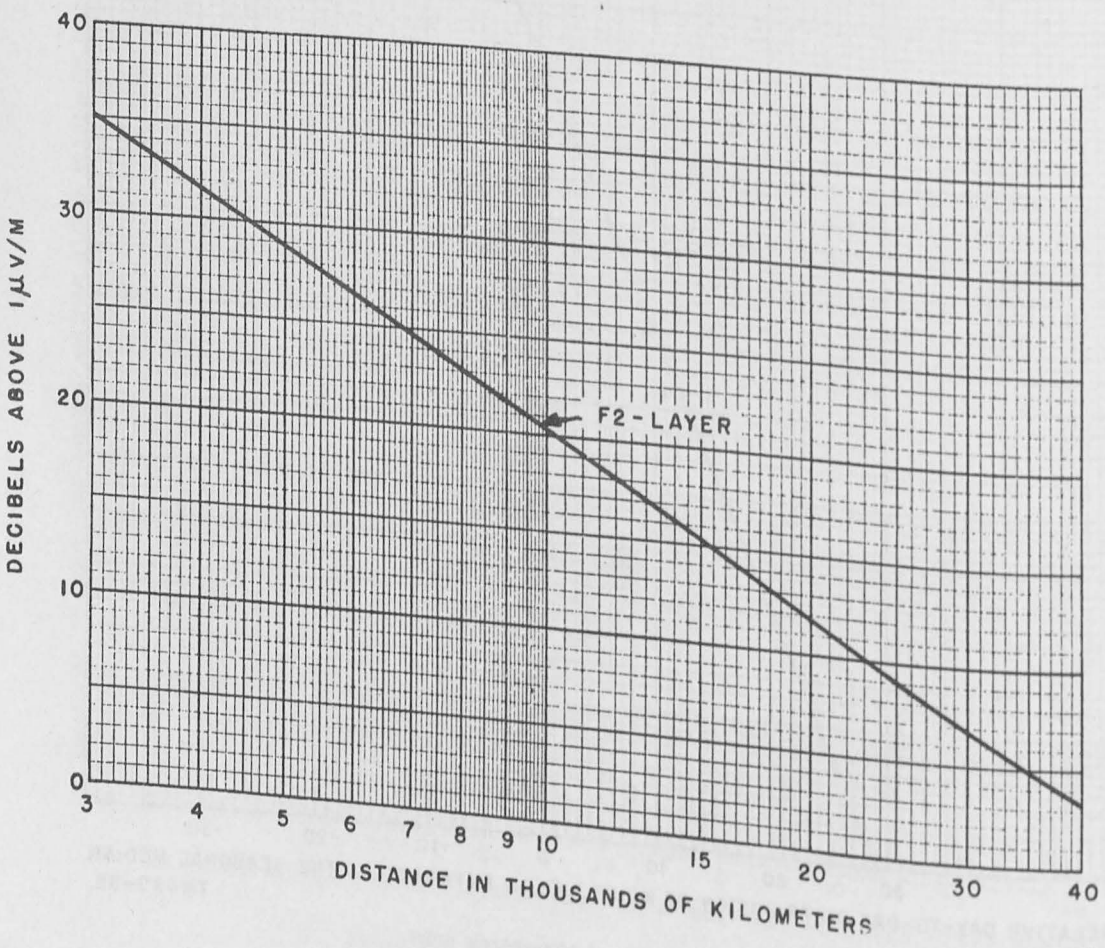


Figure 32. Slow variation of atmospheric noise.





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Figure 33. Median incident field intensity for an inverse field of 300 millivolts per meter at 1 km.

shows percentage of time that the instantaneous field intensity exceeds various values relative to the hourly median field intensity.

b. Rapid variations of noise do not have to be accounted for by fade factors. Noise is inherently variable in character and the irritability effects that noise produce on a received signal are due to its fluctuating character. The rapid fluctuations of noise are accounted for in the required signal-to-noise ratios.

64. Evaluation of Slow Variations

Slow variations in field intensities that occur from day to day, month to month, and year to year are due to variations in ionospheric layer heights and ionospheric absorption. The variations in layer heights cause changes in absorption, in addition to changes due to the daily variation in the activity of the sun. The layer heights vary from day to day and from month to month. The monthly average of the layer heights changes seasonally, and these seasonal changes are accounted for by seasonal absorption factors. A study of the variation in the median field intensities for a particular hour over the days of the month indicate that, from day to day, the time distribution approximates the statistical normal distribution. It is interesting that routes of various lengths and various transmission frequencies, at various hours of the day, all show approximately the same distribution of the hourly median field intensities referred to the monthly median of the hourly median values. The field intensity values exceeded on 90 percent of the days is approximately 6 db below that exceeded on 50 percent of the days while the field intensity exceeded on 10 percent of the days is approximately 6 db above the median value. Figure 31 shows the day-to-day distribution of hourly median sky-wave field intensity that can be expected to exceed a particular value relative to the monthly median. Figure 32 shows the day-to-day distribution of hourly median noise fields relative to the seasonal median of the hourly median values.

65. Unabsorbed Field Intensities

Received field intensities in this manual are obtained by subtracting absorption losses from field intensity values called the unabsorbed field intensities. The unabosorbed field intensity is the value of the downcoming sky wave at the receiving location if no ionospheric absorption losses had occurred. The polarization fading loss of 3 db and ground reflection losses of an assumed value of 4 db per reflection are included in the unabsorbed field intensities. The unabsorbed field is the incident wave at the receiving location and does not include the effects of ground reflection at the receiver. The values are based on a transmitting antenna which radiates an inverse distance field intensity of 186.3 millivolts per meter at 1 mile. For other values of antenna radiation, the unabsorbed field can be adjusted for the antenna gains and the antenna input power. Part A of figure 33 shows the median unabsorbed field intensity for sky waves for a single reflection from the E layer at a virtual height of 105 km and the F2 layer at a height of 320 km for distances up to 3,000 km. Part B of figure 33 shows the median unabsorbed field intensity for F2 layer heights for transmission distances over 3,000 km. The median value was obtained from the calculated unvarying value for an assumed smooth layer by accounting for the difference between the scattered and the unscattered values for a Rayleigh distribution.

Section VIII. NOISE LIMITATIONS FOR RECEPTION

66. General

a. Noise generally is classified according to its characteristics as either random or impulsive.

(1) Random (or fluctuation) noise consists of a large number of elementary impulses randomly related in time. Although random noise is irregular in waveform, its average level is measurable. The noise energy is distributed throughout the frequency spectrum without any pronounced maximum. The amount of noise power in any small frequency interval is directly proportional to the width of the interval. The instantaneous amplitude of random noise varies as the statistical normal distribution. If all the phases of the components were additive, a large voltage is

possible. There is no definite peak value for random noise and the term "crest factor" (the ratio of the peak to the rms (root mean square) value) is without an exact meaning. It is a practice to assign an arbitrary value to the crest factor corresponding to a reasonable probability. The average noise amplitude, as measured through an ideal linear detector in which the output follows the envelope faithfully, is equal to 1.25 times the rms voltage. These elementary events occur with such rapidity and irregularity that the disturbances produced in a receiver overlap and bear no coherent relationship with each other. The rms and average values of the output amplitude are directly proportional to the square root of the bandwidth of the receiver. Types of noise that are random in character are noise generated in the resistive components of receivers, noise due to the current fluctuations in vacuum tubes, and noise that arrives from interstellar space (cosmic noise).

(2) Impulse noise consists of discrete, well-separated noise impulses having a systematic phase relationship. Noise can be of a type intermediate between fluctuation and impulsive, depending upon the irregularity of the spacing of the noise impulses. If the noise impulses occur irregularly, the noise energy is distributed throughout a frequency spectrum with only a slight maximum at some particular frequency. If the noise impulses are uniformly distributed and regularly spaced, the noise energy occurs at discrete frequency values and is not spread throughout a range of frequency values or a spectrum. The response produced in a receiver by impulsive noise is dependent not only on the distribution of the peak values but also on the spacing of individual impulses. The amplitude of the response generally is directly proportional to the receiver bandwidth instead of the square root of the bandwidth. Ignition noise, such as that produced in automobiles, is impulsive noise and the crashes of local thunderstorms (atmospherics) also are impulsive.

b. The limiting factor for satisfactory communications is the ratio between the signal and noise at the indicating apparatus and not their absolute magnitudes, provided the signal is within the sensitivity limits of the apparatus (human ear or mechanical recorder). The irritability effects of noise in the presence of a signal can be evaluated only by experiment. The required quality of the output signal depends upon the intended usage, commercial high quality broadcast transmission requiring a higher quality signal than international shortwave communication service. The required signal-to-noise ratios for intelligible reception have been obtained by having a group of people listen to a certain type of signal in the presence of noise and by recording the number of persons who considered the transmission satisfactory. Only the irritability effects of random or fluctuation noises are considered, since the annoyance effect of this type of noise can be evaluated in terms of the signal-to-noise ratio. The annoyance produced by impulsive noises cannot be evaluated by a simple general method. The occurrence rate, the magnitudes, and the duration of the peaks all affect the annoyance effect of impulse noise. Since impulse noises are not all alike, no general annoyance value can be determined.

c. The signal at the receiver must be of sufficient magnitude to override the effects of noise. The required field intensity at the receiving location depends upon the receiving antenna, the bandwidth, the amount of noise produced in the receiver, the amount of local static, the type of modulation of the radio wave, the quality of service required, and the general level of noise at the receiving location.

d. Only general noise conditions can be accounted for in this manual. Many of the disturbances which induce noise into an antenna system occur under special conditions. It is not possible to predict the severity of these disturbances or their occurrence with an reliability. Atmospheric noise curves, such as those shown in this manual, are for average conditions. The effects of precipitation static are not considered in atmospheric noise. Precipitation static which arises from the interaction between the receiving antenna and snow, rain, or dust is not accounted for, although at times it may be the largest external noise source. Cosmic noise or noise introduced from interstellar space is accounted for only in a general manner since there is insufficient experimental evidence concern-

ing its variations. Man-made noises, such as those caused by electrical apparatus (automobile ignition systems, vacuum cleaners, and motors), are not accounted for in this manual. These noises depend on the special circumstances and cannot be evaluated for a general case.

67. Atmospheric Noise

a. Measurements have been made of atmospheric noise at a number of locations throughout the world at different periods of time. Although the measurements cannot be called complete, they do indicate the difference between noise at various locations, various frequencies, and differnt hours of the day. Variations in noise intensity from day to day at a particular hour fall relatively close to the seasonal median value. The seasonal variations differ with receiving locations; therefore, variations with the 11-year sunspot cycle are not well defined. Even though the origin of atmospheric noise is not completely understood, it is known that the majority of atmospheric noise (with the exception of precipitation static) originates due to thunderstorm activity. The noise level at a particular location is due to contributions from both local and distant sources. It has been shown that, on an average during a local thunderstorm, the noise level is about 10 db higher than the average noise for the same period. From this, it can be seen that the atmospheric noise level is related directly with weather conditions. The position of the equatorial weather front greatly affects the atmospheric noise at all locations. This front varies in position from day to day and its general location moves seasonally north and south with the sun. The degree of activity varies from time to time and from place to place, being much greater over land than over sea. Thunderstorms are present for about 50 percent of the days at locations in these equatorial belts. It has been estimated that there are about 2,000 thunderstorms in progress at each instant throughout the world. The thunderstorm activity in these equatorial weather belts appears to be the principal source for long-distance atmospheric noise. The principal regions of thunderstorm activity lie in equatorial regions, notably the East Indies, Equatorial Africa, Equatorial South America, and Central America, and appear to be the principal source of long-distance atmospheric noise. Storm activity is located over tropical land masses during the local summer season. Thunderstorms are more active over land and usually occur at hours from 1200 to 1700, local time. Thunderstorm activity over the sea generally occurs at night and can last for more than a day.

b. Atmospheric noise from local sources shows discrete crashes similar to impulse noise while long-distance atmospheric noise consists of rapid and irregular fluctuations with a frequency of 10 to 20 kc per second and a damped wave train of oscillations. The output response in a receiver is approximately proportional to the square root of the receiver bandwidth and thus approximates fluctuation noise. The amplitude of lightning disturbances varies approximately inversely with the frequency squared and is propagated in all directions both for ground and sky waves. Noise propagation follows normal propagation laws and, when conditions are suitable, multiple impulses are received with an increase in the noise field at the receiving location. The measurements show that the general noise field is greater at night than during the day for frequencies between 1 and 5 mc per second due to the large daytime absorption at these frequencies. At frequencies between 10 and 15 mc per second, there is little difference between day and night values. During the day, the absorption is present but the ionosphere supports these frequencies more effectively. The measurements show that, in general, the noise level is greater in the summertime, the difference varying between 5 and 20 db, depending upon the frequency and location.

c. The noise curves shown in this manual are drawn for average conditions for various noise grades (geographical locations with the same noise conditions). The relationship between noise at various locations is determined from measurements and estimates of weather conditions from meteorological data. The curves do not account for extreme noise conditions such as a thunderstorm within a few miles from the receiving location.

68. Cosmic Noise

a. The main source of noise at the receiver, at frequencies greater than about 15 mc, may be due to disturbances that originate outside of the earth. Measurements show that considerable noise is generated in interstellar space. The principal sources are located in the milky way.

b. The system of stars about the earth is called the galaxy. The milky way is a band in the celestial sphere surrounding the earth in which there is

the greatest distribution of stars of the stellar system. Star positions are determined by angular coordinates, similar to latitude and longitude on the earth, from a reference point on the celestial sphere which is an imaginary surface surrounding the earth upon which the stars appear to lie. The projection of the earth's equator upon the celestial sphere is called the celestial equator, while the projection of the earth's poles on the celestial sphere is called the celestial poles. Star positions are given by modern astronomers in right ascension (celestial longitude measured eastward on the celestial equator from a point on the celestial sphere where the path of the sun crosses the celestial equator in the spring (vernal equinox)) and the declination (celestial latitude measured from the celestial equator, north and south). Right ascension is measured in hours from 0 to 24 while the declination is measured in degrees, 0 to —90 and 0 to +90. In figure 34, the position of the milky way is shown on the celestial sphere.

c. The principal center of cosmic noise was found by various investigators to be located in the milky way at a point with a right ascension of about 18 hours and a declination of about —30°. The greatest amount of cosmic noise occurs when the portion of the sky at right ascension (18 hours) is overhead at the receiving location. Figure 35 shows the local time at which a point of right ascension (18 hours) crosses the meridian at the receiver for the months of the year.

d. The cosmic noise has the characteristics of fluctuation noise. The intensity of cosmic noise decreases rapidly with frequency and varies from hour to hour and from day to day since the noise

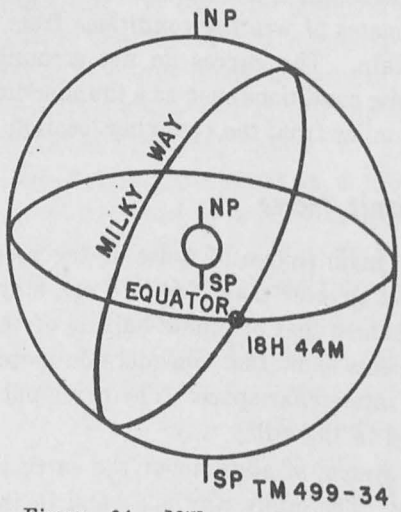


Figure 34. Milky way shown on celestial sphere.

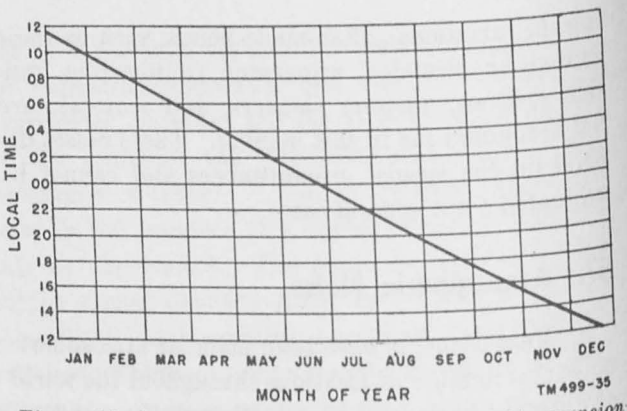


Figure 35. Local time at which the sky at right ascension (18 hours) is over the observer.

source is not distributed uniformly over the sky but is concentrated in several regions on the celestial sphere. Cosmic noise is not observed at low frequencies, probably because of the absorption in the ionosphere.

e. At the present time, considerable research is being done on the study of cosmic noise in order to find the variations in intensity with time of day, season, geographical location, frequency, and receiving antenna directivity. Based on the data available at the present time, the required incident field intensity for intelligible reception of radiotelephony in the presence of cosmic noise is given by the following equation for an antenna no more directive than a half-wave dipole:

$$E = \frac{2}{f^{1/2}} \quad \text{microvolts per meter} \qquad (18\text{mc} < f < 160\text{mc}) \qquad \text{(Eq 32)}$$

where f is the frequency in mc per second.

f. In most sky-wave communication problems, it is not necessary to determine the effects of cosmic noise. Cosmic noise does not, generally, determine the lowest useful frequencies for values less than about 30 mc. The required field intensity curve in the presence of cosmic noise is shown in figure 36.

69. Receiver Noise

a. Random noise is generated in a receiver due to its inherent characteristics. In discussing receiver noise, nonrandom noises of the types listed below are not considered, since they usually can be removed by proper design. Types of nonrandom noise are hum (power frequency and its harmonics induced into the signal channel due to faulty coupling), microphonics (noises due to mechanical vibrations such as vibrations of tube electrodes), howl (due to audio feedback from the final sound

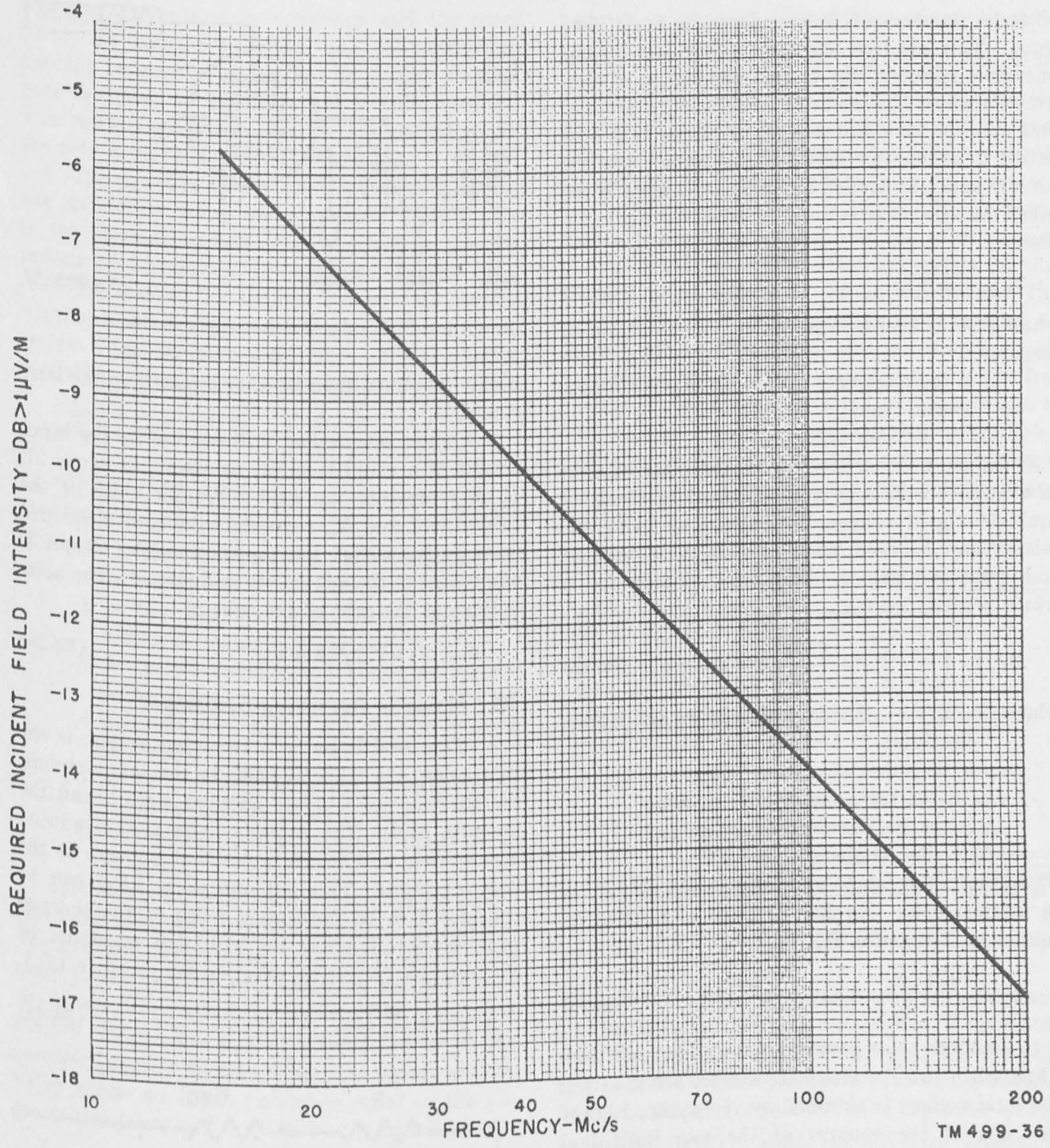


Figure 36. Required incident field intensity for a half-wave dipole in the presence of cosmic noise (for double sideband radiotelephony).

output), and motorboating (due to feedback through the power supply). The principal noises considered are thermal noise and shot noise.

b. Thermal noise is caused by the thermal motion of conduction electrons in resistors. From the statistical theory of thermodynamics, it can be shown that the rms noise voltage developed across a resistance is given by—

$$E = \sqrt{4RkT\,\Delta f} \qquad \text{(Eq 33)}$$

where R is the resistance in ohms;

T is the absolute temperature (+273°C.);

k is Boltzmann's constant (1.37×10^{-23} watts secs/degree); and

Δf is the bandwidth of the measuring system in cycles.

c. The electric current in vacuum tubes consists

of large numbers of independently emitted electrons. This electron current is not steady but fluctuates minutely due to the randomness of electron emission. These current fluctuations produce *shot* noise in vacuum tubes. In a simple tube consisting of an emitter and a single plate, when the current is not controlled by the space charge in the tube, the rms noise current is given by the equation—

$$I_n = \sqrt{2e\,I\,\Delta f} \qquad \text{(Eq 34)}$$

where I is the average value of the plate current in amperes;

e is the electronic charge (1.59×10^{-19} coulombs); and

Δf is the bandwidth in cycles.

d. In the multielement tubes, the plate current shot noise fluctuations are expressed in terms of equivalent grid voltage fluctuations by using the relationship between plate current, grid voltage, and transconductance. The noise voltage for a triode is given by—

$$E_n^2 = \left(\frac{I_n}{g_m}\right)^2 = \frac{0.644}{\sigma g_m} \times 4 \times kT_c \Delta f \qquad \text{(Eq 35)}$$

where T_c is the cathode temperature in degrees absolute;

σ is the tube parameter;

g_m is the transconductance in mhos;

k is the Boltzmann's constant; and

Δf is the bandwidth in cycles.

Thus, shot noise can be expressed in the same form as thermal noise (Eq 33) (*b* above) by using an equivalent resistance, R_{eq}.

$$R = \frac{0.644}{\sigma}\,\frac{T_c}{Tg_m} \text{ ohms} \qquad \text{(Eq 36)}$$

e. Random noise powers can be added together. Thus, when two thermal noise sources are in series, the total voltage is obtained by the square root of the sum of the squares of the two individual sources.

$$E = \sqrt{E_1^2 + E_2^2} \qquad \text{(Eq 37)}$$

It is possible to find the noise produced in a receiver by adding up the noise powers of the various components and accounting for the gain of the various stages. In an average receiver, most of the thermal noise at the receiver output is due to the thermal noise developed across the antenna and input stage resistance, and in the first tube. Noise introduced in the input stages of a receiver is more highly amplified than noise originating in the later stages.

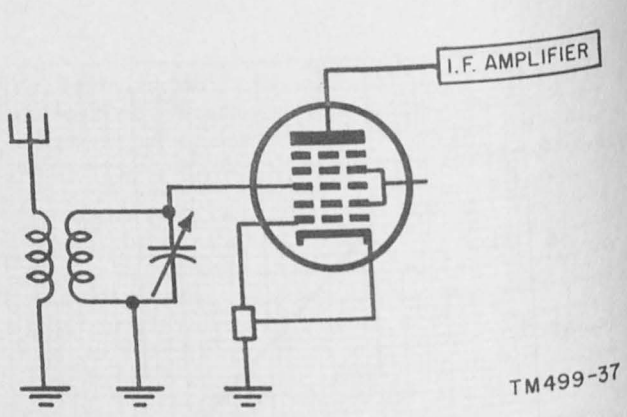


Figure 37. Receiver input circuit.

f. A noise calculation is illustrated by the input circuit of a radio receiver, as shown in figure 37. If R represents the grid-to-ground noise of the grid circuit and R_{eq} represents the equivalent grid noise resistance of the input tube, the circuit is equivalent to the one shown in figure 38. The noise voltage at the grid of the tube is—

$$E = \sqrt{4\,k\,T\,\Delta f\,(R + R_{eq})} \qquad \text{(Eq 33)}$$

70. Noise in Receiving Systems

a. The total noise in a receiving system is the tube noise, the thermal noise in the input circuit, the thermal noise in the antenna circuit, and the antenna noise. The antenna noise is the induced atmospheric and cosmic noise that appears at the receiver input. This antenna noise (E_a) can be considered to be fluctuation noise of the thermal type developed across the radiation resistance of the antenna (R_a) at an effective temperature (T_a).

$$T_a = \frac{E_a^2}{4\,k\,R_a\,\Delta f} \qquad \text{(Eq 38)}$$

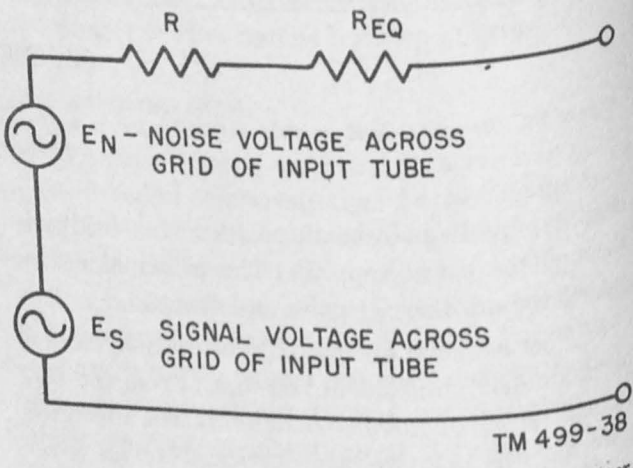


Figure 38. Equivalent input circuit of a typical receiver.

Knowing the interstage couplings and the stage gains, the resistance values, and the equivalent antenna temperature, it would be possible to compute the noise at the output of a radio receiver. This method would be difficult and would apply for only a particular set of conditions.

b. The signal-to-noise ratio of a receiving system has its highest value when the only noise source is the thermal agitation noise produced in the radiation resistance of the antenna. In this ideal receiving system, the receiver presents an infinite impedance at its input terminals to the antenna system. The signal-to-noise ratio of this perfect receiving system can be expressed as—

$$\text{Signal-to-noise power ratio of ideal system} = \left(\frac{E_s}{e}\right)^2 = \frac{S}{kT\,\Delta f} = \frac{\text{Available signal power}}{\text{ideal available noise power}} \qquad \text{(Eq 39)}$$

where E_s is the signal voltage referred to the receiver input;

e is the thermal noise voltage developed across the antenna resistance;

S is the available signal power at the receiver input;

k is Boltzmann's constant, 1.374×10^{-23} watts secs/degree;

T is the temperature of the radiation resistance in degrees absolute; and

Δf is the effective bandwidth of the receiver in cycles.

In noise analyses, it is customary to define power and noise independently of the output impedance. The available signal power and the ideal available noise power between two terminals are defined as the powers that would be absorbed in a matched output circuit. The available signal power at the receiver input is the power that the signal will develop across an input resistance equal to the antenna resistance and is given by the equation—

$$S = \frac{E_s^2}{4R_a} \text{ watts} \qquad \text{(Eq 40)}$$

The ideal available noise power is defined by the equation—

$$E_n = \frac{e^2}{4R_a} = \frac{4kT\,\Delta f R_a}{4R_a} = kT\,\Delta f \qquad \text{(Eq 41)}$$

c. An example of an ideal receiving sysem is shown in figure 39. A half-wave antenna, uneffected by the presence of ground and having no losses in itself or in the connections to the ideal receiver, is assumed. The antenna effective height, as shown by antenna theory, is $\frac{\lambda}{\pi}$ and its radiation resistance is 73 ohms. For an assumed receiver bandwidth of 6 kc and a temperature of 290° absolute, the thermal noise voltage is 0.0836 microvolts by equation 38. If the signal-to-noise ratio required for intelligible reception is 15 db (15 db corresponds to a voltage ratio of 5.6), the voltage across the receiver input must be 0.48 microvolts for this thermal noise voltage of 0.0836 microvolts. The signal voltage across the receiver input is equal to the antenna effective height multiplied by the insident signal strength. For an assumed wave frequency of 10 mc, the receiving antenna height is 9.55 meters. A required incident field intensity of 0.05 microvolts per meter will induce this signal value of 0.48 microvolts across the receiver input (fig. 39).

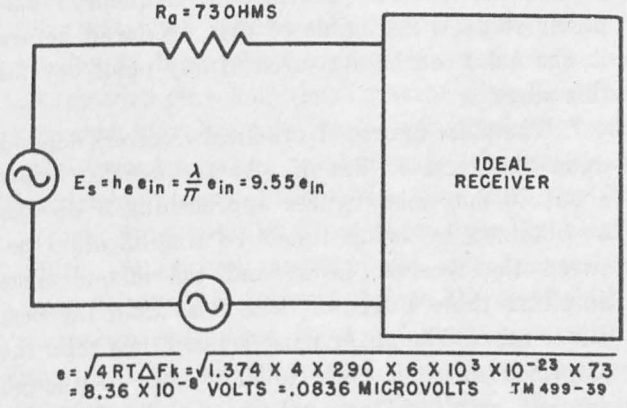


Figure 39. Ideal receiving system.

d. If the perfect receiver presented a matched resistance to the antenna resistance, the signal-to-noise power ratio would be half that for the infinite impedance case in *b* above. The signal voltage would be 0.5 of that above, while the noise would be $\sqrt{2}/2$ (0.707), since the effective resistance across the receiver input would be one-half or the resistance presented by two equal resistances in parallel.

e. Noise figures now, generally, are used to rate the noise qualities of receivers under test conditions. The noise figure of a receiver can be defined as—

$$\text{Noise figure} = \frac{\text{Signal-to-noise power ratio for an ideal receiver}}{\text{Signal-to-noise power ratio of an actual receiver}} \qquad \text{(Eq 42)}$$

The noise figure of a receiver is the ratio between the actual noise of the receiver (including the thermal noises referred to the receiver input) and the input noise, assuming the receiver to be perfect. The noise figures usually are measured by applying a noise generator to the receiver input and measuring the output voltage both with the noise generator connected and not connected, the impedance across the receiver input being the same in both cases. The noise from the noise generator is increased from zero until the output of the receiver is doubled. The added noise then is equal to the actual receiver noise. The squared raio of the noise voltage (produced by the noise generator) to the thermal voltage (that is developed across the input impedance) is the noise figure. The noise figures are expressed in power ratios or in db. When measuring the output noise, the measurements should be made so that all the noise sources are included. Since the noise generated in a receiver beyond the first i-f (intermediate-frequency) amplifier stage is negligible to that produced before it, the noise can be measured at any point beyond this stage.

f. The noise figures of practical receivers depend upon the receiver design. At frequencies below about 30 mc, noise figures approaching 3 db can be obtained by using tuned r-f amplification between the receiver input and the mixer, since amplifier tubes introduce less noise than the best mixer tubes. The mixer noise is much less than the amplified antenna noise in this case. Although pentode amplifiers are noisier than triodes, they generally are used at frequencies below 30 mc, since the externally induced noise at these frequencies is greater than the noise induced by the r-f amplification stage. In practical receivers, the best noise figure is obtained when the input impedance of the receiver is between an open circuit and an impedance match with the antenna system.

g. The required signal power at the input of an actual receiver is the required signal power for an ideal receiver multiplied by the receiver noise figure for the same signal-to-noise ratio. Figure 40 shows the required carrier field intensity to override the effects of set noise for a receiving system with a half-wave antenna connected to a receiver input through a lossless transmission line. The total receiver bandwidth is assumed to be 6 kc and the signal-to-noise power ratio required is assumed to be 15 db. If the required signal across the receiver input is 2 microvolts, the incident signal for

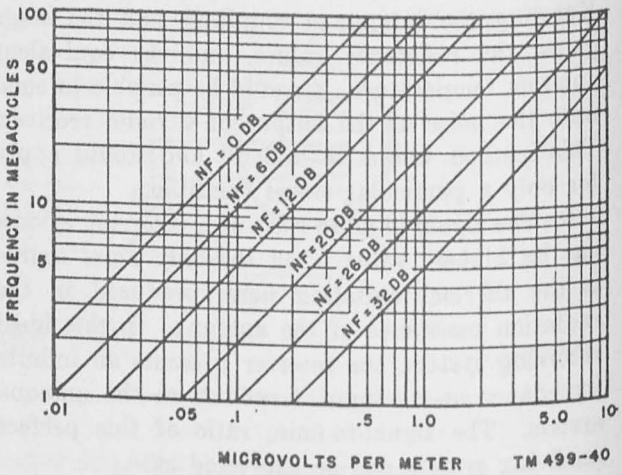


Figure 40. Carrier field intensity required to override set noise with a half-wave dipole for indicated values of receiver noise factor (amplitude modulation—two 3 kc sidebands, signal power 15 db above noise power).

10 mc (effective height 9.55 meters) is 0.21 microvolts per meter. In this case, the receiver noise figure is about 12 db.

h. Equivalent noise figures have been used also to rate the noisiness of complete receiving systems in which externally induced noises are present. For a complete receiving system, the equivalent noise figure can be written as—

$$F' = \frac{F}{L} + (EN - 1) \qquad \text{(Eq 43)}$$

where F is the noise figure of the receiver;
L is the input circuit loss factor; and
EN is the external noise factor,

$$\frac{\text{available noise power from the antenna}}{\text{ideal available noise input power}}$$

i. If the receiving system noise figure can be determined by measuring the receiver noise figure, the losses, and the external noise figure, it would be possible to determine that available antenna signal power that is required at the receiver input to produce a given signal-to-noise ratio at the output by the equation—

$$\text{Required available signal power} = \left(\begin{array}{c}\text{equivalent noise figure of the system}\end{array}\right) \times \left(\begin{array}{c}\text{ideal available noise power}\end{array}\right) \times \left(\begin{array}{c}\text{signal-to-noise ratio at receiver output}\end{array}\right) \qquad \text{(Eq 44)}$$

Although the ratio of the audio signal-to-noise at the indicating apparatus determines the intelligibility of the communication, it is more desirable to know the r-f signal-to-noise ratio required at the

receiver input. In propagation problems, the required signal strength at the antenna generally must be known. The individual receiving systems have different circuit characteristics and it is difficult to obtain the required r-f signal-to-noise ratios at the receiver input from the audio signal-to-noise ration at the receiver output. A practical approach in determining the required signal strengths is to obtain, experimentally, the required r-f signal-to-noise ratios at the receiver input for different types of modulation and services.

j. It is desirable to state precisely what is meant by a signal-to-noise ratio. Various commonly used signal-to-noise ratios are—

$$\frac{\text{rms signal voltage}}{\text{rms noise voltage}}$$

$$\frac{\text{peak signal voltage}}{\text{peak noise voltage}}$$

$$\frac{\text{average signal power}}{\text{average noise power}}$$

The most commonly used of the ratios is between the rms voltages. The term "signal voltage" requires some explanation. In case a voltage is measured in the a-f (audio-frequency) part of a radio receiver, it is easy to see that the voltage measures the magnitude of the audible signal or intelligence. In the case of a modulated r-f signal, it is more difficult to interpret what is meant by the signal voltage. For double sideband amplitude modulation at 100 percent modulation, the r-f sideband voltages which contain the intelligence are one-half the magnitude of the carrier voltage. It has been a practice of various writers to refer to the signal voltage in terms of the carrier voltage. It has been shown that, for an ideal linear detector in the case of double sideband radiotelephony, the intermediate carrier-to-noise ratio multiplied by the modulation index is equal to the audio signal-to-noise ratio. For signal sideband radiotelephony, a carrier-to-noise ratio cannot be used. It is customary to transmit only one sideband with the carrier suppressed by about 10 to 15 db. An r-f signal-to-noise ratio must be used. For fm (frequency modulation) and pulse modulation, the signal-to-noise ratios in the i-f section and in the a-f section of a receiver are almost completely unrelated. A more detailed description of the noise properties is required than a signal-to-noise ratio.

71. Minimum Required Field Intensities

a. It has been mentioned previously that useful communication is possible when the signal strength is sufficiently large to override the effects of noise. In this manual, the noise limitations are determined by minimum required field intensity curves. Curves are shown for both the necessary signal strength for intelligible reception of radiotelephony in the presence of atmospheric noise and in the presence of noise produced in average receivers. The curves are shown as the hourly median values required for intelligible reception for 90 percent of the days of low grade double sideband radiotelephony for a total receiver bandwidth of 6 kc.

b. The atmospheric noise curves are obtained from measured noise voltages which are converted into equivalent incident field strengths after increasing them to adjust for the required signal-to-noise ratio and for day-to-day variations in both sky-wave field intensities and atmospheric noise. The measured voltages correspond to the hourly median of the average atmospheric noise voltages as recorded on a long-time constant recorder. The required signal-to-noise ratio was obtained from measurements taken to determine the required carrier-to-average atmospheric noise ratio for 90 percent intelligibility of sentences per kc bandwidth. Since both average and rms fluctuation noise voltages are proportional to the bandwidth, the measurements can be used for any bandwidth, provided the noise generated in the receiving set is small compared to the external noise. The ratio used was 13.8 db for a 6-kc bandwidth. The hourly median sky-wave field intensity that is exceeded for 90 percent of the days has been shown to be 6 db below the monthly median of the hourly median values. The hourly median noise field intensity is less for 90 percent of the days than a value 10 db greater than the seasonal median of the hourly median noise intensity. Since both signal and noise vary in normal distribution, the signal-to-noise ratio can be stated to vary as the square root of the sum of the squares of the noise and signal variations. Thus, the required minimum field intensities in the presence of atmospheric noise were obtained from measured average noise voltages referred to the receiver input based on a 6-kc bandwidth. These were, in turn, converted to the required hourly median signal voltage across the receiver input for intelligible reception for 90 percent of the days by adding 13.8 db, the required

nonfading carrier-to-noise ratio for 90 percent intelligibility for low grade double sideband radiotelephony, and 11.6 db, the fading factor to convert the measurements to a 90-percent of the days basis. This required input signal to the receiver then was converted into required incident field intensity by using ground plane effective heights of the vertical noise-measuring antennas. The following equation indicates how the atmospheric noise curves were obtained:

$$E_r = \frac{k E_c}{H_e \sqrt{\Delta f}} \qquad \text{(Eq 45)}$$

where E_r is the required field intensity in microvolts per meter;
K is the experimentally obtained carrier-to-average noise ratio for the desired grade of communication per kc bandwidth;
E_c is the measured average received noise voltage referred to the antenna terminals;
H_e is the antenna effective height in meters; and
Δf is the effective receiver bandwidth in kc.

c. The atmospheric noise curves cannot be used directly to determine the required incident signal strength unless the receiving antenna effective heights for both the signal and noise are alike. There are curves shown in this manual which give discrimination gains for common receiving antennas based on omnidirectional noise. The subtraction of a discrimination gain from the minimum required incident field intensity in the presence of atmospheric noise gives the required signal strength for the particular receiving antenna used.

d. The annoyance value of noise generated in a receiver set is indicated in minimum required incident field intensity curves. These curves show the incident field intensity required at various angles at the receiving antenna that will produce a sufficient signal across the antenna input to override the effects of receiver noise. The day-to-day variations in sky-wave field intensities have been included to convert them to a 90-percent of the days basis. It has been shown experimentally that approximately 2 microvolts are required across the input of average Army receivers of 6 kc bandwidth to produce 90 percent intelligibility of 100 percent a-m (amplitude-modulated) radiotelephony when set noise alone produces the disturbance. The average receiver input impedance is assumed to be tuned out. In the rhombic antenna calculations, a 600- to 100-ohm impedance matching transformer is assumed to be connected between the antenna and the receiver with 2 microvolts being required across the 100-ohm receiver input side. Transmission line and matching impedance losses have been neglected in the curves. If these losses are known, they can be added to the required field intensity curves. The set noise curves have been calculated by an equation based on the reciprocity theorem, as follows:

$$E = \frac{24.6 \times F}{R_r \times f} \times \frac{R_r + R_L + R_z}{R_z} \times S \qquad \text{(Eq 46)}$$

to produce 2 microvolts across R_z.

where R_r is the antanna radiation resistance;
R_L is the antanna loss resistance;
R_z is the antenna load resistance;
F is the theoretical inverse field intensity in millivolts per meter produced by antenna at 1 mile in desired directions when used as a transmitting antenna, with 1 kw delivered to antenna, assuming zero for the antenna loss resistance;
f is the frequency in mc per second;
E is the required incident field intensity in microvolts per meter; and
S is a factor which accounts for variations in the incident field intensity with time.

Section IX. MODULATION AND TYPES OF SERVICE

72. General

a. Appreciable radiation from antennas is possible only at radio frequencies. In radio communication, audible frequency signals are superimposed on an h-f carrier. Audible speech covers several octaves of frequency. The frequency range from a certain value to double that value is an octave. In double sideband amplitude modulation, the range of frequencies transmitted lies within a band equal to the highest audio frequency on each side of the carrier frequency. This transmission band is only a small part of an octave at the r-f transmission frequency.

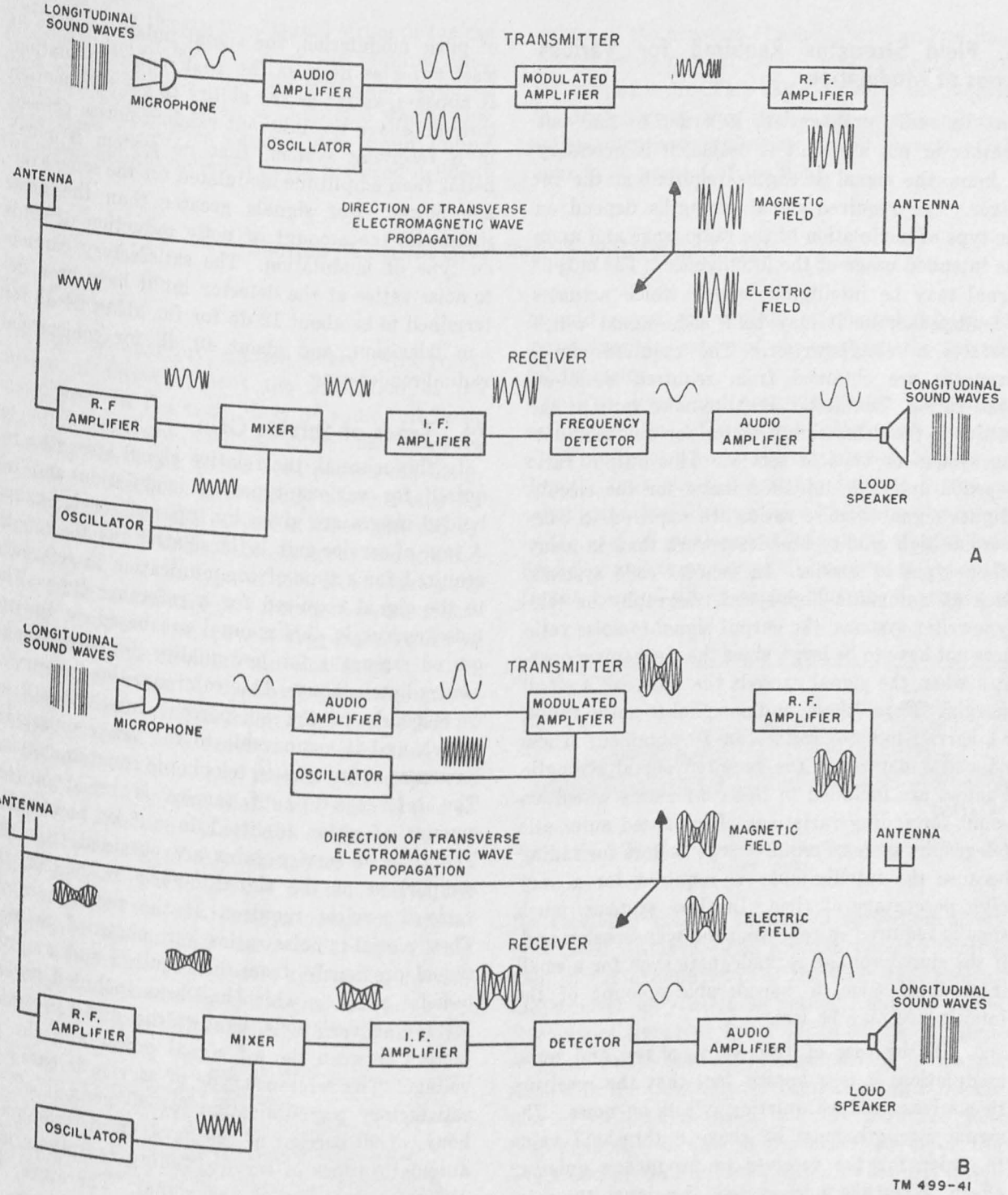


Figure 41. Life cycle of a signal transmitted by an f-m carrier (A) and by an a-m carrier (B).

b. There are various ways of modulating or superimposing intelligence on the h-f signals. Some of the commonly used forms of modulation are amplitude, frequency, phase, and pulse modulation. The pulses themselves can be amplitude frequency, or phase modulated. In figure 41, there are pictorial representations of the life history of a-m and f-m signal voltages. The figurative sketches show how low frequencies are superimposed on the carrier frequencies at the transmitter and how the received signal is demodulated (detected) at the receiving set.

73. Field Strengths Required for Various Types of Modulation

a. In radio propagation, in order to find out whether or not a circuit is usable, it is necessary to know the signal strengths required at the receiver. The required signal strengths depend on the type of modulation of the radio wave and upon the intended usage of the intelligence. (The output signal may be intelligible speech which actuates a loudspeaker or it may be a code signal which operates a teletypewriter.) The required signal strengths are obtained from required signal-to-noise ratios. The audio signal-to-noise ratio at the output is the determining factor for any modulating system or type of service. This output ratio depends upon the intended usage for the circuit. Higher signal-to-noise ratios are required in commercial high quality broadcast work than in many other types of service. In general code systems, such as automatic high-speed telegraphy or teletypewriter systems, the output signal-to-noise ratio does not have to be large, since the mechanism operates when the signal exceeds the noise by a small margin. From these audio signal-to-noise ratios, r-f carrier-to-noise ratios can be obtained. These r-f ratios determine the required signal strength. Factors are included in these h-f ratios which account for fading variations. High-speed automatic telegraphy systems require large factors for fading because the intelligibility is required for a very high percentage of time. In these systems, much time is required in repeating the transmission and, if the signal voltage is inadequate even for a small interval of time, a considerable amount of the intelligence may be lost.

b. In the case of frequency, phase, and pulse modulation, it is a known fact that the receivers themselves produce quieting effects on noise. The signal strength must be above a threshold value in order for the receiver to produce a quieting effect. When the noise exceeds the signal, the noise is the controlling factor in the output, the noise increasing greatly and usually blanketing out the desired signal. It can be stated that, in all systems of modulation, the signal-to-noise ratio must exceed an improvement threshold in order that the detector can be able to make use of the signal carrier and its sidebands in order to improve the signal-to-noise ratio. In the case of the frequency and phase modulation, the signal must be at least slightly greater than the noise, while, in the case of pulse modulation, the signal pulses must be at least twice as high as the peak noise fluctuation. It appears, as far as the ability to get information through above the inherent random noises present in a receiving system, that no system is much better than amplitude modulated for the same average power. For signals greater than the noise threshold, the amount of noise reduction depends on type of modulation. The satisfactory carrier-to-noise ratios at the detector input have been determined to be about 12 db for fm, about 24 db for a-m television, and about 40 db for commercial radio broadcasting.

74. Types of Service Gain

In this manual, the relative signal strengths required for various types of modulation and intended usages are given by types of service gains. A type of service gain is the relative signal strength required for a type of communication in reference to the signal required for a reference type. The noise curves in this manual are based on the required strengths for low quality double sideband a-m radiotelephony. This reference-type of service corresponds to the 90 percent intelligibility of speech and is comparable to the grade of service known as order wire in telephonic communications. The reference-type of service is based on the amount of noise admitted in a 6-kc bandwidth. The type of service gains are obtained from the comparison of the signal-to-noise ratios for the various services required at the receiver input. These signal-to-noise ratios were obtained, as mentioned previously, from the required audio signal-to-noise ratios to which had been included factors for fading variations, bandwidths, and conversion factors between the a-f signal power and the r-f voltage. The reference-type of service is based on satisfactory communication for 90 percent of the hours of 90 percent of the days. With high-speed automatic types of service, fading variations may cause interruption of the signal. Therefore, the type of service gains are adjusted so that communication may be expected to be reliable for 99.9 percent of the hours for 90 percent of the days. The effects of noise limiters are not included in service gain. Noise limiters are more effective in case of impulsive noise than for random or fluctuation noise, since the waveshapes of the generally used signals in random noise are similar. The service gains are for fluctuation-type noises such as atmospheric and receiver noise. The type of service gain,

when added to the required signal strength for the reference-type of service, gives the required incident signal strength for the particular type of service. Tables are given in chapter 3 which show these types of service gains. Since rapid fading variations are not included in the required incident curves in the presence of atmospheric and set noise, the reference-type of service is shown with a service gain of 8 db. This value converts the required incident curves from the values corresponding to satisfactory communication for 50 percent of the hour to 90 percent of the hour.

Section X. GROUND-WAVE PROPAGATION

75. General

a. Ground-wave propagation refers to the transmission of waves without the utilization of the ionosphere. In the early days of radio, all radio communication was assumed to be due to waves guided by the earth. It has been proven that long-distance transmission is generally possible only by sky waves, due to the excessive losses suffered by ground waves. The field intensity of the ground wave depends on the type of terrain and the path between the transmitter and the receiver, the transmitting antenna type, power, frequency, and the transmitting and receiving antenna heights.

b. The curvature of the earth hides the transmitting and receiving antenna from each other at distances beyond the horizon. In this case, the energy received is energy that is guided by the earth. The field beyond the line of sight is due to refraction (direction change due to changes in the index of refraction of the atmosphere with height) and diffraction (phenomena of the bending of the electromagnetic waves around obstacles). The energy loss at the ground causes a forward tilting of the waves above the earth, the tilting having the effect of replenishing the energy in the direction of wave travel. Thus, the partially conducting

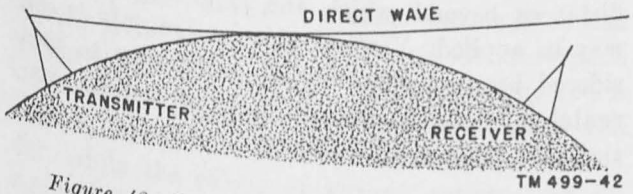


Figure 42. Receiving antenna below the horizon.

surface of the earth produces a wave-guiding effect on the radiation from the antenna. In this manual, methods are shown for the calculation of ground-wave propagation problems at distances mainly beyond the line of sight. Only vertical polarization (the electric intensity in a plane vertical to the earth) is considered, since horizontally polarized ground waves are rapidly attenuated due to the short-circuiting effect of the earth on the horizontal intensity.

c. The direct and ground-reflected components within the line of sight are illustrated in figure 43. The direct wave is the component that travels directly from the transmitting antenna to the receiving antenna. Transmission by this means occurs in the case of airplanes at heights of several hundred feet and transmission distances of a few miles. In the case of direct waves, the signal arrives at

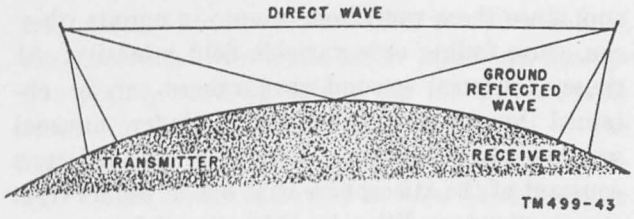


Figure 43. Direct and ground-reflected waves within the line of sight.

the receiving location because of spreading of energy with distance. The ground-reflected component of the ground wave is the wave that reaches the receiver only after reflection from the earth. For planes flying at lower altitudes, the ground-reflected component can be comparable in magnitude with the direct wave. Signal strength, in the case of elevated antennas at very high frequencies, generally is due to the combination of the direct and ground-reflected waves. When the waves are comparable in magnitude and in phase opposition, the signal strength is low, while in the case where they are in phase, the signal strength is larger because of the reinforcement due to the ground-reflected wave. The interference effect of the ground-reflected wave can cause the received field intensity to be lower or higher than that due to the direct wave alone.

d. At frequencies less than about 30 mc, the large ground-wave field strengths beyond the line

of sight are obtainable, and relatively long-distance ranges can be expected over earth of good characteristics. The ground-wave signals are strong when the conductivity of the earth is high and transmission frequency is low. At frequencies above 10 mc, the dielectric constant primarily determines the ground-wave transmission characteristics. The ground-wave signal is large with a high dielectric constant and a lower frequency. Sea water has the best transmission characteristics, the conductivity and dielectric constant being large. At frequencies greater than 30 mc, the ground-wave losses become so large that transmission is possible only at distances not greatly exceeding the line of sight. The received signal can be increased effectively by raising the antennas and increasing the antenna radiation. The bending of radio waves by refraction is important at these frequencies. Tropospheric reflection (reflection caused by sudden changes in the characteristics of air in the lower atmosphere of the earth) affect the received signals at distances beyond the line of sight. Tropospheric reflections depend on weather conditions and, since these vary from minute to minute, they can cause fading or a variable field intensity. At times, abnormal ground-wave ranges can be obtained by tropospheric waves. Under unusual weather conditions, the variation of the dielectric constant of the atmosphere with height differs from the *standard* condition in which the dielectric constant decreases gradually with height. Abnormal conditions cause either greater or smaller bending of radio waves than under normal conditions. Duct transmission is possible at very high frequencies under these conditions. These ducts are equivalent wave guides which trap energy so that it can travel abnormal distances around the earth.

76. Evaluation of Ground-Wave Field Intensity

a. The field intensity that a grounded antenna will produce at a given distance at the earth is obtained by multiplying the inverse distance field intensity value (the field intensity that the antenna produces at a standard distance over perfectly conducting earth) by some attenuation factor. This manual gives ground-wave field intensities produced by vertical antennas with an inverse distance field intensity of 186.3 millivolts per meter at 1 mile for transmission over good ground, poor ground, and sea water. It has been mentioned previously that the inverse distance field of 186.3 millivolts per meter corresponds to the field produced by a short dipole antenna at the ground plane at a distance of 1 mile over perfect earth. The field intensity at the ground for other vertically polarized ground-based antennas is obtained from the ratio of the inverse distance field intensity for the antenna used, to 186.3, multiplied by the field intensity in microvolts per meter, as given by the ground-wave field intensity curves shown in chapter 4 of this manual. Curves are included in chapter 4 which give the inverse distance field intensities of vertical and inverted L antennas such as those normally used for vertically polarized ground-wave propagation. Experimentally obtained dead-loss resistance, due to heating losses in the antenna and in the antenna ground system, are included in the curves.

b. In chapter 4, practical solutions of the field intensities for ground-wave circuits are given for both grounded and elevated antennas. In the case of elevated antennas, the field intensities are found for distances beyond the line of sight (in most cases) by multiplying the field intensity solutions (based on the assumption that the antennas are on the surface of the earth) by the height gain factors. Curves are shown which give the limiting distances beyond which the height gain factors may be applied. Vertical polarization only is considered because, generally, it is superior to horizontal polarization for low antenna heights, particularly for lower frequencies.

CHAPTER 3

PRACTICAL APPLICATIONS OF IONOSPHERIC THEORY

Section I. INTRODUCTION

77. Scope

a. In this chapter are shown practical methods for calculating various sky-wave communication problems. Antenna curves are given for various practical antennas commonly used for sky-wave communication (verticals, half-wave horizontals, and rhombics). In case the antennas are other than the ones given in this manual, the problems still can be worked, provided the user knows the gains for the antennas. The solutions mainly are graphical and no mathematics is required outside of arithmetic. The basic curves and nomograms used in the solutions are obtained from the statistical analysis of field intensity recordings for various radio circuits throughout the world. The methods show how to calculate what the most suitable frequencies are for any radio circuit at any time. By using these methods, one can determine whether or not communication is possible at various frequencies and what requirements are necessary in the equipment. The principal problem considered is the determination of the frequency limits between which a particular radio circuit can be operated. The upper limiting frequency is determined by the extent of ionization of the various layers, while the lower limiting frequency is determined by the losses that a radio wave suffers and by the noise conditions. The methods correspond to normal conditions in the ionosphere. The effects of irregularities, such as ionospheric storms and sudden ionospheric disturbances, are not accounted for, while the effects of auroral activity are accounted for under average conditions. The methods can be applied under any range of distances and for any period of time. Distances are divided into two ranges for field intensity and lowest useful high-frequency calculations: short distances, 0 to 3,000 km; and long distances, 3,000 km and greater. Nomographic solutions are given for problems in the long-distance range, while the curves are given for the short-distance range.

b. Frequencies from 3 to 30 mc usually are called the short-wave band. Most sky-wave circuits are designed to operate in this frequency range. Sky-wave communication is possible for long-distance circuits through regions of low latitudes at higher frequencies during periods of high solar activity. During the peak of the 11-year sunspot cycle, the F2 layer can support long-distance communication at frequencies as high as 50 mc or more. It has been mentioned previously that the sporadic E layer may support long-distance communication at frequencies as high as 75 mc. Generally, a sky-wave communication is used widely in army circuits. Sky waves suffer much less absorption than ground waves and are the only suitable means for long-distance circuits. Because of the large number of radio circuits used in the short-wave band, communication in this band may be subject to severe interference from both local and distant stations. Sky-wave communication should be avoided whenever it is practicable. Frequencies in the very high frequency band (from 30 to 300 mc) should be used for communication over short or moderate distances, whenever possible. At these higher frequencies, the possibility of interference and enemy interception is quite low. For point-to-point radio circuits, highly directional antennas can be used to limit the radiation to only the required direction. However, in dense jungles, where the antennas cannot be raised above the jungle growth, only sky-wave communication may be possible because of the excessive ground-wave absorption.

78. Basis of the Methods

a. The methods are based on optical-ray theory and have sufficient accuracy for practical purposes. The energy is assumed to travel along straight geometric ray paths and to be reflected at the virtual ionospheric layer heights. The virtual height, as defined in chapter 2, is the height cor-

responding to straight ray paths. Sky waves can arrive after single or multiple reflections from any of the ionized layers. Single reflection transmission is limited in distance by the curvature of the earth. For transmission by the F2 layer at an average height of 320 km, the limit is approximately 4,000 km. At great distances, communication is possible only by multiple reflections. Figure 44 illustrates various ray paths between a transmitter and a receiver.

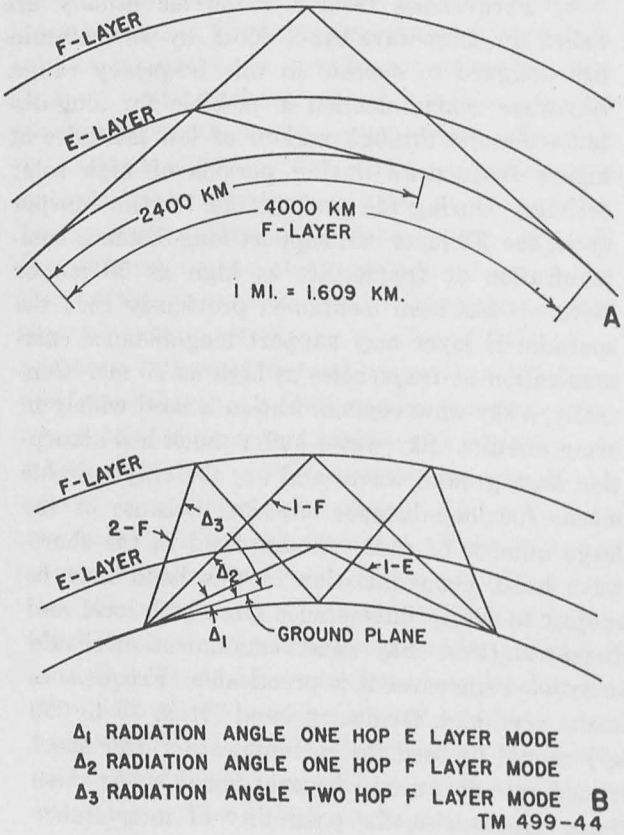


Figure 44. Distance limitations for single reflection transmission (A) and modes of transmission (B).

b. For distances below 3,000 km, various possible ray paths between the transmitting and receiving locations are assumed. The ray paths between the earth and the ionosphere are determined by an average E layer virtual height of 105 km and an average F2 layer height of 320 km, and the transmission distance. Analysis of the field intensity data indicates that it is not necessary to calculate sky-wave modes reflected from F1 layer heights. The F1 layer usually is not ionized to an extent greatly exceeding the E layer, and generally it is necessary only to account for E layer and F2 layer modes. The effect of F1 layer transmission is accounted for by assuming that a single reflection E layer transmission mode is possible at 2,400 km. The radiation angle (angle above ground plane) is zero for a single-hop E layer mode at this distance. For practical reasons, the radiation angle is assumed to be 5° for this one-hop E layer transmission mode corresponding to the angle for a single-hop reflection from a height of 225 km, which is the average F1 layer height. A F2 layer transmission mode is possible at frequencies which penetrate the E layer and are below the F2 layer MUF. In order to determine whether an F2 layer mode is possible, it first is necessary to determine whether a ray will penetrate the E layer for the angle corresponding to the mode. Figure 99 shows the radiation angles for various layer heights and transmission distances.

c. At distances greater than 3,000 km, a nomographic solution, also based on ray theory, is used (fig. 141). The nomogram is based on modes with relatively low angles above the ground plane. For most installations, limited experimentation indicates that, for long distances, the optimum angle at which the signal arrives is generally around 5°. For long-distance transmission, antennas are designed for low-angle radiation since low-angle paths suffer smaller losses. Experimental evidence has shown that, as far as ionospheric absorption is concerned, the total absorption for long-distance paths appears to be nearly independent of the number of reflections at the ionosphere. For a greater number of hops, the angle at the ionosphere is sharper and the loss per hop is smaller, the total loss being approximately the same. The ground losses favor lower radiation angles.

Section II. METHODS

79. Received Sky-Wave Field Intensity

a. General. The methods of this manual give the median downcoming sky-wave field intensities. For the distance range from 0 to 3,200 km, curves (figs. 121–140) are used; while for distances greater than 3,000 km, a nomogram (fig. 141) is used. These values are for the wave that arrives directly

from the ionosphere (incident wave) and do not include components produced by ground reflections at the receiving location. The values correspond to field intensity values that are exceeded for 50 percent of the hour on 50 percent of the days. The field intensity value for any sky-wave mode depends on the transmitting antenna input power and gain, the transmission distance, and the losses. The median incident field intensity is the median unabsorbed field intensity, less ionospheric absorption losses. The median unabsorbed field intensity for a particular circuit is obtained from the unabsorbed field based on the standard antenna (fig. 33) by accounting for the difference in antenna radiation between the actual transmitting antenna and the standard antenna.

b. Antenna Considerations. Antenna gains are given in this section for various common transmitting antennas erected over poor ground with respect to a short dipole antenna. These antenna gain values are the ratios squared of the field intensity of 1 mile produced by the particular antenna to 186.3 millivolts per meter. Gains with respect to an omnidirectional antenna are 4.8 db greater than with respect to the short dipole. The antenna gains are given for various vertical radiation angles, usually in the optimum direction in the horizontal plane. The inverse distance field intensity produced by an antenna can be given by the inverse distance field for a reference antenna multiplied by the square root of the product of the antenna input power and the antenna gain.

$$E = \frac{300}{r} \sqrt{G \times P} \text{ millivolts per meter}$$

where: r is the distance in km from the transmitting antenna;

G is the antenna gain with respect to a short dipole; and

P is the antenna input power in kw (kilowatts) (effects of heating losses included in the antenna gains).

The product of the antenna input power in kw and the antenna gain with respect to a short dipole antenna can be defined as the effective power in kw. Since the unabsorbed field intensity curves (fig. 33) are based on the radiation of a short dipole antenna with input power of 1 kw, the unabsorbed field intensities for any antenna installation are obtained by adding the effective power to the unabsorbed field intensity curve values with both being expressed in db.

c. Sky-Wave Absorption.

(1) Ionospheric absorption losses, as discussed in the theoretical section, vary inversely with frequency squared and depend upon the sun's radiation. Absorption varies with the sun's angle with respect to the ionospheric reflection point. Normal ionospheric absorption occurs only during the daylight hours, being at maximum when the sun is directly over the reflection points and zero during the night hours. Absorption for a circuit is minimum at frequencies just below the highest frequency that the ionosphere will support.

(2) It is not necessary to compute what the absorptions are in this manual. The curves (figs. 121–140) and nomograms (figs. 205–224) subtract ionospheric absorption losses from the unabsorbed field intensity values. Median incident sky-wave field intensities are obtained directly for various values of the normal absorption index K. Figures 103 through 114 show the world-wide variation of the absorption index for the months of the year. Since normal ionospheric absorption is dependent only on lower layer ionization, the absorption index does not show longitude variations. The plots give the absorption index for different local times and latitudes. It is necessary to correct the absorption index for solar activity. Analysis of the recordings shows that the absorption varies with the 11-year sunspot cycle (fig. 118). In addition, the absorption is corrected for seasonal effects (fig. 119). These seasonal effects are due to the variation of ionospheric layer heights as the sun travels seasonally north and south. Variations in layer heights change the angles of ray incidence and, thus, affect the absorption. The absorption becomes smaller as the incident ray becomes more vertical.

(3) In this manual, auroral absorption is assumed to be the same from hour to hour, month to month, and throughout the sunspot cycle. Field intensities for routes through the auroral regions are found by using the absorption index values obtained by adding an auroral index to the normal absorption index. A world-wide

plot is shown which gives the variation of auroral absorption index, K_a, with latitude and longitude (fig. 115).

80. Lowest Useful High Frequency

a. The LUF* (lowest useful high frequency) is the lower limiting frequency for communication for a particular circuit. This limiting frequency is determined by the strength of the signal at the receiving location. In order for the communication to be intelligible, the signal strength must be sufficiently strong to override the effects of noise. The LUF is the frequency at which the received field intensity is equal to the required field intensity. Received field intensities depend on the antenna radiation, transmission distance, and absorption losses, while the required field intensity depends on the noise in the receiving system. In general, the received field intensity increases with wave frequency, while the required field intensity decreases. The LUF can be obtained from the intersection of required and received field intensity against frequency curves when plotted on the same paper. In this manual, LUF's for long distances are obtained by a nomographic solution.

b. Figures 146–164 are plots giving required incident field intensities. There are curves giving the minimum field intensities to assure double sideband radiotelephone communication in the presence of atmospheric noise, and curves giving the minimum field intensities necessary to overcome receiver noise for double sideband radiotelephone communication. The required field intensity in the presence of atmospheric noise at a given location depends upon the noise grade. Figures 142–145 are world maps showing the world-wide distribution of atmospheric noise grades. The minimum required intensity curves to overcome atmospheric noise are drawn corresponding to various values of noise grades. The required field intensity curves in the presence of receiver noise are drawn for various radiation angles; the angles depend on the ionospheric layer heights, the distance, and the number of hops in the transmission path.

c. The types of service gain were defined in the theoretical section as relative signal strengths required for different types of communication to a standard type of communication. These types of service gain give the relative required signal-to-noise ratios for different services. The required incident field intensities for types of service other than the low quality double sideband radiotelephony reference service are obtained by adding the type of service gains to the required incident field intensities of this manual (fig. 120).

d. Discrimination gains are subtracted from the required incident field intensities in presence of atmospheric noise. Directive antennas discriminate against atmospheric noise in favor of the signal. Small incident field intensities are needed to give the necessary signal-to-noise ratio required for intelligible communication (figs. 165–181).

e. LUF's are obtained from the comparison of the received median incident field intensities and the required median incident field intensities, which are adjusted for type of service and discrimination gains in the case of the atmospheric noise limitation, and for the type of service gains in the case of the receiver noise limitation.

81. Lowest Effective Power

The LEP (lowest effective power) is the minimum transmitting antenna effective power required for satisfactory communication for a particular circuit at a given frequency. The difference in db between the received field intensity based on the reference antenna radiation (300 millivolts per meter at 1 km) and the required field intensity determines the LEP in db. If the received incident field intensity is 10 db greater than the required incident field intensity, the LEP is —10 db. This indicates that satisfactory communication is obtainable with an antenna that has an inverse distance field intensity 10 db lower than 300 millivolts per meter at 1 km. If the antenna gain were 1, then the required antenna input power would be —10 db or 100 watts.

82. Maximum Usable Frequencies

a. The upper limiting frequency for sky-wave communication over a particular circuit is determined by the MUF. The MUF is the monthly median of the daily highest frequencies that can be used for sky-wave transmission over a particular transmission path at a particular hour of the day. It depends on the extent of ionization of the ionized layers. MUF's vary with geographic location of the ionospheric reflection, points, the time

*LUF replaces the abbreviation LUHF as a result of the Stockholm meeting, in July 1948, of the CCIR (International Radio Consulting Committee).

of the day, the season, and solar activity. In this manual, MUF's are obtained for any circuit by using nomograms and predictions which give world-wide distributions of MUF's for certain standard distances. These monthly predictions, which are published 3 months in advance in TB 11–499–( ), give MUF's for the F2 layer, the E layer, and the sporadic E layer. No prediction charts are prepared for the F1 layer, its effects being approximated in the E layer nomogram. The effects of variations with longitude are accounted for in the case of the F2 and the sporadic E layer prediction charts. Two F2 layer charts, a zero distance MUF (F2 ZERO MUF) and 4,000 km MUF (F2 4000 MUF), are prepared for three geographic zones, east (E zone), west (W zone), and the intermediate (I zone). Single charts are prepared for the E layer and the sporadic E layer, the longitudinal variations being accounted for in the sporadic E chart by three different ordinate scales corresponding to the three geographic zones. Typical charts are shown in figures 92–96. The MUF for any route is the highest MUF for any of the layers.

b. In this manual, for distances of less than 4,000 km, the MUF's are found from the ionospheric conditions at the midpoint of the great circle path between the transmitter and the receiver. Transmission can be controlled by the E layer, the F1 layer, or the F2 layer. Due to the variability of the sporadic E layer and the relative inaccuracy of sporadic E predictions, the MUF for a route often is calculated without attempting to account for the sporadic E layer. The E and F2 layer MUF's for the circuit distance are found from the F2 layer predictions for zero and 4,000 km distances and the E layer predictions for a 2,000-km distance by using the nomograms which give the MUF's for any distance up to 4,000 km from the predicted values. The effect of the P1 layer is accounted for in the E layer nomogram in which it is assumed that the F1 layer MUF slightly exceeds the E 2000 MUF at distances between 2,000 and 4,000 km.

c. For transmission distances exceeding 4,000 km, the F2 layer nearly always controls the transmission. In this manual, the E layer and the sporadic E layer MUF are not calculated for distances greater than 4,000 km. The F2 4000 MUF is found at 2,000 km distances from each end of the transmission path; the lower of the two values is the MUF for the circuit. Experimental evidence indicates that when the ionosphere is ionized sufficiently at points 2,000 km from ends of the transmission path to reflect a particular wave frequency, sky-wave transmission generally is possible.

d. The actual upper limiting frequency selected for circuit operation is taken at a frequency value below the MUF for the circuit. The MUF's have been stated to be a monthly median value, a frequency value exceeded on one-half of the days of the month. When the transmission frequency is somewhat below the MUF, the circuit reliability is increased. This insures against the probability that the operating frequency is greater than the MUF for the particular day. The FOT* (optimum traffic frequency), equal to 85 percent of the MUF for the F2 layer, is the usual upper limiting frequency. The daily maximum frequency is equal to or exceeds the FOT for about 95 percent of the days for most locations and seasons. Since the day-to-day variation in E layer ionization is small, the FOT for transmission by the combined E–F1 layer is equal to the MUF. In some problems, an upper limit, called the HPF (highest probable frequency), is used. In case of the F2 layer, the HPF is taken as 15 percent above the MUF, while for the E layer it is the MUF value. During moderate ionospheric storms, communication often can be assured by operating at slightly lower frequencies than normal, since critical frequencies usually are lower than normal during these periods.

e. In order to determine the probability of sporadic E layer support, it often is desirable to find out what the MUF is for this layer. The sporadic E MUF is obtained by using the chart given in the TB 11–499 prediction series for the monthly median value of sporadic E layer MUF at vertical incidence, fE_s. The MUF for a 2,000-km distance is obtained by multiplying this vertical incident value by 5. The sporadic E FOT for 2,000 km is obtained by subtracting 4 mc from the sporadic E MUF. The MUF or FOT for any transmission distance is obtained from the 2,000-km values by using the regular E nomogram.

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*FOT (optimum traffic frequency) replaces the term "optimum working frequency" and its abbreviation OWF as a result of the Stockholm meeting of CCIR (International Radio Consulting Committee) in July 1948.

Section III. CALCULATIONS FOR MAXIMUM USABLE FREQUENCIES

83. Explanation of Methods

a. The MUF's are obtained by a graphical process. The energy is assumed to travel along a ray path in the plane determined by the great circle that can be drawn between the transmitting and receiving locations. Based on ray theory, the only energy that can arrive at the receiving location must travel in the great circle plane since the energy travels in a straight path and is assumed not to be deflected sidewards at the ionosphere. The degree of ionization of the ionosphere at a point midway between the transmitting and receiving antennas determines the MUF's for routes less than 4,000 km long. For paths greater than 4,000 km, experience has shown that the MUF can be determined by the extent of ionization at points of 2,000 km from the ends of the great circle paths between the two locations. All the charts used in the graphical method (prediction charts, a great circle chart, and a world map), are drawn to the same scale in modified cylindrical coordinates. These charts, nomograms, and a piece of transparent paper (overlay) are all that are necessary for the solution of the MUF between any two locations, for any hour of the day corresponding to the month and year of the prediction charts. The nomograms convert the MUF's of the prediction charts which are based on standard distances to MUF's for the circuit distance.

b. The method is based on the assumption that points at equal latitudes have the same ionospheric conditions for equal local times. The purpose behind the overlay is to determine graphically the ionospheric conditions at the control points (midpoint or 2,000 km points) at hours referred to a time base. The user generally is interested in finding the MUF for hours referred to some standard clock (civil time for any zone or Greenwich civil time).

c. Civil time measures the mean time that is taken by the sun to travel around the earth (due to the rotation of the earth about its axis). When the hours of the day are referred to any point on the earth, they are hours of local time referred to that point. Time generally is based on various reference meridians at points 15° apart in longitude (the distance the mean sun travels in an hour). The time reference most commonly used is zero longitude time or GCT (Greenwich civil time). Everyone is familiar with the United States time zones—eastern, central, mountain, and Pacific time. The seventy-fifth meridian time is EST (eastern standard time) and the ninetieth meridian time is central standard time, etc. The hours of time usually are measured from local midnight through 24 hours.

d. The purpose of the great circle map (fig. 98) is to determine the position of the great circle path between the transmitter and the receiver and the control points. The great circle chart shows various great circles between two points on the equator at opposite sides of the earth as they appear on a modified cylindrical projection. It is shown in the study that an infinite number of great circles are possible between two polar points (points on opposite sides of a sphere). The transmitting and receiving points determine one great circle that crosses the equator and this great circle path is one of the infinite number of great circles between the two polar points.

e. MUF's for any circuit are found by the following procedure: A piece of transparent paper is placed over the world map (fig. 97), and a horizontal line is drawn corresponding to the equator line on the world map. A vertical line also is drawn at the longitude which is desired for a time reference. If the line is drawn at zero degrees longitude, the hours are in GCT. Marks are placed on the overlay at positions corresponding to the locations of the transmitting and receiving stations. This overlay next is placed on the great circle chart (fig. 98) with the equatorial index line of the overlay coinciding with the equatorial line of the great circle chart. By sliding the overlay horizontally until the station points are on the same great circle or are the same proportional distance between adjacent circles on the great circle chart, the great circle path can be drawn in. The path midpoints for a route less than 4,000 km long can be located by using (as a distance scale) the dotted numbered curves on the great circle chart. These dot-dashed curves are plots showing points of equal distance from the polar points of the great circle chart. The distances along a great circle path between two dot-dashed lines is 1,000 km; 500-km points are shown by dotted lines. For paths longer than 4,000 km, mark the F2 layer control points 2,000 km

from each end of the transmission path. There are two ways of traveling from one point to another on a great circle. The second point can be reached by traveling in either direction along the great circle. The short path generally is used. This overlay which now has the control points marked on it is placed back on the world map and the zones in which the control points lie can be noted. The zone line can be sketched in during the initial operation when the station points are marked on the overlay. If this is done, there is no necessity of placing the overlay on the world map again to determine the zones in which the control points lie. The MUF's for the standard distances of the charts now can be determined by placing the overlay on the proper prediction charts with the equatorial lines coinciding. The overlay is slid horizontally until the time reference line coincides with the desired time on the chart. The hours with respect to the time reference line are determined by placing the reference line on any vertical line on the prediction chart corresponding to a local hour.

f. To obtain the MUF's for distances less than 4,000 km, two F2 layer prediction charts (F2 ZERO MUF and the F2 4000 MUF), the E 2000 MUF chart, the F2 MUF nomogram, the E-F1 layer nomogram, and the overlay are required. The MUF's are read at the path midpoint by placing the overlay on the prediction charts with the equatorial lines coinciding, the vertical time reference line set at the desired hour. The prediction charts used correspond to the zone in which the path midpoint lies. The F2 layer MUF nomogram (fig. 102) is used to find the MUF for the transmission distance. This nomogram has a vertical *ZERO MUF* scale on the left and a vertical *4000 MUF* on the right. Between the two scales are *vertical distance lines* with zero km on the left and 4,000 km on the right. Equal frequency values on the two vertical scales are connecting, thus forming a MUF grid. To find the F2 layer MUF for the transmission distance, lay a straightedge from the ZERO MUF reading on the left vertical scale to the 4000 MUF reading on the right scale and read the MUF of the distance on the frequency grid at the intersection of the vertical distance line corresponding to the transmission distance and the straightedge. The E-F1 nomogram (fig. 100) is used to obtain the combined E layer and F1 layer MUF for the transmission distance. The nomogram consists of three vertical scales: on the left is the E 2000 MUF scale, on the right is the *distance in kilometers scale*, and in the center is the *MUF in megacycles scale*. The MUF is obtained by laying a straightedge from the E 2000 MUF value on the left scale to the transmission distance on the right scale and reading the E-F1 layer MUF corresponding to the transmission distance on the center scale. The MUF for the circuit is the higher of the two MUF's as read above. The sporadic E MUF generally is not read. The value of the sporadic E MUF can be obtained by using the sporadic predictions for vertical incidence, fE_s. These are converted into a sporadic E for a 2,000-km distance by multiplying by 5. The procedure for obtaining the sporadic E MUF for a given distance is the same as for a normal E layer from then on.

g. For distances greater than 4,000 km, the F2 layer generally controls the transmission. The MUF based on the F2 layer transmission is obtained by reading the F2 4000 MUF values at the control points (2,000 km from the path ends) by placing the overlay on the prediction charts with the equatorial lines coinciding and the time reference line set at the desired hour. The MUF's are read on the prediction charts for the zones in which the control points lie. If the control points lie in different zones, the MUF is read for each control point on the chart for its zone. The lower of the two F2 4000 MUF's always is taken as the MUF for the route. Often, it is desirable to check whether the normal E layer or the sporadic E layer controls communication. For these layers, the control points are taken at distances of 1,000 km from the path ends. The MUF's for the 2,000-km distance are used as the MUF's for these long transmission distances. Again, the lower of the two E 2000 MUF's for the control points determines the MUF for the circuits. The sporadic E MUF for a 2,000-km distance again is obtained by multiplying the vertical incident values by 5.

84. Example of MUF Calculation for Distance Less than 4,000 km

The MUF is desired for the following circuit:

Station location:	
Cincinnati, Ohio	39.13° N, 84.42° W
Baton Rouge, La.	30.47° N, 91.18° W
Transmission distance	1,200 kilometers
Month and year	June 1946
Time of day	1200 EST

a. Place a piece of transparent paper on the world map (fig. 97) and draw in a horizontal line

at the equator and a vertical line at 75° west longitude. Place dots over the station locations. It is noted that both stations lie within the W zone. The midpoint of the great circle path between the stations must lie within the W zone. Figure 45 indicates the operation.

b. Place the overlay on the great circle chart (fig. 98) with the equatorial lines on the overlay and the great circle chart coinciding, and slide the overlay until station positions lie on the same great circle. Locate the path midpoint, using the dash-dotted curves as a distance scale. Sketch in the great circle path and mark the midpoint (fig. 46).

c. Place the overlay on the F2 ZERO MUF, W zone chart fig. 93) with the equatorial lines coinciding, and slide horizontally until the vertical reference line lies over the 1200 line on the prediction chart. The F2 ZERO MUF for 1200 EST is shown to be 7.7 mc. With the overlay placed on the F2 4000 MUF chart (fig. 94) in a similar manner, the F2 4000 MUF for the W zone is shown to be 21.8 mc. Repeat the process with the E 2000 MUF chart (fig. 92). The E 2000 MUF is shown to be 18.2 mc. (See figs. 47–49).

d. The F2 layer MUF is obtained by using the F2 layer nomogram (fig. 102) and the values for the F2 ZERO MUF and the F2 4000 MUF along with the transmission distance. The transmission distance is 1,200 km, as indicated in the great circle chart. Lay a straightedge from the F2 ZERO MUF value (7.7 mc) to the F2 4000 MUF value (21.8 mc) and read the F2 layer MUF for the 1,200-km distance. This value is shown to be 11.3 mc (fig. 50).

e. The E–F1 layer MUF is read by using the E layer nomogram (fig. 100) and the value of the E 2000 MUF obtained above. The MUF value is read by setting the straightedge on the E 2000 value (18.2 mc) and the transmission distance (1,200 km). This value is 15.0 mc (fig. 51).

f. The MUF's at 1200 EST for the 1,200-km route between Cincinnati and Baton Rouge during June 1946 are 15.0 mc. The higher MUF is used since it is the highest frequency usable over the route. The FOT for the route is 15.0 mc also, since

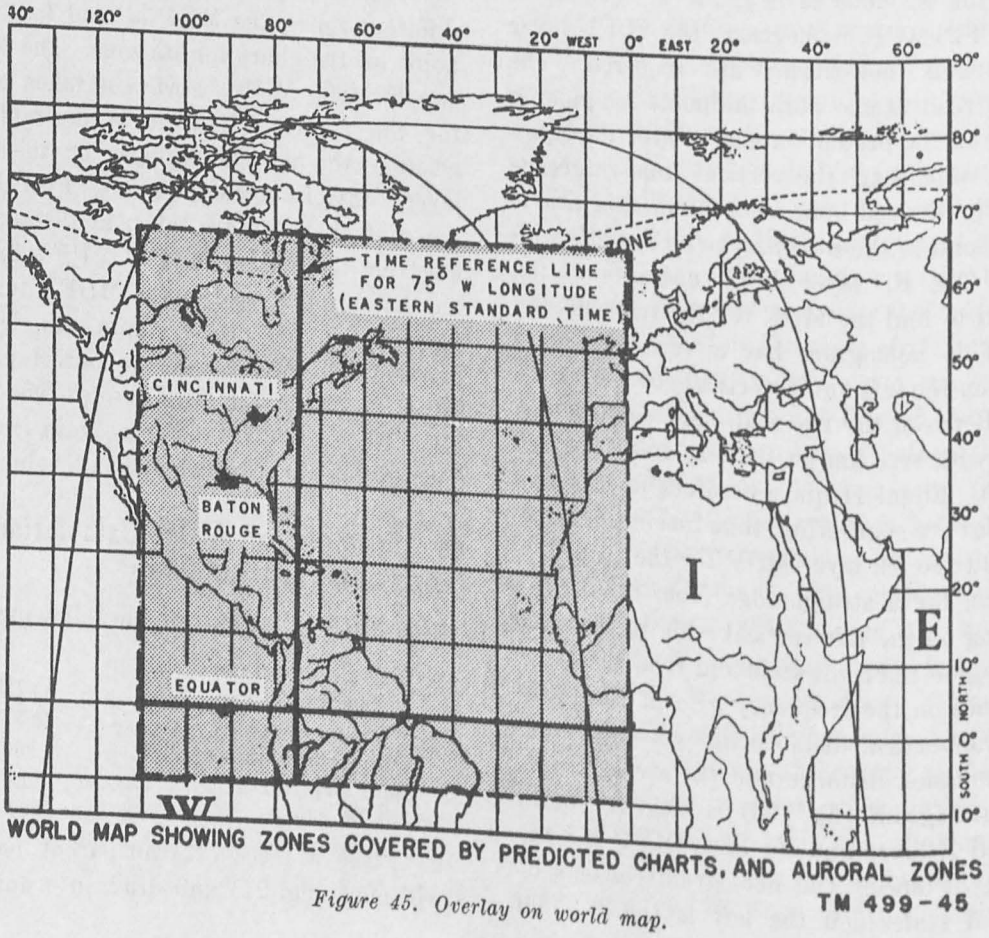


Figure 45. Overlay on world map.

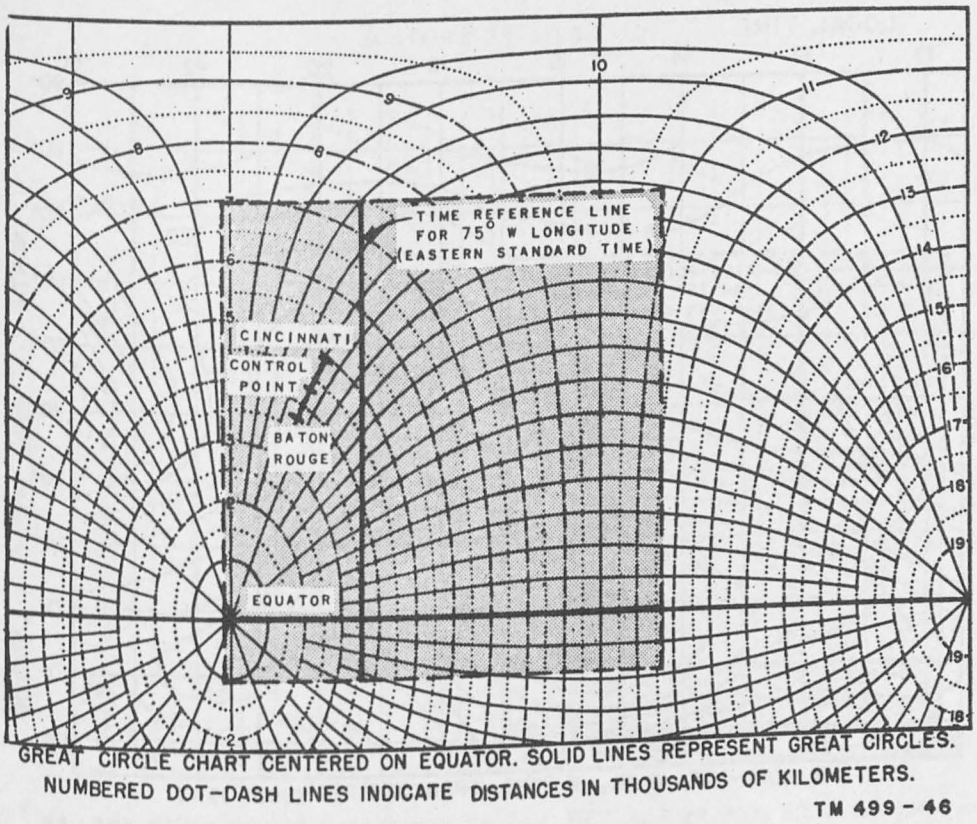


Figure 46. Overlay on great circle chart.

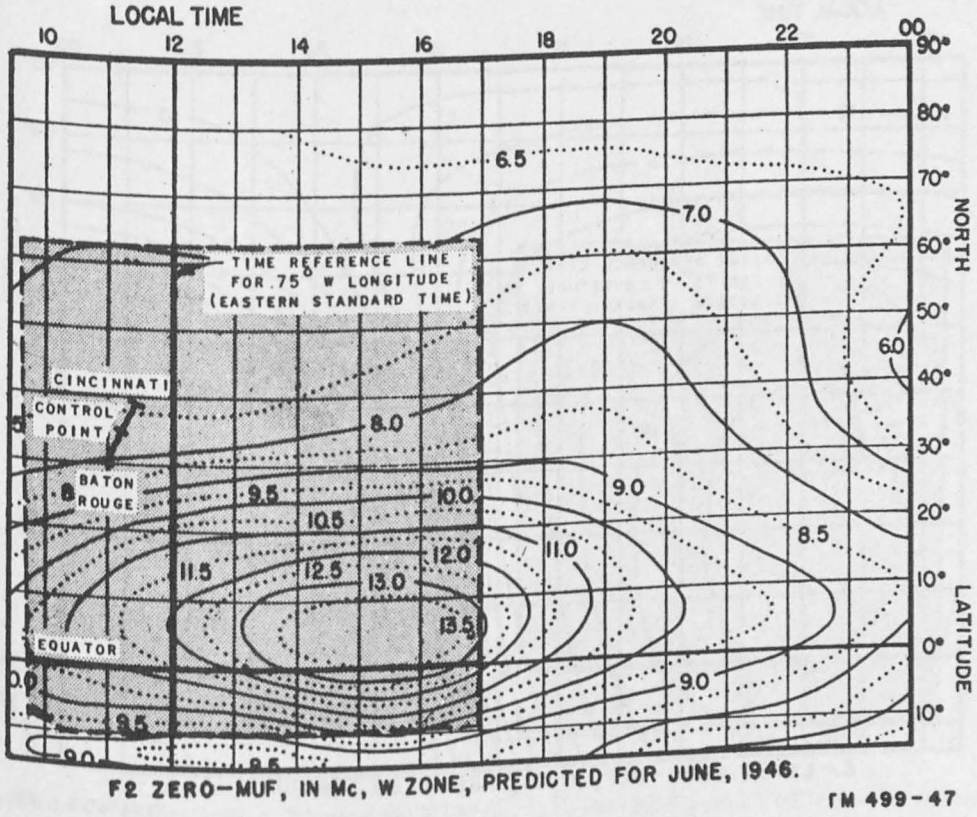


Figure 47. Overlay on F2 Zero MUF, W zone chart.

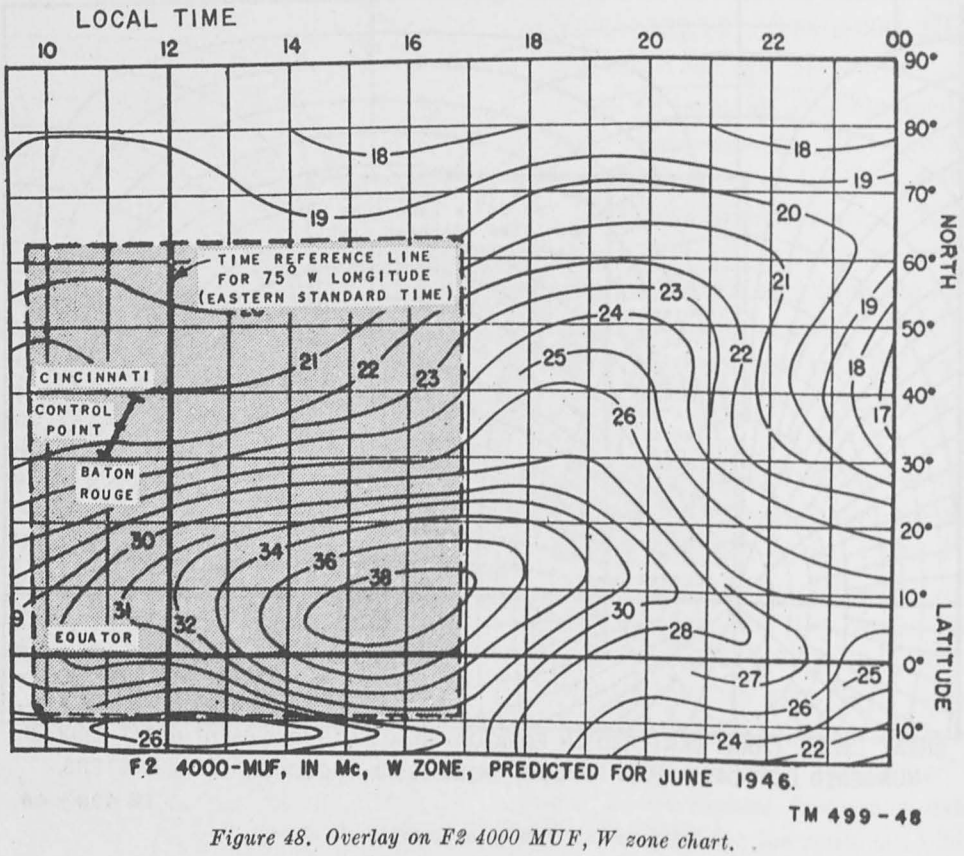


Figure 48. Overlay on F2 4000 MUF, W zone chart.

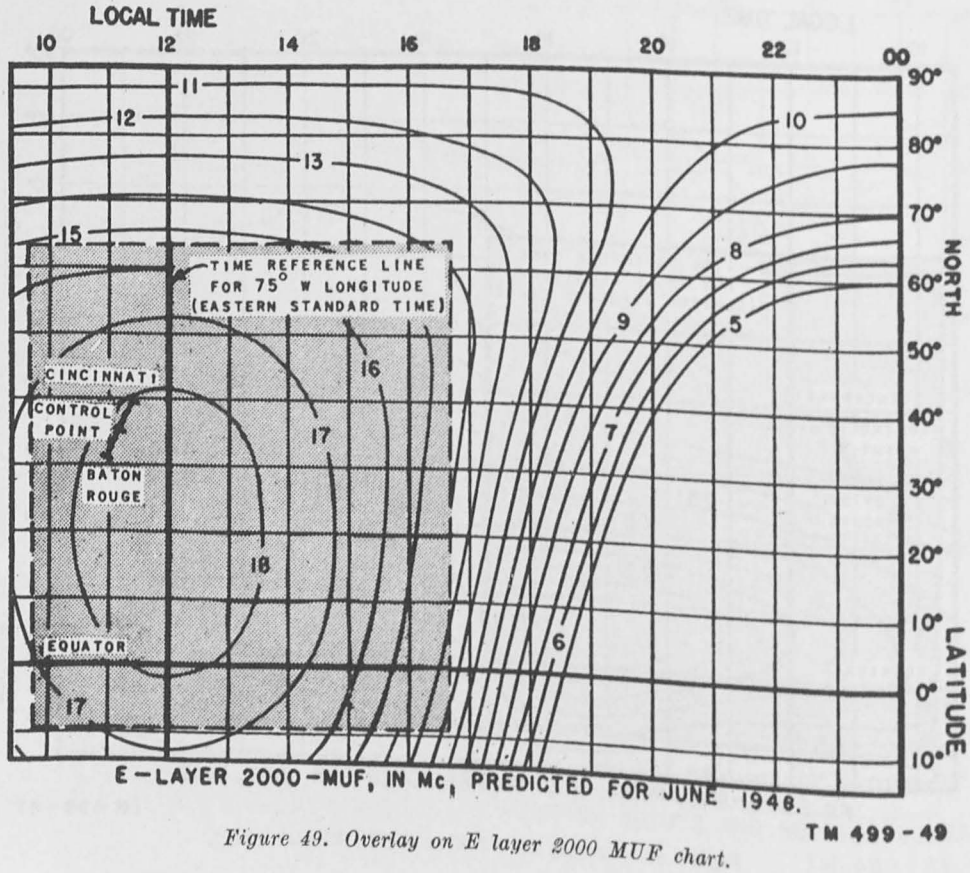


Figure 49. Overlay on E layer 2000 MUF chart.

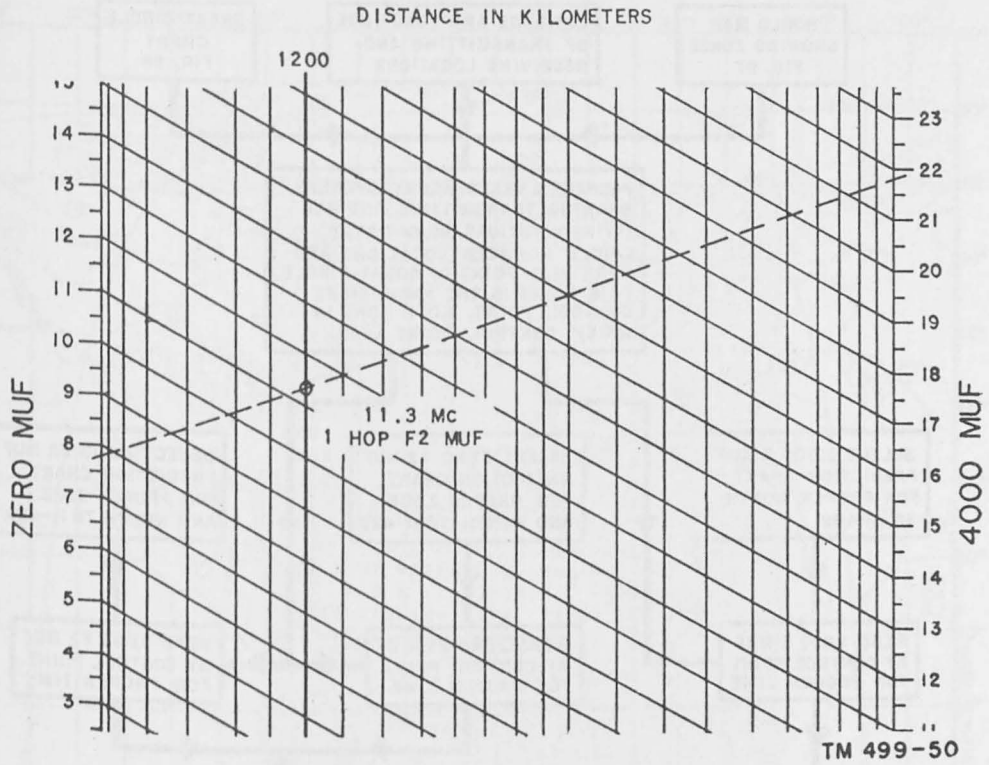


Figure 50. Nomogram for transforming F2 Zero MUF and F2 4000 MUF to equivalent MUF's at intermediate transmission distances.

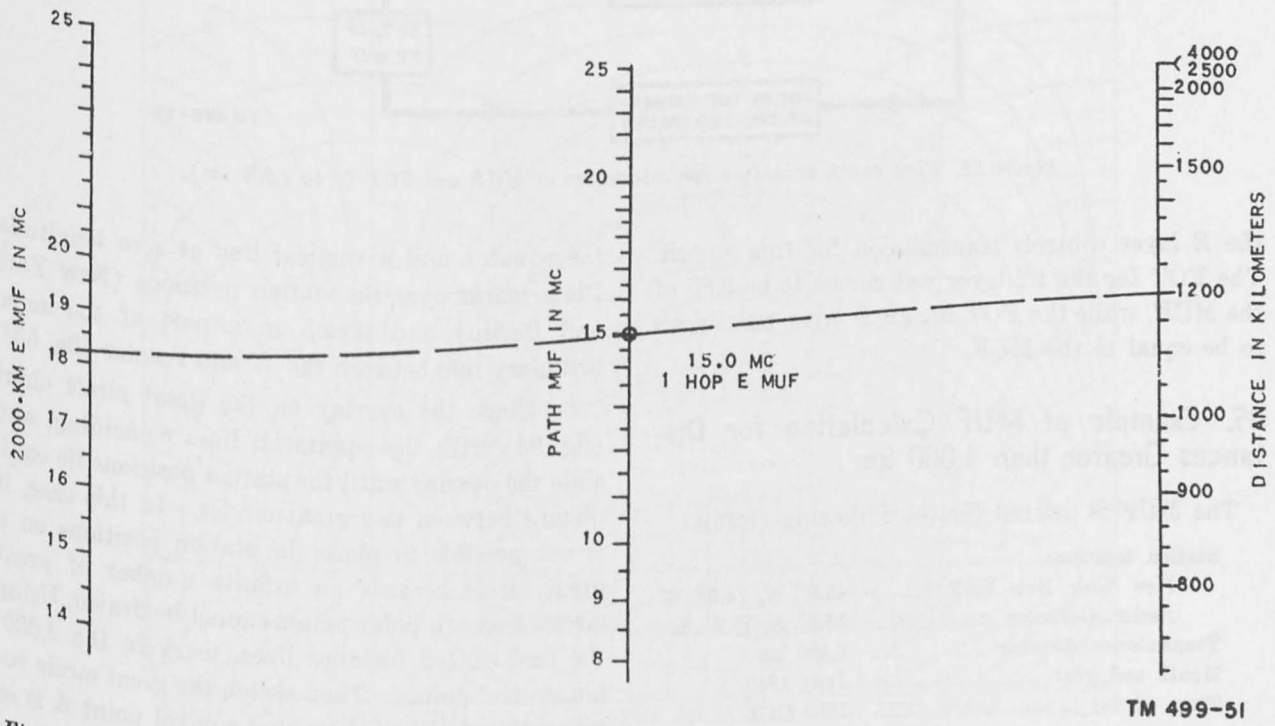


Figure 51. Nomogram for transforming E layer 2000 MUF to equivalent MUF's and FOT's due to combined effect of E layer and F1 layer at other transmission distances.

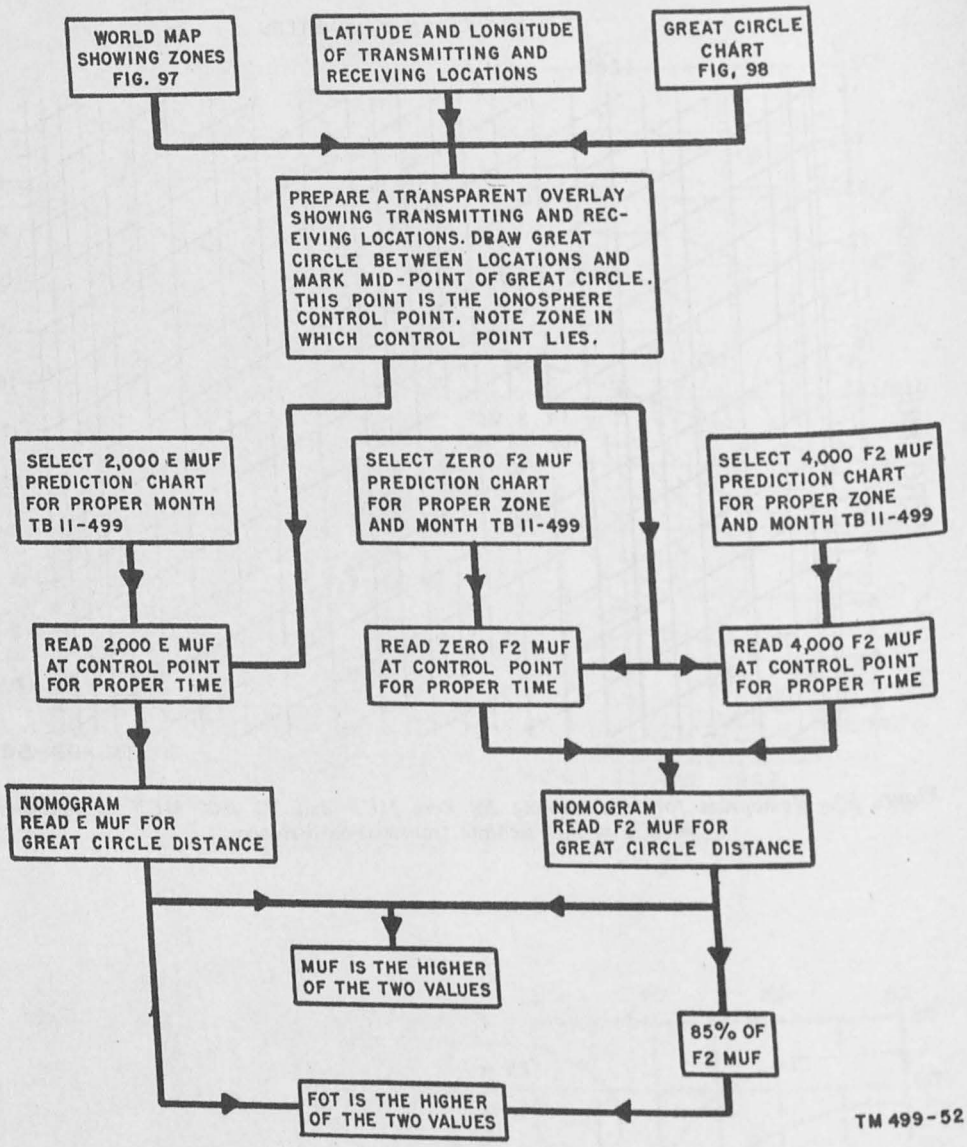


Figure 52. Flow chart, procedure for calculation of MUF and FOT (0 to 4,000 km).

the E layer controls transmission for this circuit. The FOT for the F2 layer was shown to be 0.85 of the MUF, while the FOT for an E layer was shown to be equal to the MUF.

85. Example of MUF Calculation for Distances Greater than 4,000 km

The MUF is desired for the following circuit:

Station location:	
New York, New York	40.8° N, 74.0° W
Berlin, Germany	56.6° N, 13.2° E
Transmission distance	6,400 km
Month and year	June 1946
Time of day	1200 GCT

a. Place a piece of transparent paper on the world map (fig. 97) and draw a horizontal line at the equator and a vertical line at zero longitude. Place marks over the station positions (New York and Berlin) and sketch in a part of the zonal boundary line between the W and I zones (fig. 53).

b. Place the overlay on the great circle chart (fig. 98) with the equatorial lines coinciding, and slide the overlay until the station positions lie equidistant between two great circles. In this case, it is not possible to place the station positions on a great circle because an infinite number of great circles between polar points cannot be drawn. Using the dash-dotted distance lines, mark in the 2,000-km control points. Then sketch the great circle between the stations. Note that control point A is in the W zone and control point B is in the I zone (fig. 54).

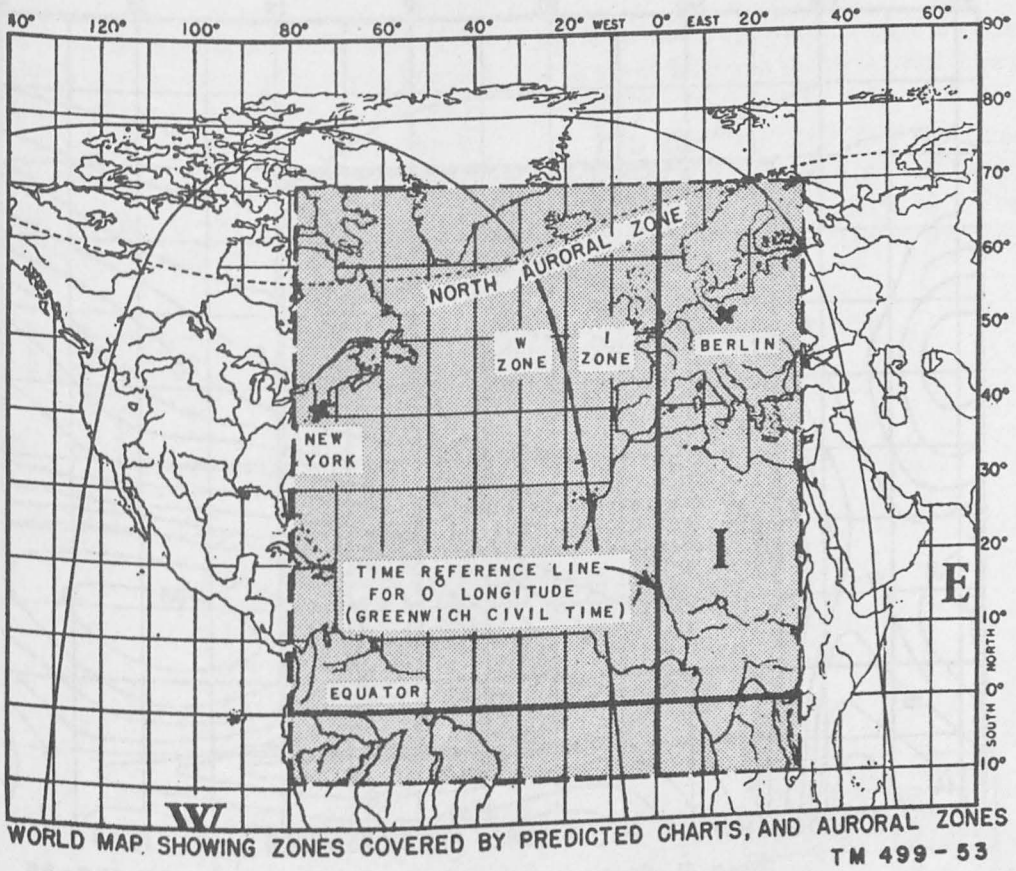


Figure 53. Overlay on world map.

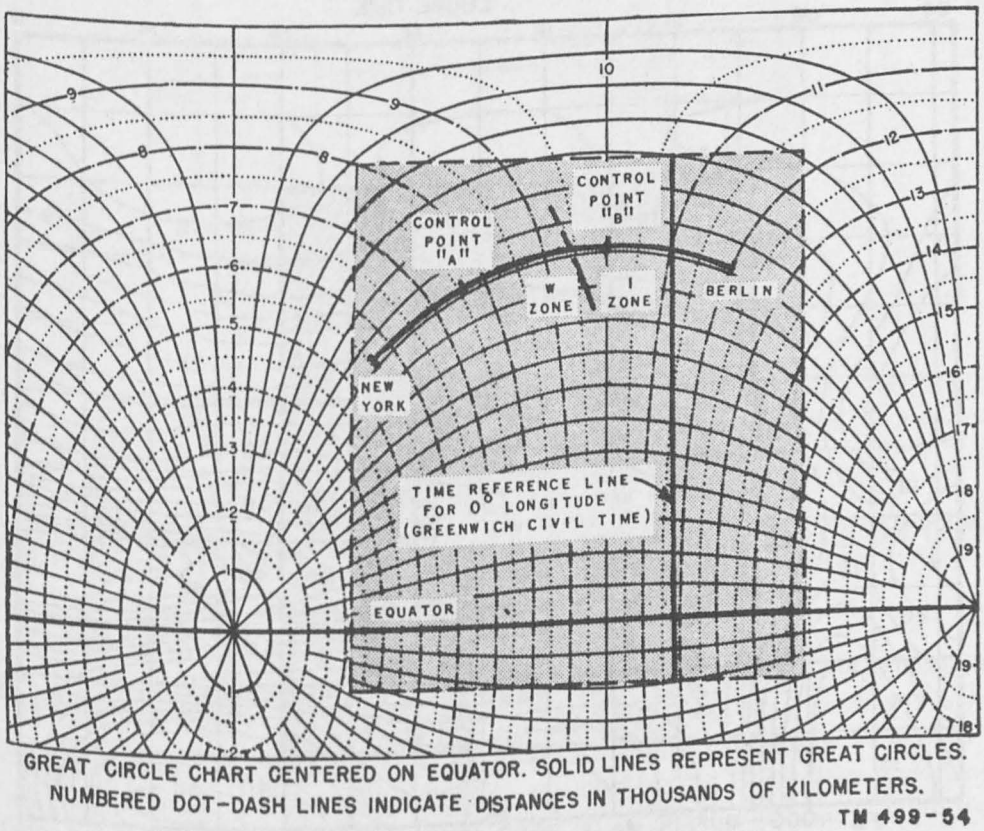


Figure 54. Overlay on great circle chart.

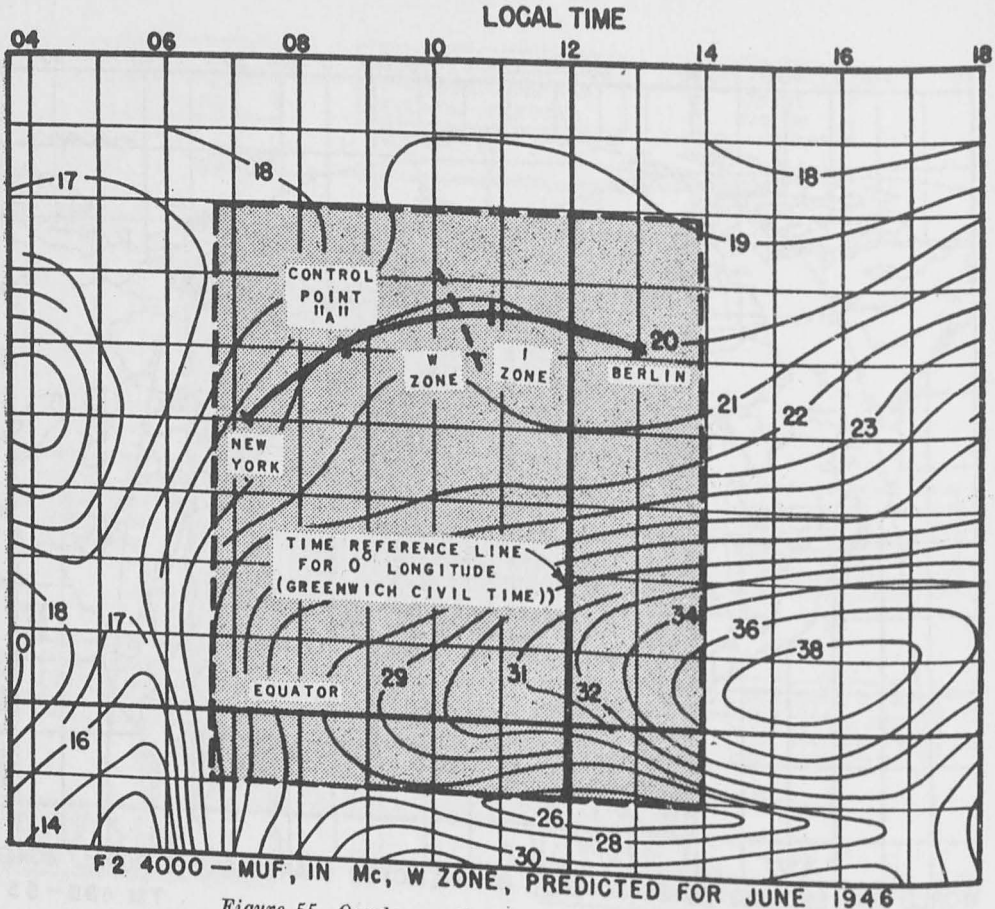


Figure 55. Overlay on F2 4000 MUF, W zone chart. TM 499-55

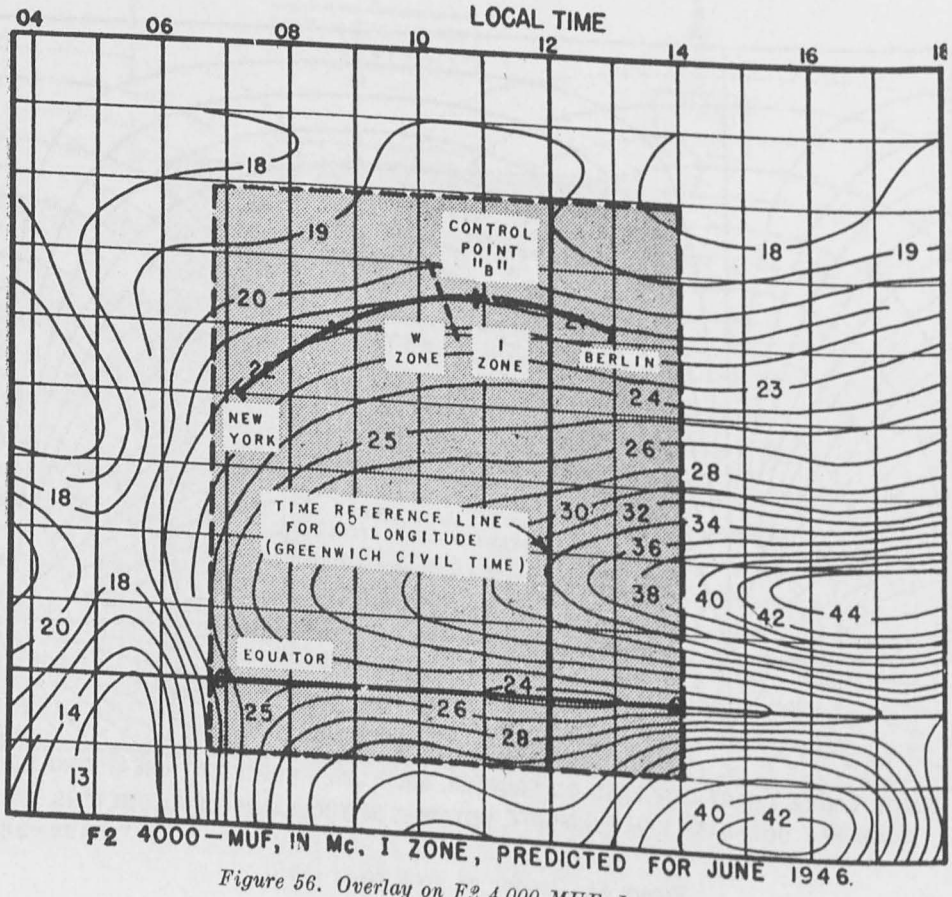


Figure 56. Overlay on F2 4,000 MUF, I zone chart. TM 499-56

c. Place the overlay on the June F2 4000 MUF W zone on the prediction chart with the equatorial lines coinciding and the time reference meridian at 1200 local time on the prediction chart. The F2 4000 MUF for control point A is 20.1 mc (fig. 55).

d. Place the overlay on the F2 4000 MUF prediction chart for the I zone for June 1946. Read the MUF at control point B with the time reference lines set at 1200 and the equatorial lines coinciding. This MUF is 20.9 mc (fig. 56).

e. The MUF for 1200 GCT for June 1946 between New York and Berlin is 20.1 mc (the lower of the two control point MUF's). The FOT for the circuit is 17.1 mc or 0.85 of the MUF.

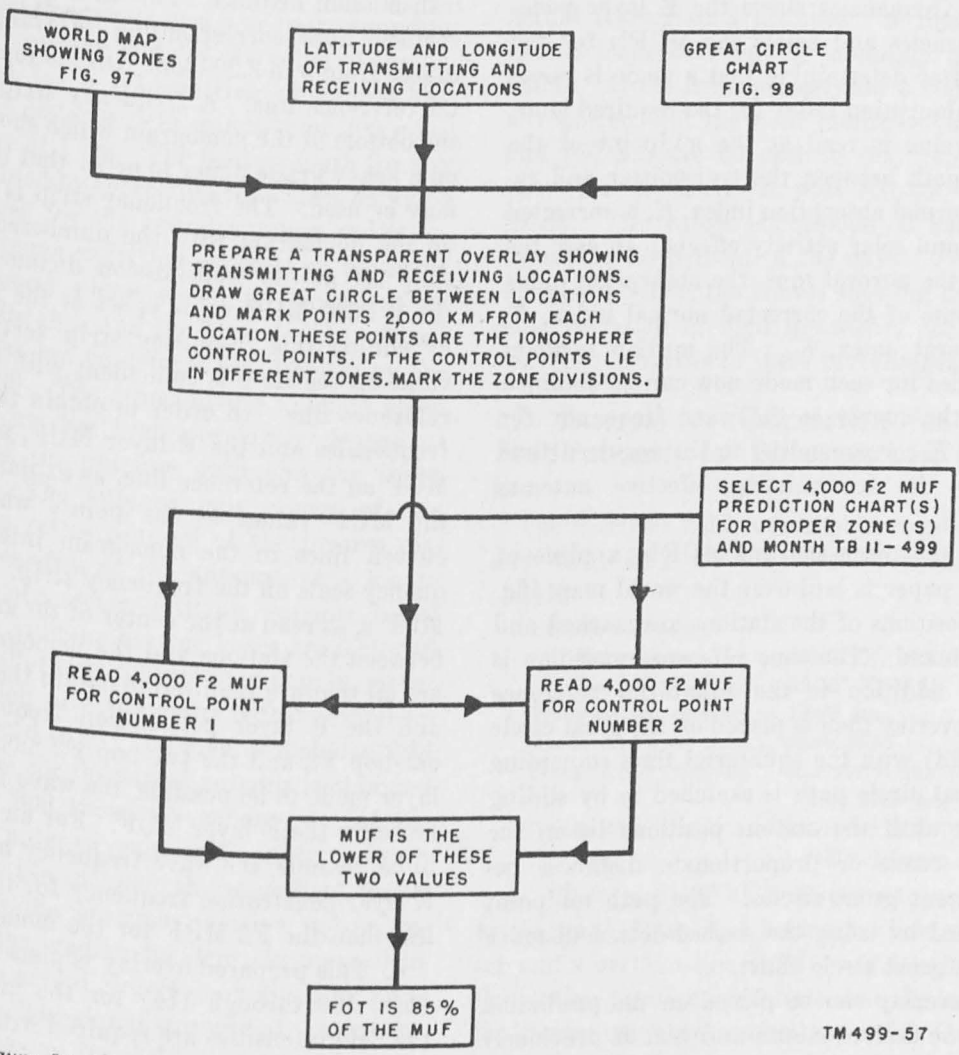


Figure 57. Flow chart, procedure for calculation of MUF and FOT (4,000 km and greater).

Section IV. CALCULATION FOR SKY-WAVE FIELD INTENSITIES FOR DISTANCES FROM 0 TO 3,000 km

86. Explanation of Methods

a. The median downcoming sky-wave field intensities for frequencies from 2 to 30 mc are obtained from a set of curves (figs. 121–140). Curves give the values in db referred to 1 microvolt per meter at distances of 0 to 200, 400, 800, 1,600, 2,400, and 3,200 km for one- and two-hop F layer modes and the one-hop E layer mode at various values of absorption index. The curves give the incident field for an antenna radiation of 300 millivolts per meter at 1 km and do not include the ground reflected

components at the receiver. These hourly median values include polarization fading losses and an average ground reflection loss in the case of the two-hop mode. The field strength at the receiving location is determined for this distance range by first determining which of the three modes is possible and then determining which gives the strongest signal. The F2 layer transmission modes are possible only at frequencies above the E layer penetration frequencies and below the MUF's for the F2 layer. After determining that a mode is possible, find the absorption index for the required hour. This index value is read at the midpoint of the great circle path between the transmitter and receiver. The normal absorption index, K, is corrected for seasonal and solar activity effects. In case the path crosses the auroral zone, the absorption index used is the sum of the corrected normal index, K, and the auroral index, K_a. The median incident field intensities for each mode now can be obtained by reading the curves at the wave frequency for the value of K corresponding to the required time and adding the transmitting effective antenna power.

b. As in the discussion on MUF's, a piece of transparent paper is laid over the world map (fig. 97). The positions of the stations are marked and the zone is noted. The time reference meridian is marked, in addition to the equatorial reference line. This overlay then is placed on the great circle chart (fig. 98) with the equatorial lines coinciding and the great circle path is sketched in by sliding the overlay until the station positions lie in the same great circle or proportionate distances between adjacent great circles. The path midpoint is determined by using the dashed-dotted distance scale of the great circle chart.

c. This overlay can be placed on the prediction charts for the desired month and year as previously explained, to obtain the F2 layer and E layer MUF's for standard distances. The F2 layer nomogram (fig. 102) is used to obtain the one-hop and two-hop F2 layer MUF's for the circuit. For the one-hop F2 layer MUF, the nomogram is read at the intersection of the vertical line corresponding to the transmission distance and the straightedge which is set at the F2 ZERO MUF value on the left vertical scale and the F2 4000 MUF value on the right vertical scale. The two-hop F2 layer MUF for the transmission distance is obtained from the same nomogram by reading at half the circuit distance. Thus, the one-hop and two-hop MUF's can be obtained by one setting of the straightedge. An F2 layer transmission mode is possible if a ray at the angle corresponding to the mode can penetrate the E layer. Figure 101 is a nomogram with which it is possible to obtain not only the E layer MUF for transmission distance but also the E layer penetration frequencies for one-hop F2 and two-hop F2 layer modes for the transmission distance. This nomogram has various vertical lines corresponding to transmission distances from 0 to 3,200 km. On the top is a horizontal reference line. A frequency strip is shown on the bottom of the nomogram which should be copied on a heavy grade paper in order that the nomogram may be used. The frequency strip is set vertically on the nomogram with the numbered edge of the strip set at the transmission distance in km and the E 2000 MUF value is set at the reference line by sliding this frequency strip vertically until a value on the strip is coincident with the horizontal reference line. In order to obtain the penetration frequencies and the E layer MUF, set the E 2000 MUF on the reference line, as explained, and read the MUF values at the points where the three curved lines in the nomogram intersect the frequency scale on the frequency strip. Thus, E 2000 MUF's, as read at the center of the great circle path between the stations and the nomogram (fig. 101), are all that are required to obtain the E layer MUF and the E layer penetration frequencies for the one-hop F2 and the two-hop F2 modes. For an E layer mode to be possible, the wave frequency must be below the E layer MUF. For an F2 layer mode to be possible, the wave frequency must exceed the E layer penetration frequency for the mode and be less than the F2 MUF for the mode.

d. This prepared overlay is placed on the K ring (figs. 103 through 114) for the month for which the field intensities are required with the equatorial lines coinciding and the time reference line set at the required hour. The K value is read at the path midpoint. This K value is multiplied by a seasonal correctional factor (fig. 119) and a solar activity correction factor (fig. 118). The solar activity correction factor can be obtained from the predicted curve of the figure or can be obtained by using the monthly running average monthly sunspot number, as shown in TB 11–499 for the desired month. If the running sunspot number is used, the solar activity factor is obtained by noting from the scales of figure 118 the factor which corresponds with a value of the sunspot number. This overlay,

when placed on the auroral absorption chart (fig. 115), can be used to determine the auroral absorption index, if any. The auroral index is read at the path midpoint; no corrections are applied to the auroral index since the auroral index values are average values. The absorption index is the sum of auroral and the normal indices for the hour.

e. The median incident sky-wave field intensities can be read directly from the curves, figures 121–140, by reading the curves at a point corresponding to the wave frequency and for the value of the absorption index for a transmitting antenna which has an inverse distance field intensity of 300 millivolts per meter at 1 km. The field strength for any circuit is obtained by correcting the values obtained from the curves for the actual antenna radiation. The actual antenna radiation depends on the angle above the ground plane which is dependent on transmission distance and the layer height. These radiation angles can be determined directly by the use of figure 99. The transmitting antenna effective power in kw has been previously defined as the product of the antenna gain and the input power in kw. The antenna gain curves of this manual are the ratios squared of the inverse distance field intensities of the antenna at 1 km to 300 millivolts per meter with an antenna input power of 1 kw. Antenna heating losses are included in the gain calculations. These antenna gain curves have scales which give the gains both in numbers and in db referred to 1. The inverse distance field intensity at 1 km for the actual antenna is obtained by multiplying 300 times the square root of the product of the antenna gain and input power in kw. With both the incident sky-wave field intensity curves and the antenna effective power expressed in db, the median incident sky-wave field intensity for the actual circuit is obtained by adding these values. The signal strength of the strongest mode is taken as the field strength. In case two modes have identical strengths, no correction is made. The sky-wave modes of equal intensity will produce severe fading and the signal strengths of the modes cannot be assumed to add.

f. The above procedure can be used to obtain the field intensity at any frequency for any hour of the day. To find the variation of the field intensities over the day, it is necessary only to repeat the process at various hours and plot the results. To find the wave frequency at which the field intensity is the strongest, it is necessary to plot the field intensities at the particular hour for various frequencies. The strongest field intensities are obtained at frequencies just below the MUF. This short-distance field intensity method gives the answers for various specified distances. When the transmission distance lies between two of the distances for which curves are drawn, the field intensity is calculated for the two bounding distances, using the same antenna radiation for the modes as is obtained at the angles corresponding to the actual transmission distance. A linear interpolation is made between the bounding field intensity values. If the field intensity for a 500-km distance is required and the field intensity values for 400 and 800 km are 60 and 40 db, respectively, the value for 500 km is 40 plus 300/400 times 20, or 55 db. The values correspond to hourly median values for 50 percent of the days. For other percentages of time, the curves showing the rapid and slow variation of field intensities can be used to convert the values to these percentages.

87. Example of Calculation for Sky-Wave Field Intensity for Distances Less than 3,000 km

The received field intensity is required at 8 mc and 1200 EST at Cincinnati for the following circuit:

Station Locations:	
Baton Rouge, La.	30.47° N, 91.18° W.
Cincinnati, Ohio	39.13° N, 84.42° W
Transmission distance	1,200 km
Month and year	June 1946
Transmitting antenna	Horizontal half-wave 60′ high over poor ground
Transmitter	Radio Set SCR–399, 300 watts radiotelephone service

a. Place a piece of transparent paper on the world map. Draw in a horizontal line at the equator and a vertical line at 75° west longitude. Mark the station positions and note that the midpoint of the transmission path must be within the W zone. Place this overlay on the great circle chart with equatorial lines coinciding and slide horizontally until the station positions lie on the same great circle. Mark the path midpoint and sketch in the great circle path, using the dash-dotted distance scale to measure the pathlength and locate the midpoint. The pathlength is 1,200 km. See figure 46 for the short-distance MUF problem.

b. Place this overlay on the prediction charts for June 1946 and obtain the F2 ZERO MUF, the F2 4000 MUF, and the E 2000 MUF for 1200 EST. These values, as shown in the short-distance MUF problems, are 7.7, 21.8, and 18.2 mc, respectively

(see figs. 47–49). Obtain the one-hop and two-hop F2 layer mode MUF's by using the F2 ZERO MUF and the F2 4000 MUF values with the F2 MUF nomogram (fig. 102). These values are read at the transmission distance and at one-half the transmission distance. Figure 58 shows that these values are 11.3 and 8.6 mc, respectively. Using the E layer MUF and penetration nomogram (fig. 101), obtain the E layer MUF and the E layer penetration frequencies for the one-hop and two-hop F2 modes by setting the frequency strip at the E 2000 MUF value, 18.2 mc, on the horizontal reference line. These values are 6.7, 4.6, and 15.0 mc, respectively. It can be seen that, for a wave frequency of 8 mc, all three of the modes are possible. See figure 59 for the values of the E MUF and the one-hop and two-hop F2 E layer penetration frequencies.

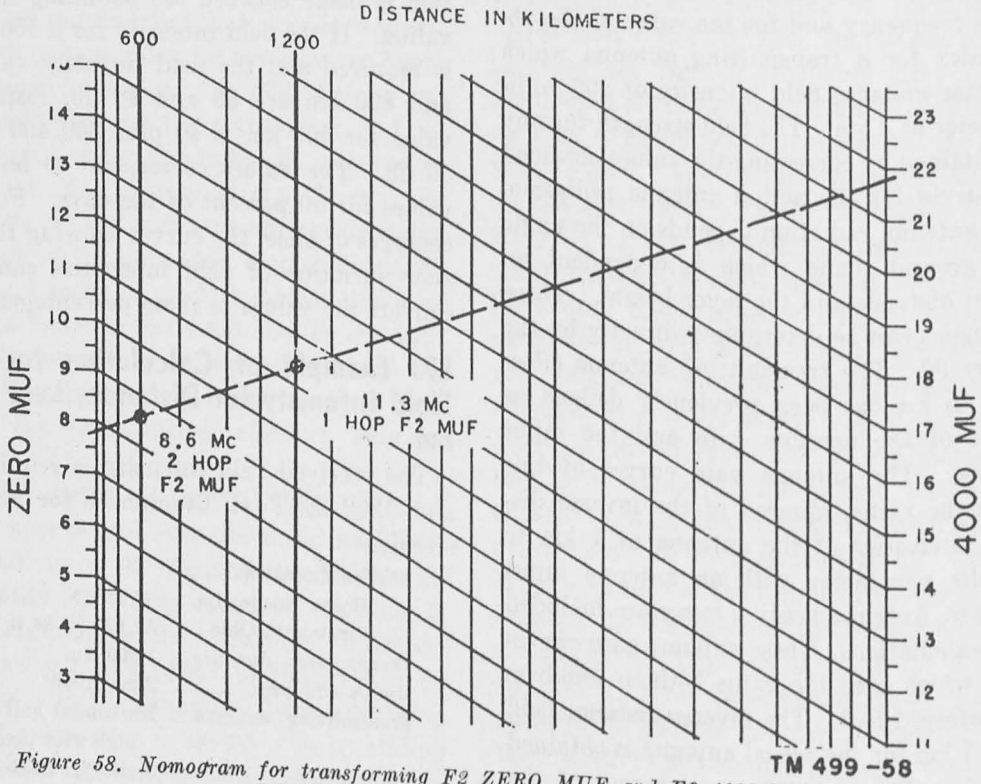


Figure 58. Nomogram for transforming F2 ZERO MUF and F2 4000 MUF to equivalent MUF's at intermediate transmission distances.

c. Place the overlay on the *K* ring for June with the equatorial lines coinciding and the time reference line set at 1200 EST. Read the *K* value at the path midpoint; the value is 0.96. From figure 119, it is seen that the seasonal correction factor is 0.7; and, from figure 118, it can be seen that the solar activity factor is 1.46. By multiplying these two factors by the *K* value, the corrected *K* is obtained; this value is 0.98. The path does not cross the auroral zone, as can be seen by placing the overlay on the auroral index map (fig. 115). See figure 60 for the reading of the absorption index, *K*.

d. Read figure 99 at the transmission distance of 1,200 km to obtain the radiation angles for the one-hop and two-hop F2 layer transmission modes and the one-hop E layer transmission mode. These angles are 25°, 44.5°, and 75°, respectively (fig.

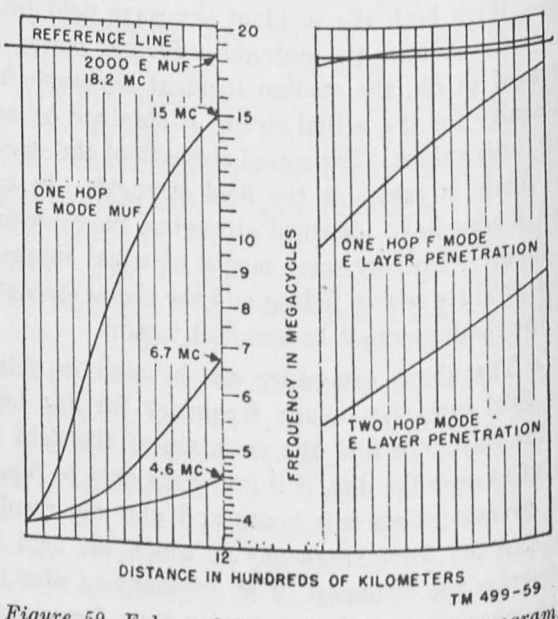


Figure 59. E layer MUF and penetration nomogram.

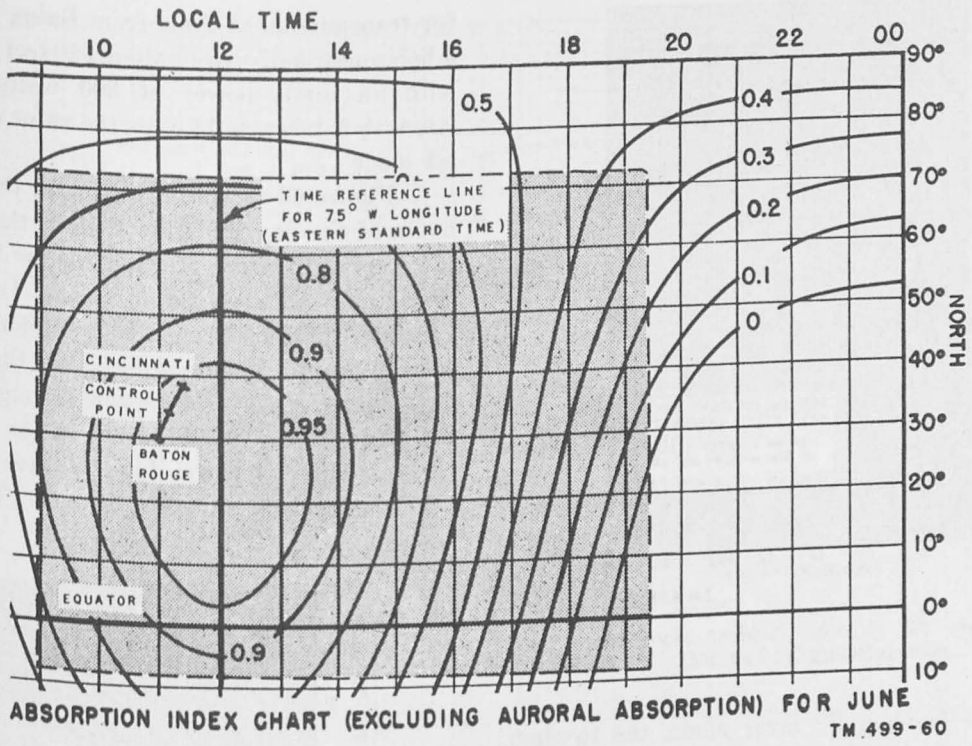


Figure 60. Overlay on absorption index chart.

61). Read the antenna curve (fig. 188) for the transmitting antenna, a half-wave horizontal 60 feet above poor earth, at the wave frequency of 8 mc. The antenna gains for these angles are 1.7, −1.3, and −5.0 db, respectively. The antenna input power is 300 watts or −5.2 db referred to kw power. The effective powers for the three modes are −3.5, −6.5 and −10.2 db referred to 1 kw. See figure 62 for the radiation of the transmitting antenna.

e. The median sky-wave field intensities for the three modes can be obtained from the curve (figs. 130–132) by reading the curves at 8 mc and an absorption index value of 0.98 for an antenna with an inverse distance field of 300 millivolts per meter at 1 km (figs. 63–65). These values are 18, 9, and

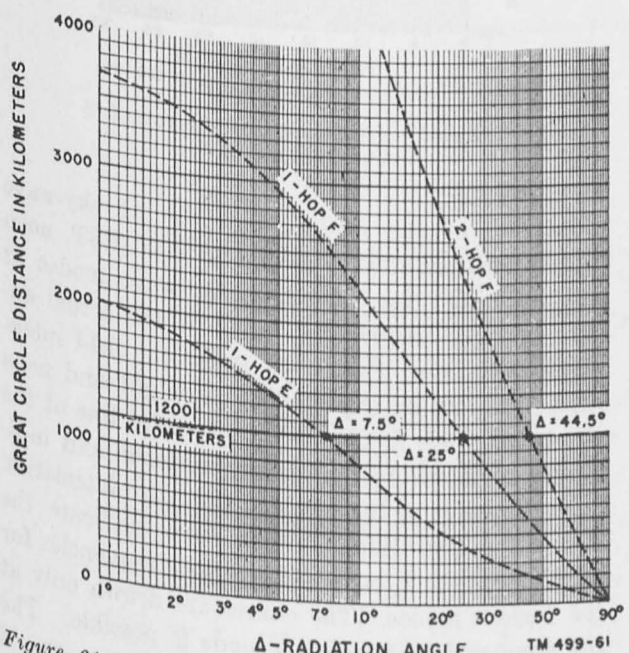


Figure 61. Radiation angle versus great circle distance.

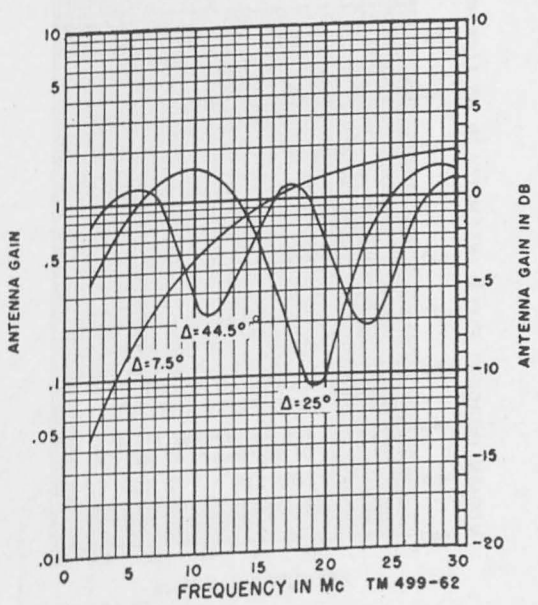


Figure 62. Gain of a half-wave horizontal antenna (erected 60 feet above ground).

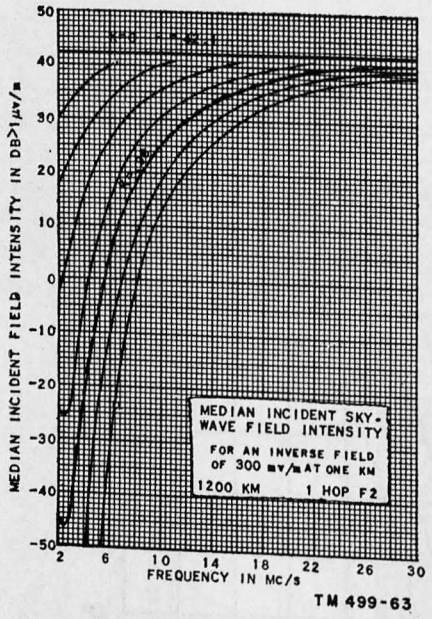


Figure 63. Median incident sky-wave field intensity (1-hop F2).

2 db for the one-hop F2 layer mode, the two-hop F2 layer mode, and the one-hop E layer mode, respectively. Adding the effective powers for the three modes —3.5, —6.5, and —10.2 db, respectively, and median sky-wave field intensities (based on 1 kw effective power) results in the following median downcoming sky-wave incident field intensities for the 1 F2, the 2 F2, and 1 E modes 14.5, 2.5, —8.2, db, respectively. The listed field intensities are those received in Cincinnati at 1200

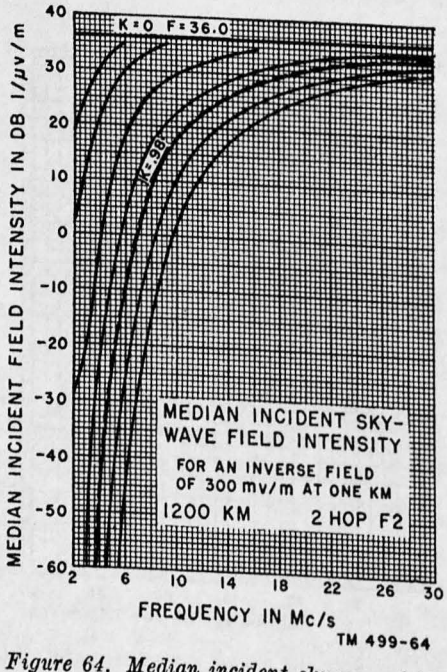


Figure 64. Median incident sky-wave field intensity (2-hop F2).

for transmission at 8 mc from Baton Rouge, using a horizontal half-wave antenna 60 feet above ground with an input power of 300 watts. The field strength is taken as 14.5 db, the value of the strongest mode.

f. Figure 66 shows the variation throughout the hours of the day for June 1946 of the MUF's and E layer penetration frequencies for the transmission circuit between Baton Rouge, Louisiana, and Cincinnati, Ohio. Table I is a tabulation of the absorption indices, the MUF's and the penetration frequencies at 4-hour intervals throughout the day for June 1946. Table II shows the variation of effective antenna power for the three transmission modes at various wave frequencies. Table III is a

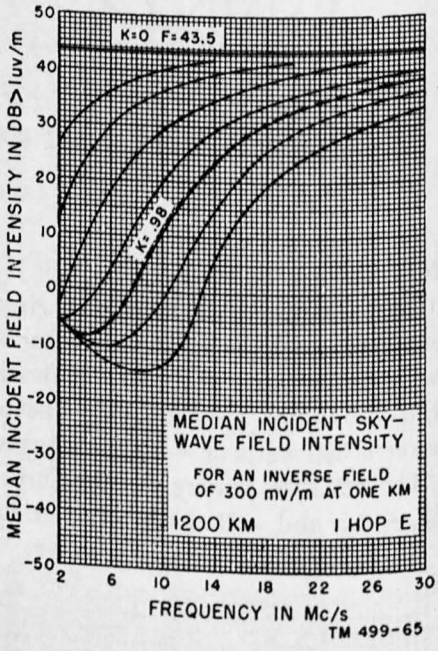


Figure 65. Median incident sky-wave field intensity (1-hop E).

tabulation of the median downcoming sky-wave field intensities at 1200 EST and 0000 EST, noon and midnight, for the three sky-wave modes at various wave frequencies, based on the actual antenna radiation. Figure 67 shows the field intensities that can be expected at midnight and noon at various wave frequencies. The solid line of the curves is drawn for the strongest mode and indicates the value of the received sky-wave intensities. Vertical dotted lines on this curve indicate the MUF's and the E layer penetration frequencies for the various modes. The curves are drawn only at the frequencies at which a mode is possible. The one-hop F2 layer mode is possible between the E

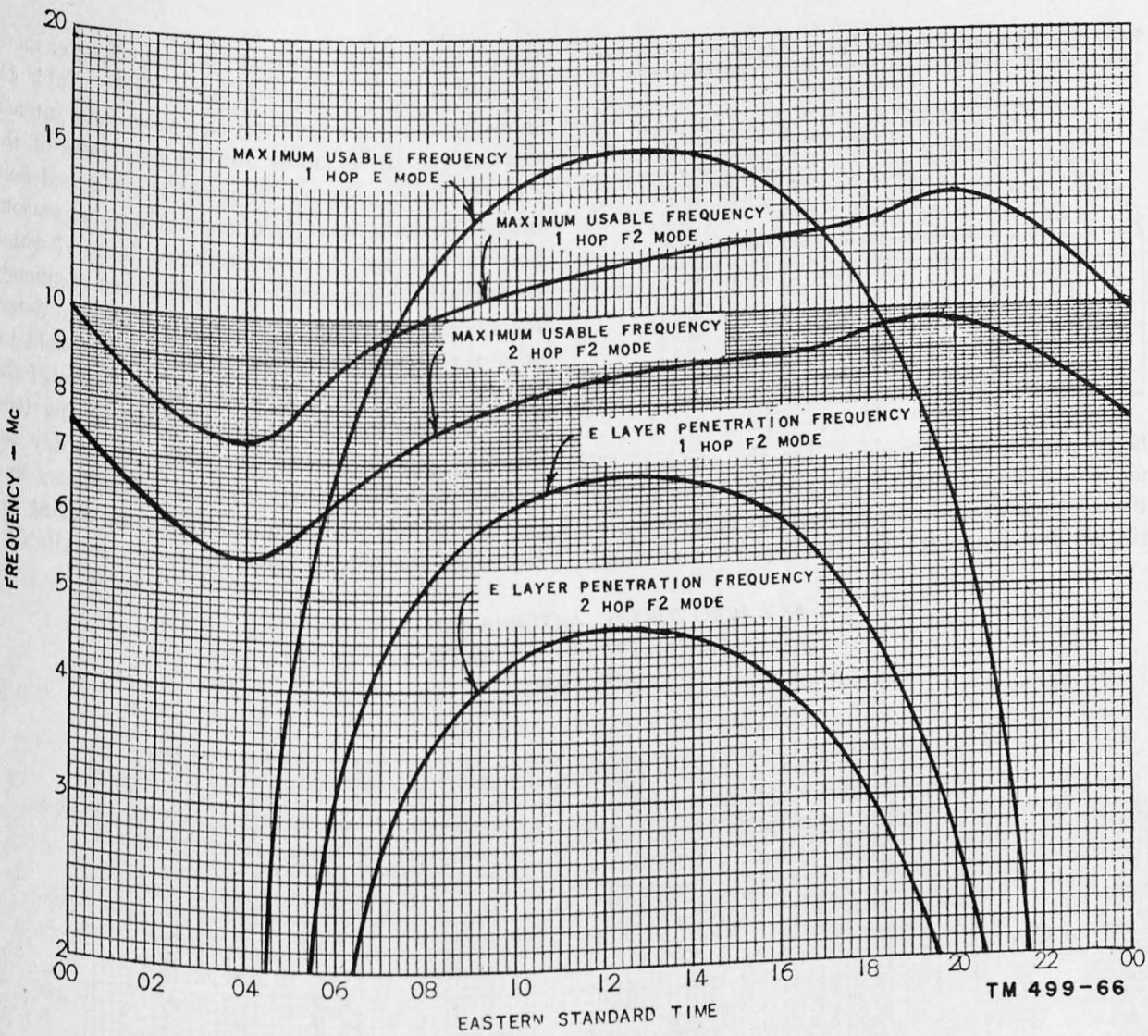


Figure 66. MUF's and E layer penetration frequencies (Baton Rouge to Cincinnati) for June 1946.

Table I. Maximum Usable Frequencies and E Layer Penetration Frequencies, Baton Rouge to Cincinnati.

(1) EASTERN STANDARD TIME	(2) ABSORPTION INDEX "K" AT CONTROL POINT	(3) CORRECTED "K" (2) X 1.46 X 0.7	(4) F2 ZERO MUF	(5) F2 4000 MUF	(6) E 2000 MUF	(7) 1 HOP F2 MODE MUF	(8) 2 HOP F2 MODE MUF	(9) 1 HOP E MODE MUF	(10) E LAYER PENETRATION FREQUENCIES: 1 HOP F2	(11) E LAYER PENETRATION FREQUENCIES: 2 HOP F2
00	---	---	6.7	19.0	---	9.9	7.5	---	---	---
04	---	---	5.0	13.7	---	7.3	5.5	---	---	---
08	.50	.51	6.7	19.7	13.9	10.1	7.5	11.2	5.1	3.4
12	.96	.98	7.7	21.8	18.2	11.3	8.6	15.0	6.7	4.6
16	.78	.80	8.1	23.6	16.4	12.1	9.0	13.5	6.0	4.0
20	.13	.13	8.6	26.8	7.3	13.3	9.7	6.0	2.7	1.8

Table II. Effective Antenna Power Half-Wave Horizontal Transmitting Antenna, 60 Feet High, Baton Rouge to Cincinnati.

Frequency in Megacycles	Xmtr Power (300 Watts) DB>1 KW	Antenna Gain in DB λ/2 Horiz 60° High			Effective Power DB>1 KW		
		1F Mode Δ = 25°	2F Mode Δ = 44.5°	1E Mode Δ = 7.5°	1F Mode (2) + (3)	2F Mode (2) + (4)	1E Mode (2) + (5)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
2	-5.2	-4.6	-1.3	-13.5	-9.8	-6.5	-18.7
3	-5.2	-3.0	-0.3	-11.5	-8.2	-5.5	-16.7
4	-5.2	-1.8	0.5	-10.0	-7.0	-4.7	-15.2
5	-5.2	-0.6	0.8	-8.5	-5.8	-4.4	-13.7
6	-5.2	0.3	0.8	-7.2	-4.9	-4.4	-12.4
8	-5.2	1.7	-1.3	-5.0	-3.5	-6.5	-10.2
10	-5.2	2.0	-5.5	-3.2	-3.2	-10.7	-8.4
12	-5.2	1.2	-6.0	-2.0	-4.0	-11.2	-7.2
14	-5.2	-1.0	-3.2	-0.8	-6.2	-8.4	-6.0

layer penetration frequency for the one-hop F2 mode and the one-hop F2 layer MUF; the two-hop F2 layer mode is possible between the E layer penetration frequency for the two-hop F2 mode and the F2 layer MUF, while the one-hop E layer mode is possible up to one-hop E layer MUF. Table IV shows median downcoming sky-wave field intensities for the three modes for various hours of the day for 6 mc. Figure 68 shows the received field intensities for a wave frequency of 6 mc at various hours of the day. Curves similar to figure 67 which show the field intensities plotted against frequency for various hours of the day can be used to determine the frequency at which the greatest field intensity can be obtained at the various hours of the day. Curves similar to figure 68 show the field intensity plotted against the hours of the day for transmission for a particular wave frequency and can be used to show the number of hours during the day when the chosen wave frequency is suitable.

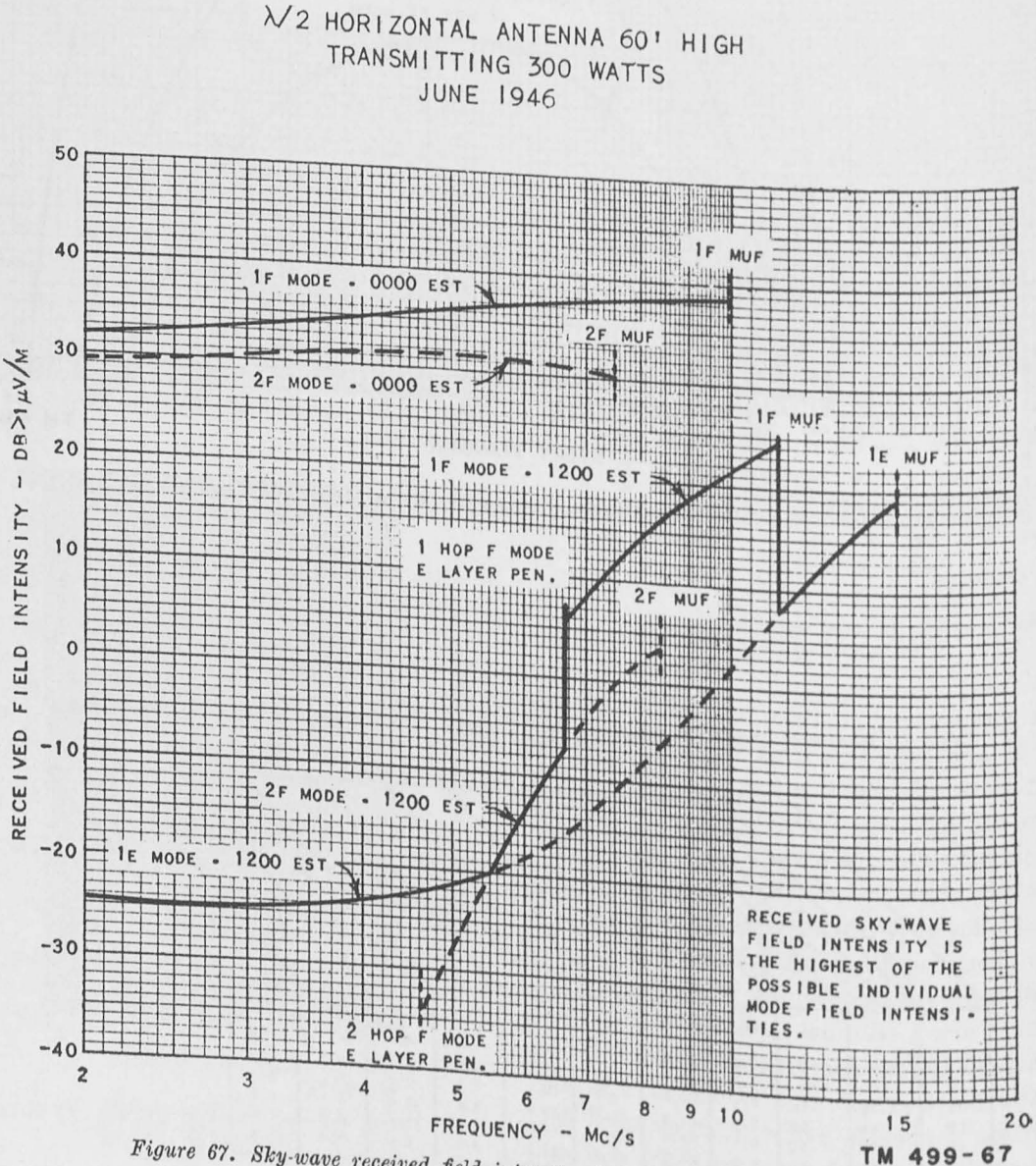


Figure 67. Sky-wave received field intensity (Baton Rouge to Cincinnati).

Table 111. Sky-Wave Received Field Intensity, Baton Rouge to Cincinnati.

		1200 EST K=.98					0000 EST K=0			
		FIELD INTENSITY FOR 300 MV/M AT ONE KILOMETER			FIELD INTENSITY BASED ON THE EFFECTIVE POWER			FIELD INTENSITY FOR 300 MV/M AT ONE KILOMETER		FIELD INTENSITY BASED ON THE EFFECTIVE POWER
FREQUENCY IN MEGACYCLES	1 HOP F MODE	2 HOP F MODE	1 HOP E MODE	1 HOP F MODE	2 HOP F MODE	1 HOP E MODE	1 HOP F MODE	2 HOP F MODE	1 HOP F MODE	2 HOP F MODE
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
2	-45.0		-5.5	-54.8		-24.2	42.1	36.0	32.3	29.5
3	-42.0		-8.0	-50.2		-24.7	42.1	36.0	33.9	30.5
4	-20.0	-45.0	-8.0	-27.0	-49.7	-23.2	42.1	36.0	35.1	31.3
5	-6.5	-22.5	-7.5	-12.3	-26.9	-21.2	42.1	36.0	36.3	31.6
6	5.0	-9.0	-5.5	0.1	-13.4	-17.9	42.1	36.0	37.2	31.6
8	18.0	9.0	2.0	14.5	2.5	-8.2	42.1	36.0	38.6	29.5
10	25.0	17.5	11.0	21.8	6.8	2.6	42.1	36.0	38.9	25.3
12	30.0	22.5	18.0	26.0	11.3	10.8	42.1	36.0	38.1	24.8
14	33.0	25.5	23.0	26.8	17.1	17.0	42.1	36.0	35.9	27.8

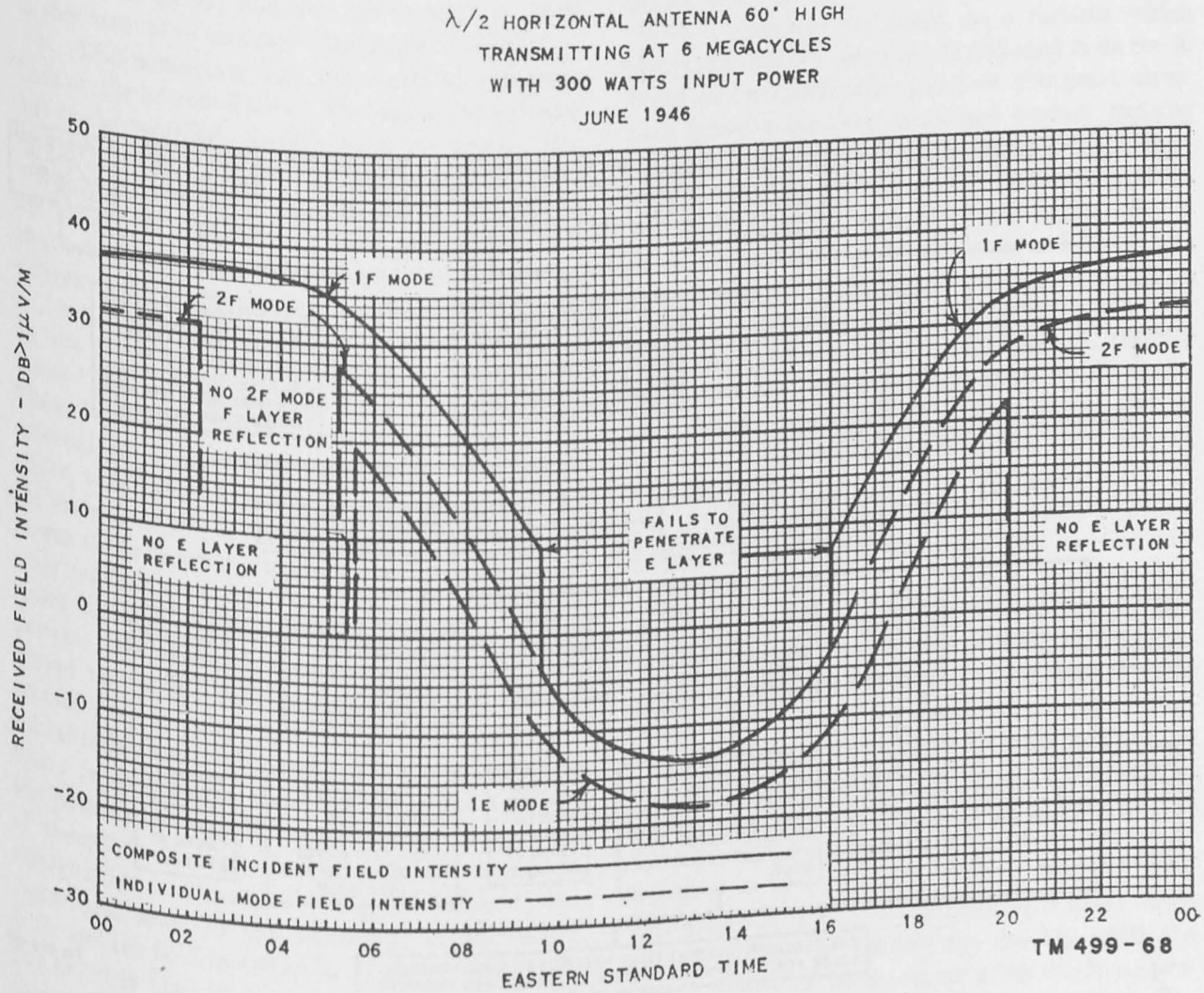


Figure 68. Received field intensity (Baton Rouge to Cincinnati).

Table IV. Received Field Intensity, Baton Rouge to Cincinnati.

EASTERN STANDARD TIME	CORRECTED "K"	FIELD INTENSITY 300 MV/M AT ONE KILOMETER			FIELD INTENSITY BASED ON THE EFFECTIVE POWER		
		1 HOP F MODE	2 HOP F MODE	1 HOP E MODE	1 HOP F (3)-4.9 DB	2 HOP F (4)-4.4 DB	1 HOP E (5)-12.4 DB
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
00		42.1	36.0		37.2	31.6	
04		42.1	36.0		37.2	31.6	
08	.51	25.0	16.0	16.5	20.1	11.6	3.6
12	.98	5.0	-8.5	-5.5	0.1	-12.9	-17.9
16	.80	12.0	1.0	0.5	7.1	-3.4	-11.9
20	.13	38.0	33.0	35.0	33.1	28.6	22.6

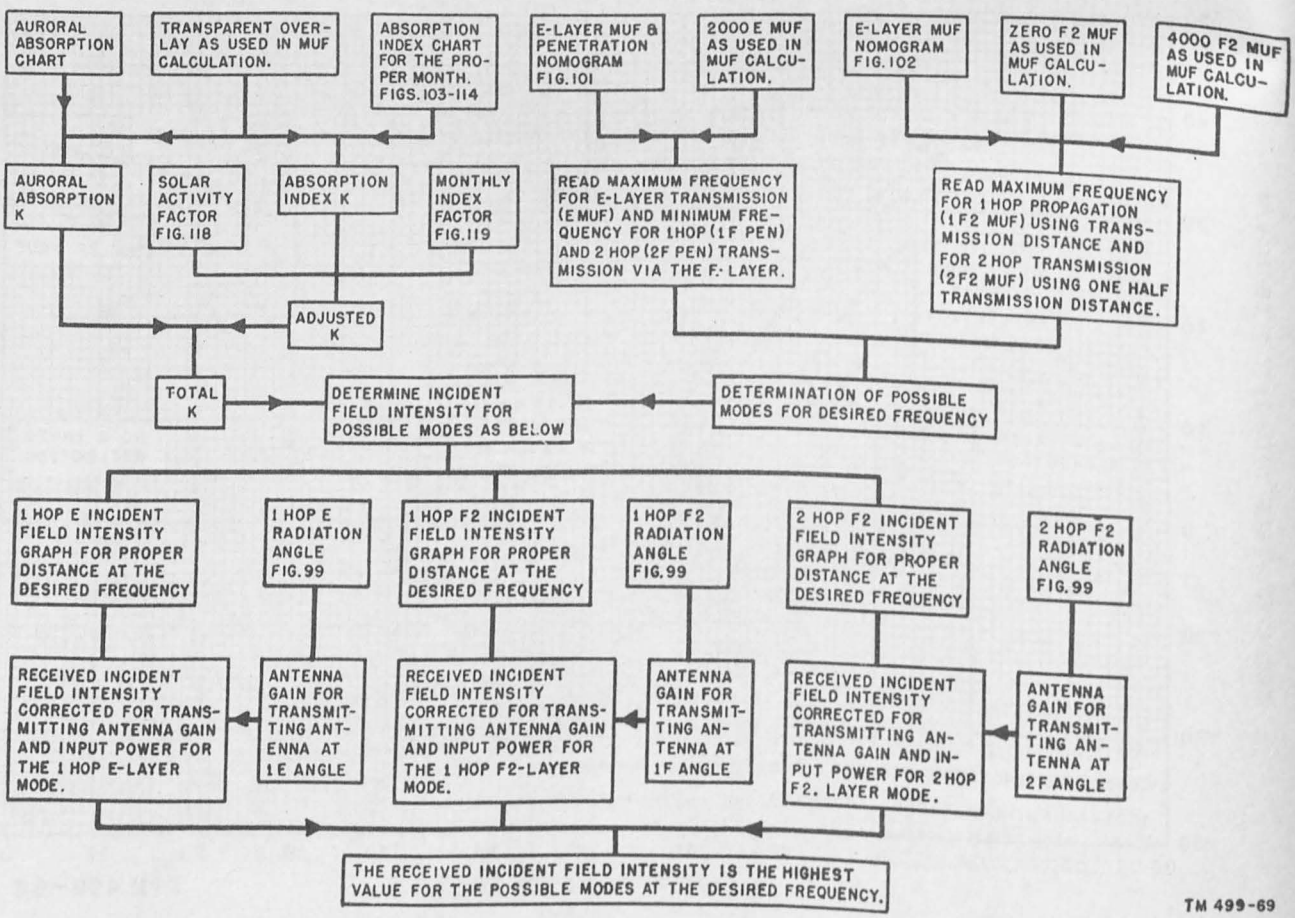


Figure 69. Flow chart, received incident field intensity calculation, 0 to 3,000 km.

Section V. CALCULATIONS FOR SKY-WAVE FIELD INTENSITIES FOR DISTANCES GREATER THAN 3,000 KM

88. Explanation of Methods

a. Median downcoming incident field intensities are obtained from 1 to 30 mc for distances greater than 3,000 km by using figure 141. The field intensity can be obtained by the nomogram, provided the absorption index, the transmission distance, the wave frequency, and the modified effective power are known. This nomogram is based on transmission modes of low radiation angles. The ground reflection losses are included along with the polarization fading losses. Ground-reflected components at the receiving location are not included. This nomogram can be used for transmission at radiation angles up to about 15°, since the angles of wave arrival are difficult to determine for long-distance transmission paths; however, no attempt is made in this manual to use any other angle than 5°.

b. The nomogram has two vertical reference lines on the left-hand side. The one to the extreme left is the *modified effective power* reference line, while the other is the distance in *thousands of kilometers* reference line. On the right-hand side of the nomogram is a vertical scale marked the $\overline{K}d$. Between the $\overline{K}d$ and the *thousands of Kilometers* reference lines are vertical frequency lines with a 1-mc line on the right and the 30-mc line on the left. Radiating from the zero $\overline{K}d$ value toward the left are straight lines forming a fan. These lines are marked in field intensities in db referred to 1 microvolt per meter. The power slider, which should be copied and used as a movable scale, is at the bottom of the nomogram. This power slider is set vertically so that the numbered scale marked *modified effective power in decibels* is set on the effective power reference line at the extreme left of the nomogram and the slider is moved vertically until the effective power of the transmitting antenna is coincident with the horizontal index mark of the effective power reference line. In addition to the effective power scale on the power slider, there is a distance scale in terms of thousands of km. To find a field intensity, a straightedge is placed from the $\overline{K}d$ value on the right-hand scale to the *thousands of kilometers* scale and the field intensity in db above 1 microvolt per meter is read on the field intensity grid at the intersection of the straightedge and the vertical line corresponding to the wave frequency, the power slider being set so that the index line lies on the transmitting antenna effective power.

c. For transmission paths greater than 3,000 km in length, $\overline{K}d$ is used as the absorption index. For these long distances, the absorptions correlate with the average value of K over the transmission path and not the K at the center point of the path. Due to the multiplicity of ionospheric reflection points, the K value at the midpoint of the path is not sufficient as an absorption index. The variable relating the angle of the sun and a nondeviative ionospheric absorption for long paths is the K value averaged over the transmission path multiplied by the path length in the daylight region. The $\overline{K}d$ values are obtained in this manual by the use of nomograms. These nomograms are based on a formula which shows that the $\overline{K}d$ value can be obtained from the K value at one particular point on the great circle path between the transmitter and receiver and the path length in the daylight region. For a completely night path, the $\overline{K}d$ value obviously is zero. For paths entirely in the daylight region, the K value at the midpoint of the path and the transmission distance in thousands of km are all that is required (fig. 116). For paths partly in the daylight region, the $\overline{K}d$ can be obtained by reading the K value at the end of the path which lies in the daylight region and the length of the portion of the path in the daylight region in thousands of km (fig. 117).

d. To find the sky-wave field intensity for a long-distance circuit, it is necessary first to find out whether transmission is possible at the wave frequency. The wave frequency must be less than the MUF for the route. An overlay is prepared, as shown under the calculation of MUF's. A piece of transparent paper is placed on the world map (fig. 97), and the station positions are marked. A horizontal line is drawn at the equator and a vertical line is drawn at the longitude value which is desired as the time reference. This overlay then is placed on the great circle chart (fig. 98), with the equatorial lines coinciding and the great circle path is located by sliding the overlay until the station points lie on the same great circle or proportional distances between two great circles. The

dash-dotted scale of the great circle path is used to locate the path midpoint and control points at 2,000 km from the path ends, provided the path length is greater than 4,000 km. For path lengths less than 4,000 km, the MUF is obtained for the F2 layer by placing the overlay on the prediction charts corresponding to the zone in which the path midpoint lies. The F2 ZERO MUF and the F2 4000 MUF are read at the midpoint by placing the overlay on the predictions with the equatorial lines coinciding and the time reference lines set at the desired hour. Using these two MUF's for the standard distances of zero and 4,000 km, the F2 layer MUF's for the transmission distance is read on the F2 layer MUF nomogram. At distances greater than 3,000 km, the F2 layer MUF generally exceeds the E layer MUF. The possibility of E layer support can be checked by laying the overlay on E 2000 MUF predictions with equatorial lines coinciding and the time reference set at the desired hour and reading the MUF at the path midpoint. This E 2000 value and the transmission distance can be used in the E layer nomogram to find the E layer MUF for transmission distance. For path lengths greater than 4,000 km, the overlay is placed on the F2 4000 MUF charts corresponding to the zone in which the control points lie, with the equatorial lines coinciding and the time reference line set at the desired hour. The MUF is read at the 2,000-km control points. The lower of the two MUF's for the two control points is the MUF for the route. For transmission to be possible, the wave frequency must be lower than the MUF for the circuit.

e. This overlay now is placed on the K ring for the particular month with the equatorial lines coinciding and the time reference line set at the desired hour. If all the transmission path lies in the daylight (K is greater than zero for the entire path), the K value is read at the center of the path. If the entire path does not lie in daylight, mark the point where K is zero and read the K value at the other end of the daylight portion. The length of the path in the daylight can be obtained by placing the overlay back on the great circle chart. The dot-dashed lines can be used to determine the length of the line within the daylight portion of the path. Thousands of km points usually are marked on the overlay in the initial operation when the overlay is prepared. If these points are marked on the great circle path, it is not necessary to place the overlay back on the great circle chart since the points can be used to estimate the length of the great circle path. To obtain the $\overline{Kd}$ value for a circuit entirely in daylight, the K (km) value at the path midpoint and the transmission distance are used with the daylight nomogram (fig. 116). For paths partly in the daylight region, the K value (K1) at the end point which lies in the day region and the path length in the day region are used with the part daylight $\overline{Kd}$ nomogram (fig. 117). If both end points of a path lie within daylight but the path crosses the night region, the $\overline{Kd}$ is obtained for each daylight portion separately and the results are added. If the path length is greater than the range of the nomogram, the $\overline{Kd}$ value is obtained by dividing the path into two sections. The $\overline{Kd}$ value obtained for each separate section and the values for the two sections then are added. Using figures 119 and 118, the $\overline{Kd}$ is corrected for seasonal and solar activity variations by multiplying the seasonal and solar activity factors by the $\overline{Kd}$ value.

f. In case the transmission path crosses an auroral region, the auroral $\overline{Kd}$ value must be added to the normal $\overline{Kd}$. The overlay is placed over the auroral index map (fig. 115) with the station points on the corresponding locations on the map (the auroral index map is drawn for latitudes and longitudes since no time variation is assumed in the auroral activity throughout the day). The K_a value is read at several short intervals along the portion of the path within the auroral region and these values are averaged. The K_ad is equal to the product of the average K_a by the distance in thousands of km in the auroral region. The $\overline{Kd}$ value for a path that crosses the auroral zone is equal to the sum of the auroral K_ad and the corrected normal $\overline{Kd}$.

g. The radiation angle for transmission paths greater than 3,000 km is taken as 5° in this manual. To find the received field intensity, the transmitting antenna effective power must be known. This power was defined in kw as the product of the antenna gain and the antenna input power in kw. In db, the effective power is equal to the antenna gain expressed in db referred to 1 plus the antenna input power expressed in db deferred to 1 kw. The power slider of the field intensity nomogram for 3,000 km and greater (fig. 141), has a scale marked as modified effective power in db referred to 1 kw. For field intensity calculations, the modified effective power is simply the effective power of

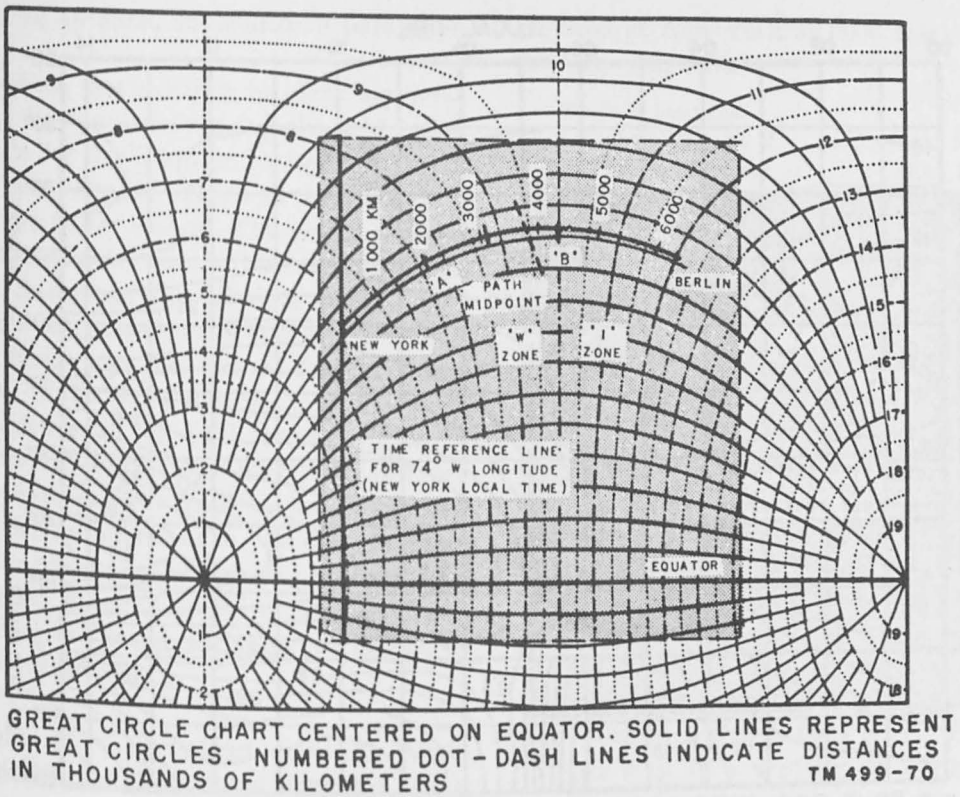


Figure 70. Overlay on great circle chart.

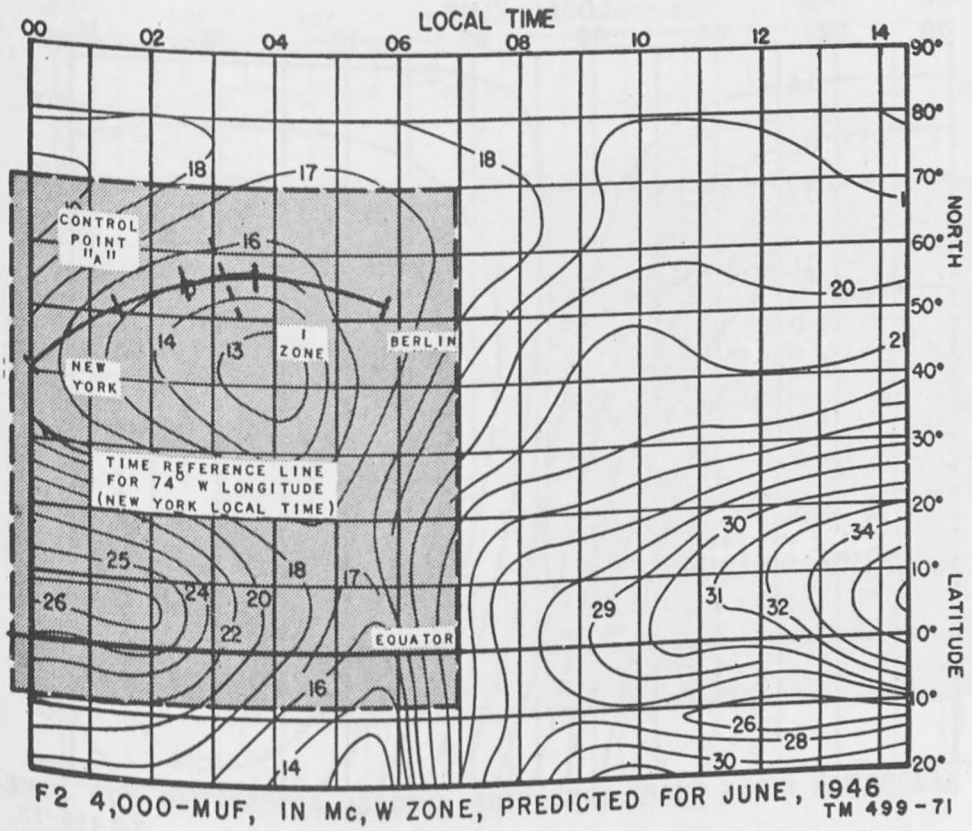


Figure 71. Overlay on F2 4000 MUF, W zone, chart.

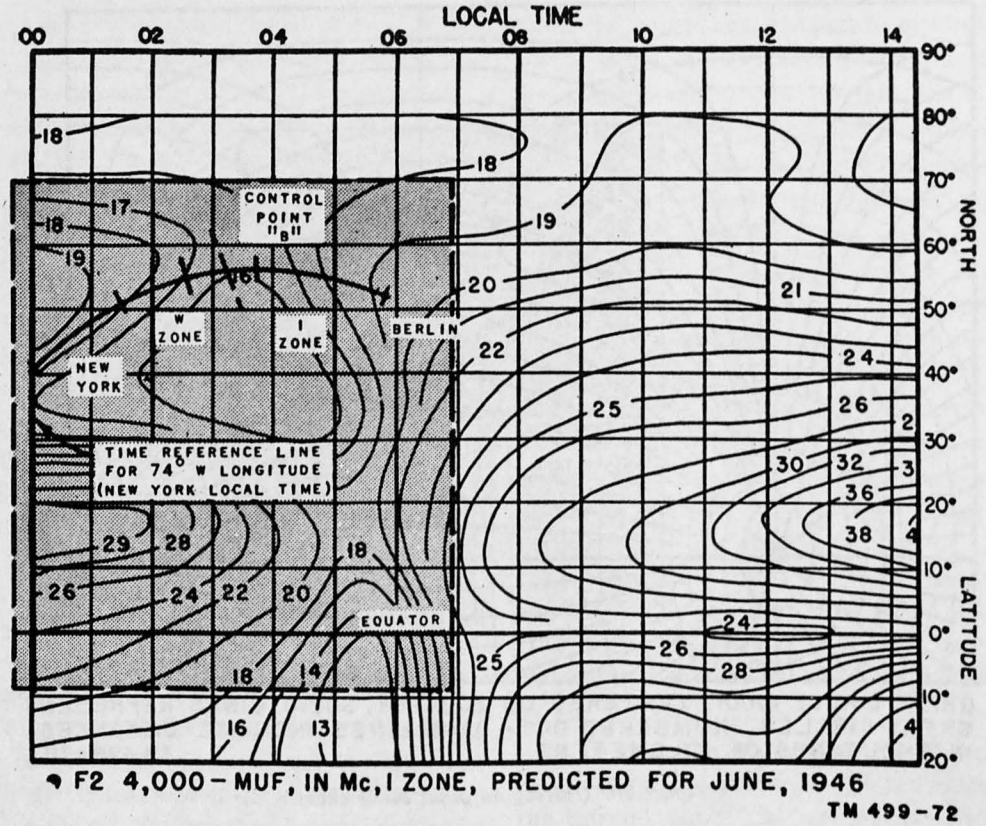


Figure 72. Overlay on F2 4000 MUF, I zone, chart.

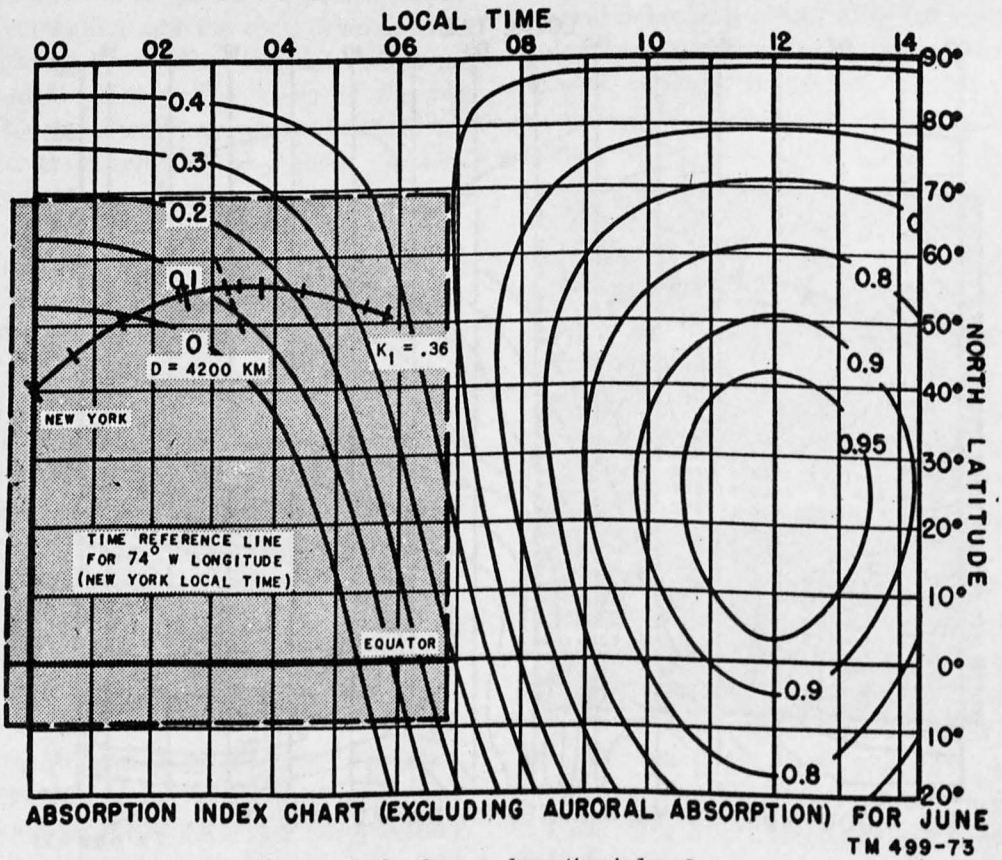


Figure 73. Overlay on absorption index chart.

the transmitting antenna, as defined in paragraph 79.

h. The median downcoming incident sky-wave field intensity is obtained by using the field intensity nomogram for 3,000 km and greater with the straightedge set at the $\overline{Kd}$ value and the distance in km scale on the power slider. The power slider is set so that the effective power lies over the horizontal index line along the effective power index line. The field intensity is read at the intersection of the straightedge and the vertical frequency line corresponding to the wave frequency in mc. This value is indicated in the field intensity grid in microvolts per meter referred to 1 microvolt per meter. The values correspond to hourly median value for 50 percent of the days. In case the value is required for other percentages, the received field intensity can be adjusted by using figures 30 and 31, which show the rapid and slow variations of field intensity with time.

89. Example of Calculation for Sky-Wave Field Intensity for Distances Greater than 3,000 km

The received incident sky-wave field intensity is required at New York at 0000 local midnight for the following circuit:

Stations locations:	
New York, N. Y.	40.8° N, 74.0° W
Berlin, Germany	52.6° N, 13.2° E
Transmission distance	6,400 km
Transmitter power	10 kw
Transmitting antenna	Type A rhombic over poor ground
Month and year	June 1946

a. Lay a piece of transparent paper over the world map (fig. 97). Mark the station location and sketch in the zone dividing line. Draw in a horizontal line at the equator and a vertical reference line through the position of New York. By drawing the time reference line through the receiving location at New York, the hours are the local hours at New York. The local time at New York differs from EST because of the 1° difference (longitude of New York 74.0 W) in longitude. Since 1° of longitude corresponds to 4 minutes of time, 0000 New York local time is 0004 EST. The sun moves 15° per hour in a westerly direction. Place this overlay on the great circle chart (fig. 98) with the equatorial lines coinciding and slide horizontally until the station location lies at proportional dis-

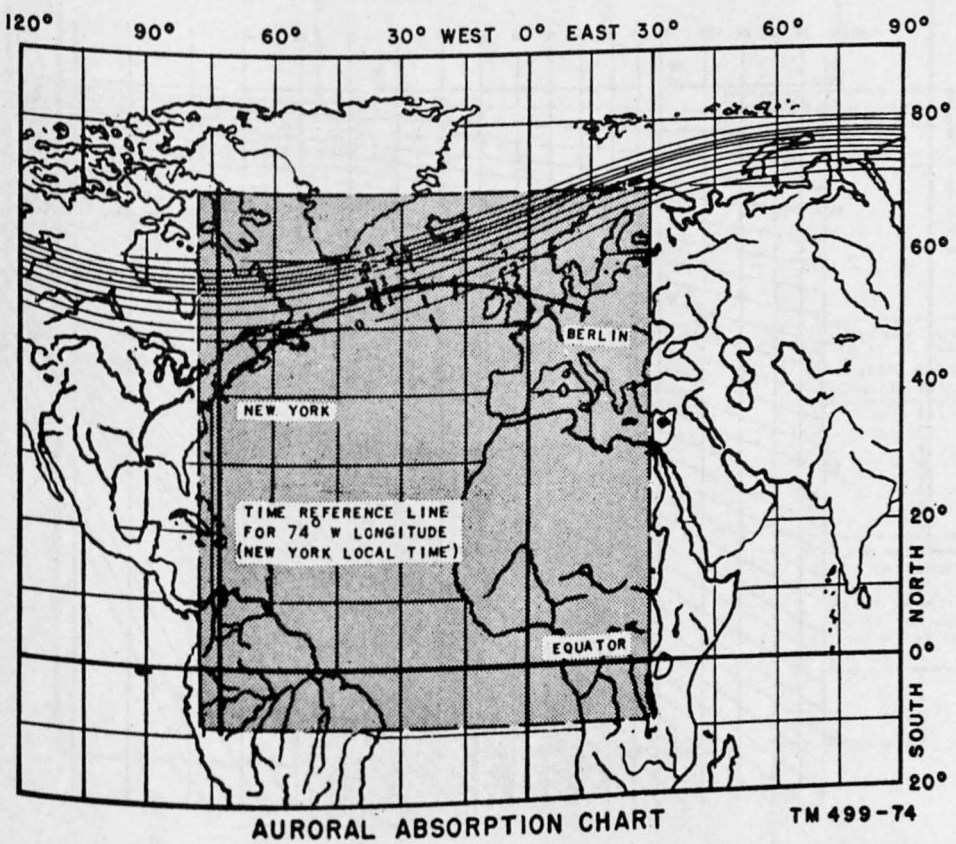


Figure 74. Overlay on auroral absorption chart.

tances between two adjacent great circles. Sketch in the great circle path and, using the dash-dotted lines of the great circle chart as a distance scale, mark the path midpoint and the control points at 2,000 km from the ends of the path. Also lightly mark in points at 1,000-km distances from the New York location. Note in which zone the control points lie and label them according to the zones. The westerly one is marked "A," while the other is marked "B" (fig. 70).

b. Place the overlay on the F2 4000 MUF prediction chart for the W zone for June 1946 with the equatorial lines coinciding and the time reference line set at 0000 and read the value for control point A. Repeat the process, using the I zone F2 4000 MUF chart for June 1946 and read at the B control point. The two values are 15.3 and 16.2 mc. The MUF for the circuit is the lower of these values. Communication is possible at the 14 mc wave frequency since it is below the MUF for the hour. See figures 71 and 72 for the MUF readings.

c. Place the overlay on the K ring for June (fig. 108) with the equatorial lines coinciding and the time reference line set at 0000 local time. It is noted that not all the circuit is in daylight at this hour. Following the procedure for partly daylight paths, read the K value at the end of the path in the daylight region. The K_1 for the daylight point (Berlin) is 0.36. Using the 1,000-km points, estimate the path in the daylight region. The portion of the path is 4,200 km. With this K_1 value and the distance in the daylight path, the $\overline{Kd}$ can be obtained from nomogram (fig. 117). This value is 0.81. The seasonal index factor for June is 0.7 and the solar activity factor for June 1946 is 1.46, as indicated in figures 119 and 118. Had the field intensity been required for 1200 local time, the path would have been entirely in the daylight re-

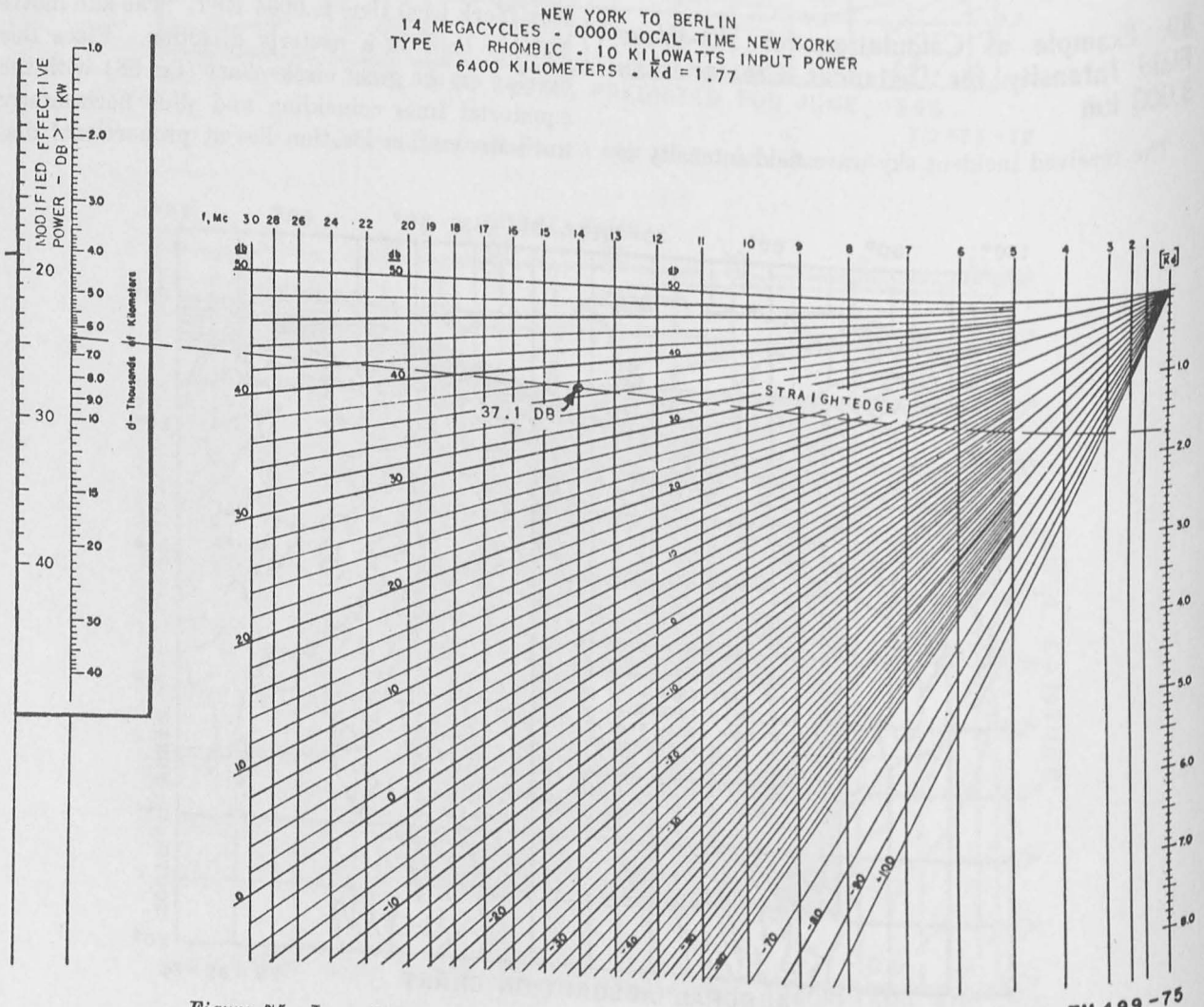


Figure 75. Long distance received field intensity example (New York to Berlin).

gion. In this case, the K would have been read at the center of the path and the $\overline{K}d$ would have been obtained from the nomogram for daylight paths (fig. 116). The corrected $\overline{K}d$ at 0000 local time at New York is the product of the $\overline{K}d$ from the nomogram, the seasonal correction factor, and the solar activity factor. The $\overline{K}d$ value is 0.81 times 0.7 times 1.46 or 0.83. See figure 73 for the reading of the K value.

d. Place the overlay over the auroral index chart (fig. 115) with the equatorial lines coinciding with the position marks of the overlay placed over their positions on the chart. Read the auroral Ka values at intervals of approximately 500 km within the portion of the path in the auroral zone and estimate the length of the path in thousands of km. Average the K values and multiply by the length of the path in the auroral zone in km. The average Ka value is 0.27 and the path length in the auroral zone is 3.5 thousand km. The auroral $\overline{K}d$ is the product of the two, or 0.94. The $\overline{K}d$ value for the transmission path is the sum of the auroral $\overline{K}d$ and the corrected $\overline{K}d$; it is 1.77 at 0000 local time New York. See figure 74 for the Ka reading.

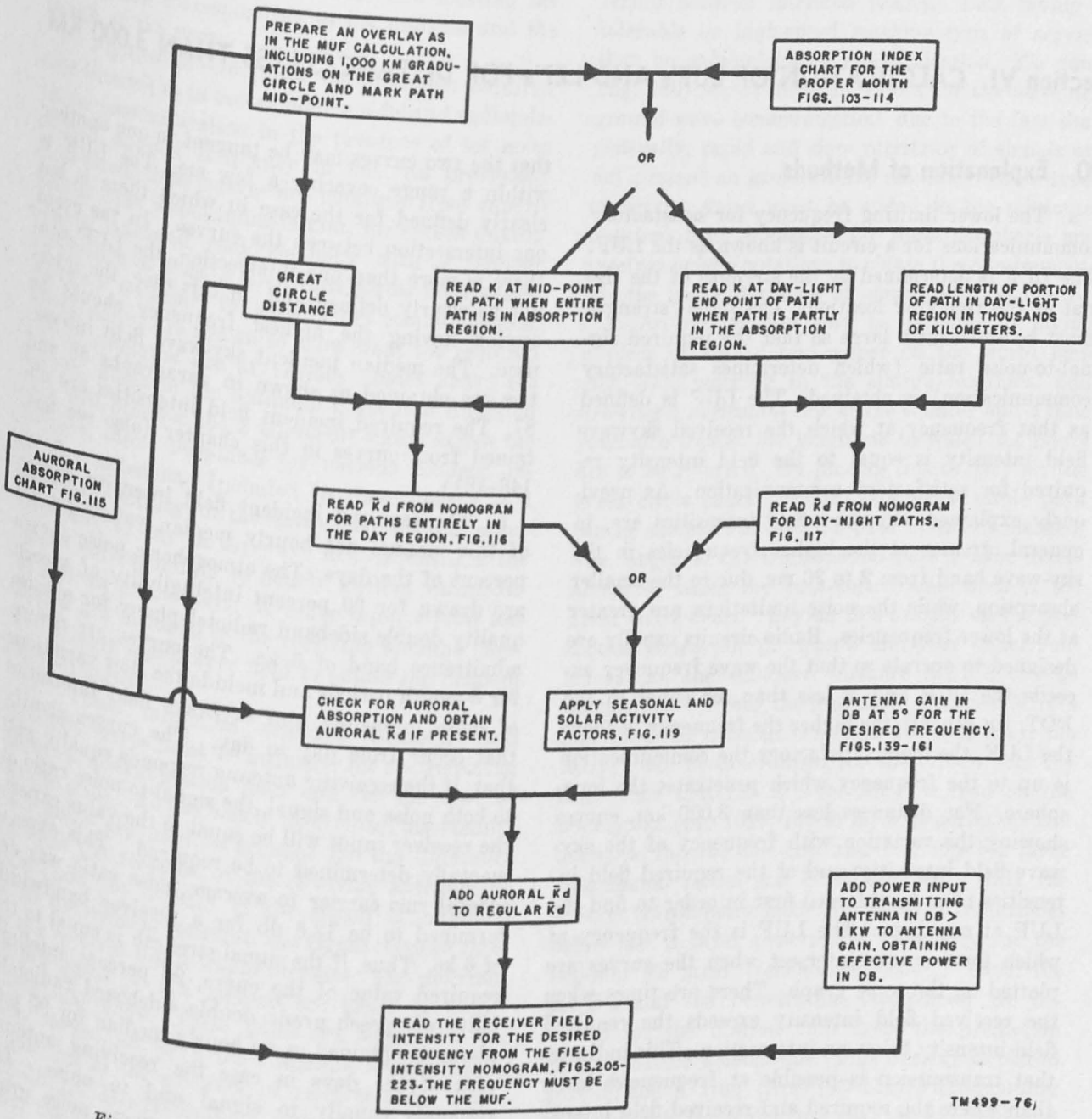


Figure 76. Flow chart, received incident field intensity calculation (3,000 km and greater).

e. The transmitting antenna for the circuit was shown as Signal Corps type A rhombic antenna. This antenna has sides 375 feet long and an interior angle of 70°. The antenna is constructed horizontally 65 feet above the earth. Figure 191 indicates the gain for this antenna for the transmission frequency of 14 mc and an optimum radiation angle of 5°. The antenna gain is 7.7 and the antenna input power is 10 kw. Thus, the effective power is the product of these: 77 kw. Expressed in db, the effective power is 18.9 db referred to 1 kw. See figure 266 for the conversion of powers into db. The median incident sky-wave field intensity now can be found, since the $\overline{K}d$ value, the modified effective power, the transmission distance, and the wave frequency are known. Setting the power slider (figs. 75 and 141) with the modified effective power set at 18.9 db on the horizontal index mark and a straightedge set between the $\overline{K}d$ value of 1.77 to the transmission distance of 6,400 km, the field intensity value is read at 14 mc. The field intensity is 37.1 db above 1 microvolt per meter or 70.3 microvolts per meter at midnight in New York for a wave frequency of 14 mc.

Section VI. CALCULATION OF LUF's AND LEP's FOR DISTANCES LESS THAN 3,000 KM

90. Explanation of Methods

a. The lower limiting frequency for satisfactory communications for a circuit is known as the LUF. The LUF is determined by the strength of the signal at the receiving location. The signal strength must be sufficiently large so that the required signal-to-noise ratio (which determines satisfactory communication) is obtained. The LUF is defined as that frequency at which the received skywave field intensity is equal to the field intensity required for satisfactory communication. As previously explained, sky-wave field intensities are, in general, greater at the higher frequencies in the sky-wave band from 2 to 30 mc, due to the smaller absorption, while the noise limitations are greater at the lower frequencies. Radio circuits usually are designed to operate so that the wave frequency exceeds the LUF and is less than, or equal to the FOT. In general, the higher the frequency is above the LUF, the more satisfactory the communication is up to the frequency which penetrates the ionosphere. For distances less than 3,000 km, curves showing the variation with frequency of the sky-wave field intensities and of the required field intensities must be obtained first in order to find the LUF at any hour. The LUF is the frequency at which these curves intersect when the curves are plotted on the same graph. There are times when the received field intensity exceeds the required field intensity below an intersection. This indicates that transmission is possible at frequencies lower than where the required and received field intensities are equal. In addition, there is a possibility that the two curves may be tangent to one another within a range covering a few mc. The LUF is clearly defined for the case in which there is but one intersection between the curves. In the event there is more than one intersection, the LUF cannot be clearly defined and, in this case, the intersection having the highest frequency should be used. The median incident sky-wave field intensities are obtained as shown in paragraphs 86 and 87. The required incident field intensities are obtained from curves in this chapter (also see figs. 146–181).

b. The required incident field intensity curves of this manual are hourly median values for 90 percent of the days. The atmospheric noise curves are drawn for 90 percent intelligibility of speech quality double sideband radiotelephony for a noise admittance band of 6 kc. The curves are drawn for 3-month periods and include the slow variations of noise intensities and sky-wave field intensities that occur from day to day. The curves signify that, if the receiving antenna responds equally well to both noise and signal, the signal-to-noise ratio at the receiver input will be equal to the value experimentally determined to be required. This experimental rms carrier to average noise ratio was determined to be 13.8 db for a receiver bandwidth of 6 kc. Thus, if the signal strength is equal to the required value of the curve, 90 percent intelligibility of speech grade double sideboard radiotelephony is obtained as an hourly median for 90 percent of the days in case the receiving antenna responds equally to signal and to noise. The noise curves are drawn for various noise grade

values, a low noise grade number indicating a lower atmospheric noise than a high one. Figures 142–145 show the world-wide variation of noise grades for each of four 3-month periods. In figures 146–164, the minimum required field intensities to assure radiotelephone communication in the presence of atmospheric noise are plotted against frequency in mc for three seasonal periods, for noise grades 1.0, 1.5, 2.0, 2.5, and 3.0, while only one curve is drawn for noise grades 3.0, 3.5, 4.0, 4.5, and 5.0. The user can determine what the noise grade is at the receiving location by looking at the world noise distribution maps (figs. 142-145) and locating the noise grade corresponding to his position and the month of the year.

c. Figures 165–181 show the minimum required field intensities to assure double sideband radiotelephone communication in the presence of set noise plotted against frequency in mc. As previously mentioned, these curves are obtained from experimental data which indicate that, for speech quality double sideband radiotelephony with a receiver bandwidth of 6 kc, 2 microvolts across the receiver input are necessary for satisfactory communication. These curves are drawn to show what the required signal strengths are at various angles above the ground plane in the optimum horizontal direction that will produce the 2 microvolt signal across the receiver input terminals for various common receiving antennas. Included in these curves is a factor accounting for the slow variations that occur from day to day in sky-wave field intensities, the curves corresponding to hourly median values for 90 percent of the days. Average input circuit loss factors are included in the receiving antenna effective heights which were used to obtain the incident field strength.

d. These minimum required incident field strength curves must be adjusted for the receiving antenna discrimination gain and for the type of service gain. As previously mentioned, discrimination gains are used to account for the difference between the response of the receiving antenna for noise and for signal. If the signal is amplified while the noise is constant, the signal-to-noise ratio at the receiver input would increase. The discrimination gains of this manual are based on omnidirectional noise. These gains are shown on the same curves that show the minimum required field intensities in the presence of receiver noise (figs. 165–181). Discrimination gains are subtracted from the minimum required field intensity in the presence of atmospheric noise. If set noise is the limiting factor, these gains are not used.

e. Figure 120 shows the types of service gains. These gains show the relative signal strengths required for various moduation methods and intended usages. A higher signal-to-noise ratio is required for higher quality services. These types of service gains show the relative required signal-to-noise ratios with respect to the reference speech quality type of communication. Fading factors, accounting for rapid variations in field intensities are included in these service gains, the factor differing between intended usages. Less fading is tolerable on high-speed machine type of services than on radiotelephone communication. The table (fig. 120) shows different values for sky-wave and ground-wave communication, due to the fact that, generally, rapid and slow variations of signals are not present on ground-wave circuits. These types of service gains must be added to the minimum required field intensities for the atmospheric and receiver noise limitations to obtain the requirements for the particular type of communication used.

f. An overlay first must be prepared by laying a piece of transparent paper on the world map (fig. 97), marking in the station locations, and drawing a horizontal line at the equator and a time reference line at the longitude to which the hours are to be referred. By placing this overlay on the great circle chart (fig. 98), the great circle path can be sketched in and the path midpoint marked. The length of the transmission path can be determined by using the dash-dotted scale lines of the great circle chart. Laying this overlay on the prediction charts for the month and year under consideration, the standard distance MUF's can be determined. From the standard distance MUF's and the MUF nomograms (figs. 100 and 102), the MUF's can be determined for the circuit. At the same time that the E layer MUF is read on the nomogram (fig. 101), the E layer penetration frequencies for the one-hop and two-hop F2 layer tranmission modes can be determined. Only the E layer transmission mode is possible at frequencies below the E layer penetration frequency for the two-hop F2 layer transmission mode. Thus, the MUF's and the penetration frequencies are obtained for the desired hour from the prediction charts and the nomograms. This overlay is placed next on the K ring (figs. 103–114) corresponding to the month for which the LUF is required and the K value is read at the path midpoint. The K

value then is corrected for the seasonal and solar activity effects (figs. 119 and 118). If the transmission path crosses the auroral zone, the auroral K_a value is added to the normal K values above. The radiation angles for the three modes corresponding to the transmission distance are determined from figure 99. Using these radiation angles, the antenna gains can be determined from the antenna curves of this manual (figs. 182–204). The downcoming incident field intensity now is obtainable directly for the desired hour for each of the three modes from the median incident field intensity curves (figs. 121–140). The curves are read at various wave frequencies for the K value for the hour at which the LUF is required. To these values of field intensity in db are added the antenna effective powers in db (the antenna gain in db plus the antenna input power expressed in db). Thus, the median incident sky-wave field intensity values are obtained at various frequencies for the three transmission modes. Using these values and the MUF penetration frequencies, a curve can be drawn which shows the received field intensities for the various sky-wave modes. The curves for each mode are drawn only at the frequencies where a particular mode is possible. The one-hop E layer transmission mode is possible up to the E layer MUF; the one-hop F2 layer transmission mode is possible at frequencies between the E layer penetration frequencies for the mode and the one-hop F2 layer MUF; and the two-hop F2 layer transmission mode is possible between the E layer penetration frequency for the modes and the two-hop F2 layer MUF.

g. The required incident field intensities are obtained for the three transmission modes by using the atmospheric noise curves (figs. 146–164), the set noise curves (figs. 165–181), and the discrimination gains from figure 120. The atmospheric noise curve corresponding to the noise grade at the receiving location for the month in consideration must be used. These noise grade values are obtained from figures 142–145. The atmospheric noise curve for the circuit then is chosen from the various curves drawn for various noise grades and seasons. The atmospheric noise curves of this manual are shown for various hours of local time at the receiving location. LUF's can be determined by using the longitude of the receiving location as the time reference meridian or any other longitude. In case the time reference is any other than that of the receiving location, the atmospheric noise curves must be referred to the time reference line chosen. For example, if the LUF's are required at 1200 EST, 75° W longitude, and the receiving location is at 70° W longitude, a time conversion factor of 20 minutes or five-fifteenths of an hour must be used. The atmospheric noise curves must be read at 1220 local time from the curves, the 1220 local time at 70° W longitude occurring at 1200 EST. For each frequency and transmission mode, the required field intensity must be obtained individually from the atmospheric and set noise curves. The set noise curve for receiving antennas is read at the angle for the transmission mode and for the required frequency. The set noise limitation is the sum of the value from the noise curve and the type of service gain. The atmospheric noise limitation value is obtained by reading the atmospheric noise curve at the desired time, subtracting the discrimination gain of the type of receiving antenna used for the radiation angle corresponding to the mode and the wave frequency, and adding the type of service gain. For a given frequency, the required incident field intensity for a transmission mode is the greater of the two limitations above. It is necessary to plot the required incident field intensities for the three modes against frequency at each hour for which the LUF is required. The higher of the two limitations is plotted.

h. The LUF for any hour now is obtained from a graph on which the received modes are plotted against frequency between the frequency limits at which these modes are possible. The LUF is the lower of the three frequencies at which the received incident field intensity and the required incident field intensity are equal, the LUF being obtained for each mode separately. In case the required and received curves for a mode intersect at more than one frequency, the frequency of the highest intersection is recommended as the lower limiting frequency for the particular mode. The LUF's vary for a circuit over the hours of the day and, in general, are greatest at noon. For circuits in this distance range with moderate transmitting antenna effective powers, the night time LUF values generally are less than 2 mc. In case the LUF obtained for the one-hop E transmission mode is less than the penetration frequency for the two-hop F2 layer transmission mode, the LUF for the circuit is the one-hop E layer mode LUF.

i. The LEP has been defined as the minimum transmitting antenna effective power that is required for satisfactory communication over a cir-

cuit at a given time. The LEP can be obtained at any frequency for any circuit and hour for which the required incident field intensity and the received incident field intensity curves are available. At a given frequency for a particular mode, the difference between the received and required field intensities indicates the difference in effective power from that required. If the received incident field intensity is 20 db referred to 1 microvolt per meter and the required incident field intensity is 10 db referred to 1 microvolt per meter, 10 db more effective power than necessary are used. The LEP is obtainable by subtracting this difference in effective power from the effective power being used at the transmitting antenna. If the transmitting antenna effective power were —10 db and the received field intensity exceeds the required field intensity by 10 db, the LEP would be —20 db. If the transmitting antenna had a gain of zero db, the required input power would be —20 db or 10 watts for the particular frequency. The lowest of the three LEP's for the three transmission modes is the LEP for the circuit.

91. Example of Calculation for LUF and LEP for Distances Less than 3,000 km

The LUF and LEP is required at 1200 EST for Cincinnati, Ohio, for the following circuit:

Station locations:	
Cincinnati, Ohio	39.13° N, 84.42° W
Baton Rouge, La.	30.47° N, 91.18° W
Transmission distance	1,200 km
Month and year	June 1946
Transmitting antenna	Horizontal half-wave 60 feet high over poor ground
Receiving antenna	Same as above
Transmitter	Radio Set SCR-399, 300 watts
Type of service	Manual cw

a. Place a piece of transparent paper on the world map (fig. 97). Mark the station location and a horizontal line at the equator and a vertical line at longitude 75° W. Both stations are in the W zone, and the path midpoint is in the W zone also. Place the overlay on the great circle chart (fig. 98) with the equatorial lines corresponding and slide it horizontally until the station positions lie on the same great circle. Sketch in the great circle path and mark the midpoint, using the dash-dotted lines of the great circle chart as a scale.

b. Successively, place the overlay on the F2 ZERO MUF, W zone, chart, the F2 4000 MUF, W zone, chart, and the E 2000 MUF chart with the equatorial lines coinciding and the time reference line set at 1200 local time. Read the MUF's corresponding to the standard distances. The values of the F2 ZERO MUF, the F2 4000 MUF, and the E 2000 MUF for June 1946 are 7.7, 21.8, and 18.2 mc, respectively. Using the F2 layer nomogram (fig. 102) and the F2 layer MUF's for the standard distances, read the MUF corresponding to the transmission distance and that corresponding to half the transmission distance. The one-hop F2 layer MUF and the two-hop F2 layer MUF are 11.3 and 8.6, respectively. See figure 58 for the reading of the F2 layer MUF's. Using the E MUF and penetration frequency nomogram (fig. 101) and the E 2000 MUF, read the E layer MUF for the transmission distance, the one-hop F2 mode E layer penetration frequency, and the two-hop F2 mode E layer penetration frequency by setting the frequency strip so that the E 2000 MUF value, in mc, lies on the reference line and the slider is vertically set so that the numbered edge lies on the vertical line corresponding to the 1,200-km transmission distance. These values are 15.0, 6.7, and 4.6 mc, respectively. It can be seen that the one-hop E layer mode is possible up to 15.0 mc and the one-hop F2 layer mode is possible between 6.7 and 11.3 mc (fig. 59).

c. Place the overlay on the June K ring with the equatorial lines coinciding and the time reference line set at 1200 and read the K value at the path mid-point; this value is 0.96. Multiplying this by the seasonal correction factor for June, 0.7, and the solar activity for June 1946, 1.46, the corrected K value for 1200 EST is 0.98. This transmission path does not pass through the auroral zone as can be noted by laying the overlay on the auroral absorption index chart. Thus, the K value for the route is 0.98 for 1200 EST (fig. 60).

d. Using the median incident sky-wave field intensity curves (figs. 121–140), read the values corresponding to an inverse distance field of 300 millivolts per meter at 1 km for a K value of 0.98 at frequencies of 2, 4, 6, 8, 10, and 12 mc. These values are tabulated in table VI. Read the radiation angles corresponding to the three modes from

figure 99. The one-hop F2 layer, the two-hop F2 layer, and the one-hop E layer mode radiation angles are 25.0°, 44.5°, and 7.5°, respectively. Using the gain curve for a horizontal half-wave antenna, 60 feet above ground (fig. 188), read the antenna gains in db corresponding to the radiation angle at the same frequencies mentioned above. Express the antenna input power in db referred to 1 kw (—5.2 db). The effective powers (—5.2 db + antenna gain in db) at these frequencies are tabulated in table V. Add these effective powers to the median incident sky-wave field intensities based on the reference antenna to obtain the median sky-wave field intensity for the actual installation at 1200 EST for June 1946. Table III indicates the tabulation. Using the tabulated field intensity values and the MUF's and the E layer penetration frequencies, plot the received incident sky-wave field intensities for the transmission modes (fig. 78).

e. The required incident field intensity now is found separately for each of the three modes. Obtain the atmospheric noise limitation by first finding the noise grade (fig. 144) corresponding to the position of the receiving location and the month of the year. Find the local time at the receiving station, Cincinnati, Ohio, at 1200 EST. The longitude of Cincinnati, Ohio, is 84.42 W while the longitude on which EST is based is 75° W. The longitude difference, when expressed in time, indicates the time differences for hours referred to Cincinnati and hours referred to the seventy-fifth meridian. This time difference in hours is obtained by dividing the longitude difference in degrees by 15. The time difference in minutes is—

$$\frac{84.42 - 75.0}{15} \times 60 = 38 \text{ minutes}$$

The local time at Cincinnati is 1122 hours, since Cincinnati is 38 minutes in time west of the reference meridian. Read the atmospheric noise curve (fig. 158) corresponding to the noise grade for June at Cincinnati, 3.0 at 1122 local time at various frequencies. Obtain the discrimination gain for the horizontal half-wave, 60-foot high receiving antenna at the mode angle from figure 188 at these frequencies. From figure 120, note that the type of service gain for manual continuous wave radiotelegraphy is —9 db. The required incident field intensity in presence of atmospheric noise for a mode at a given frequency is the sum of the value from the atmospheric noise curve at the frequency, the discrimination gain from the receiver noise curve with its sign changed at the frequency, and the type of service gain from the type of service gain table. The values of the required incident field intensities in the presence of atmospheric noise for the three modes at 1200 EST are listed in table VI, columns 6–8. The set noise limitation for a particular mode at a given frequency is obtained by reading the receiver noise curve corresponding to the receiving antenna (fig. 173) at the angle corresponding to the mode and the frequency, and adding the type of service gain (—9 db) from figure 120. The required incident field intensities in the presence of receiver noise are given in table VI, columns 9, 10, and 11, for each of the three modes at various wave frequencies. The minimum required incident field intensity for the circuit is the greater of the two noise limitations at each frequency (table VI, columns 15–17). From the tabulated values on the same figures as the received median incident field intensity curves (fig. 78), the required minimum field intensity curves are drawn for each of the transmission modes between the frequency values at which each of the modes are possible.

f. The LUF for Cincinnati receiving Baton Rouge at 1200 EST is 5.4 mc, as shown by the lowest of the three intersections of the received and required field intensity curves corresponding to the three modes. The LUF is satisfactory for 90 percent of the days. In case transmission occurs in both directions, the LUF for the circuit usually is taken as the higher of the two LUF's for the two directions.

g. The LEP for any frequency can be found by subtracting the required incident field intensity for each transmission mode from the received incident field intensity and then subtracting this difference from the transmitting antenna effective power at the given frequency for the corresponding transmission modes. The LEP for the circuit is the lowest of the values for the three transmission modes. At 8 mc, the differences between the required and received incident field intensities for the circuit of the LUF problem above are 32.5, 17.5, and 3.3 db, corresponding to the one-hop F2 layer mode, the two-hop F2 layer mode, and the one-hop E layer mode, respectively. The transmitting antenna effective power is the sum of the

antenna gain in db for the mode angle and the antenna input power expressed in db. The effective powers are —3.5, —6.5, and —10.2 db for the one-hop F2 layer mode, the two-hop F2 layer mode, and the one-hop E layer mode, respectively. The LEP for the three modes are —36, —24, and —13.5 db. The LEP for the circuit, being the lowest of the values for the three modes, is —36 db. Satisfactory communication is possible for Cincinnati receiving Baton Rouge at 1200 EST in June 1946 for a transmitting antenna effective power of at least —36 db at 8 mc.

Table V. Lowest Effective Power Calculation, Cincinnati Receiving Baton Rouge (1200 EST —Manual CW—8MC).

MODE	RECEIVED INCIDENT FIELD INTENSITY BASED ON EFFECTIVE POWER	REQUIRED FIELD INTENSITY CORRECTED FOR TOS (15) TABLE VII	DIFFERENCE (2)–(3)	TRANSMITTING ANTENNA EFFECTIVE POWER DB REFERRED TO 1 KW	LOWEST EFFECTIVE POWER DB REFERRED TO 1 KW (5)–(4)
(1)	(2)	(3)	(4)	(5)	(6)
1F	14.5	-18.0	32.5	-3.5	-36.0
2F	2.5	-15.0	17.5	-6.5	-24.0
1E	-8.2	-11.5	3.3	-10.2	-13.5

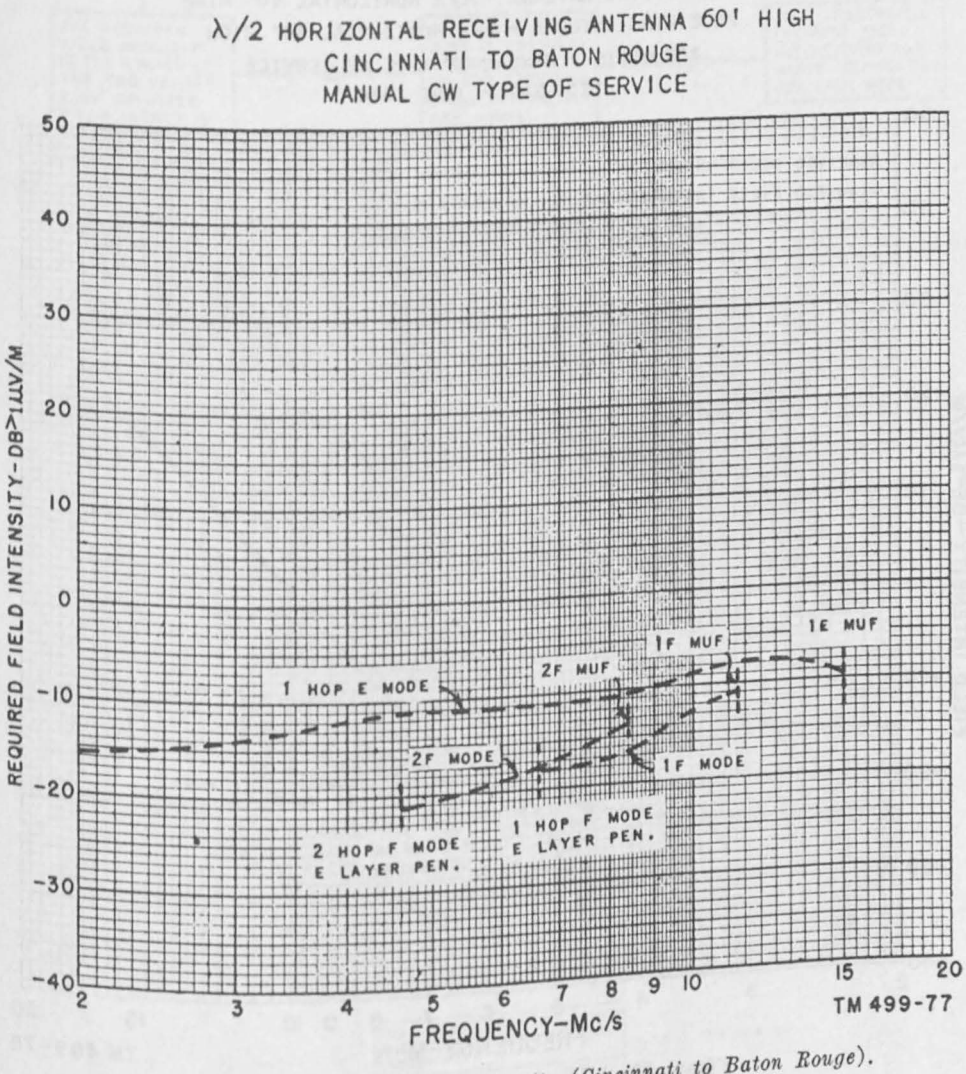


Figure 77. Minimum required field intensity (Cincinnati to Baton Rouge).

Table VI. Minimum Required Field Intensity, Cincinnati to Baton Rouge.

FREQUENCY IN MEGACYCLES	REQ. FIELD INTENSITY IN PRESENCE OF ATMOS. NOISE	DISCRIMINATION GAIN λ/2 HORIZ. ANT. 60° HIGH			REQUIRED FIELD INTENSITY CORRECTED FOR DISCRIMINATION GAIN				REQUIRED FIELD INTENSITY IN PRESENCE OF SET NOISE			REQUIRED FIELD INTENSITY (GREATER OF SET OR ATMOSPHERIC NOISE)			REQUIRED FIELD INTENSITY CORRECTED FOR MANUAL CW (-9 DB)		
		1F MODE Δ=25°	2F MODE Δ=44.5°	1E MODE Δ=7.5°	1F MODE (2)-(3)	2F MODE (2)-(4)	1E MODE (2)-(5)	1F MODE Δ=25°	2F MODE Δ=44.5°	1E MODE Δ=7.5°	1F MODE (6) OR (9)	2F MODE (7) OR (10)	1E MODE (8) OR (11)	1F MODE (12)-9 DB	2F MODE (13)-9DB	1E MODE (14)-9 DB	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	
2	-6.5	27.5	28.8	18.0	-34.0	-35.3	-24.5	-16.5	-17.8	-7.0	-16.5	-17.8	-7.0	-25.5	-26.8	-16.0	
3	-4.3	25.5	26.6	16.0	-29.8	-30.9	-20.3	-14.5	-15.6	-5.0	-14.5	-15.6	-5.0	-23.5	-24.6	-14.0	
4	-0.9	23.0	24.5	14.0	-23.9	-25.4	-14.9	-12.0	-13.5	-3.0	-12.0	-13.5	-3.0	-21.0	-22.5	-12.0	
5	3.0	22.0	23.5	13.5	-19.0	-20.5	-10.5	-11.0	-12.5	-2.5	-11.0	-12.5	-2.5	-20.0	-21.5	-11.5	
6	6.0	21.0	21.0	13.5	-15.0	-15.0	-7.5	-10.0	-10.0	-2.5	-10.0	-10.0	-2.5	-19.0	-19.0	-11.5	
8	10.6	20.0	17.0	13.5	-9.4	-6.4	-2.9	-9.0	-6.0	-2.5	-9.0	-6.0	-2.5	-18.0	-15.0	-11.5	
10	13.0	17.0	12.0	13.0	-4.0	1.0	0.0	-6.0	-1.0	-2.0	-4.0	1.0	0.0	-13.0	-8.0	-9.0	
12	13.2	15.0	10.0	12.5	-1.8	3.2	0.7	-4.0	1.0	-1.5	-1.8	3.2	0.7	-10.8	-5.8	-8.3	
14	12.6	12.5	9.5	12.5	0.1	3.1	0.1	-1.5	1.5	-1.5	-0.1	3.1	0.1	-8.9	-5.9	-8.9	
16	9.8	7.5	10.0	12.0	2.3	-0.2	-2.2	3.5	1.0	-1.0	3.5	1.0	-1.0	-5.5	-8.0	-10.0	
20	2.0	8.0	10.0	11.5	-6.0	-8.0	-9.5	3.0	1.0	-0.5	3.0	1.0	-0.5	-6.0	-8.0	-9.5	

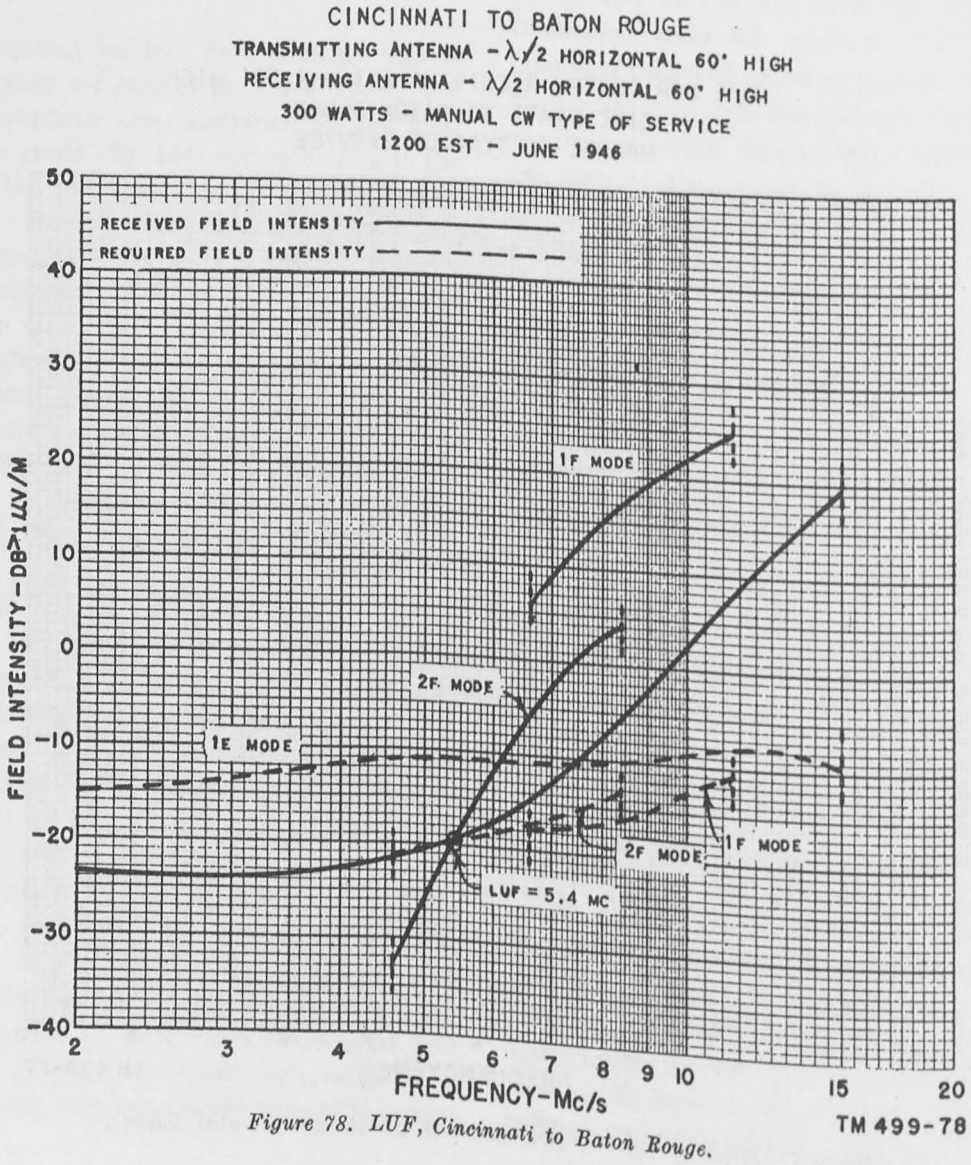


Figure 78. LUF, Cincinnati to Baton Rouge.

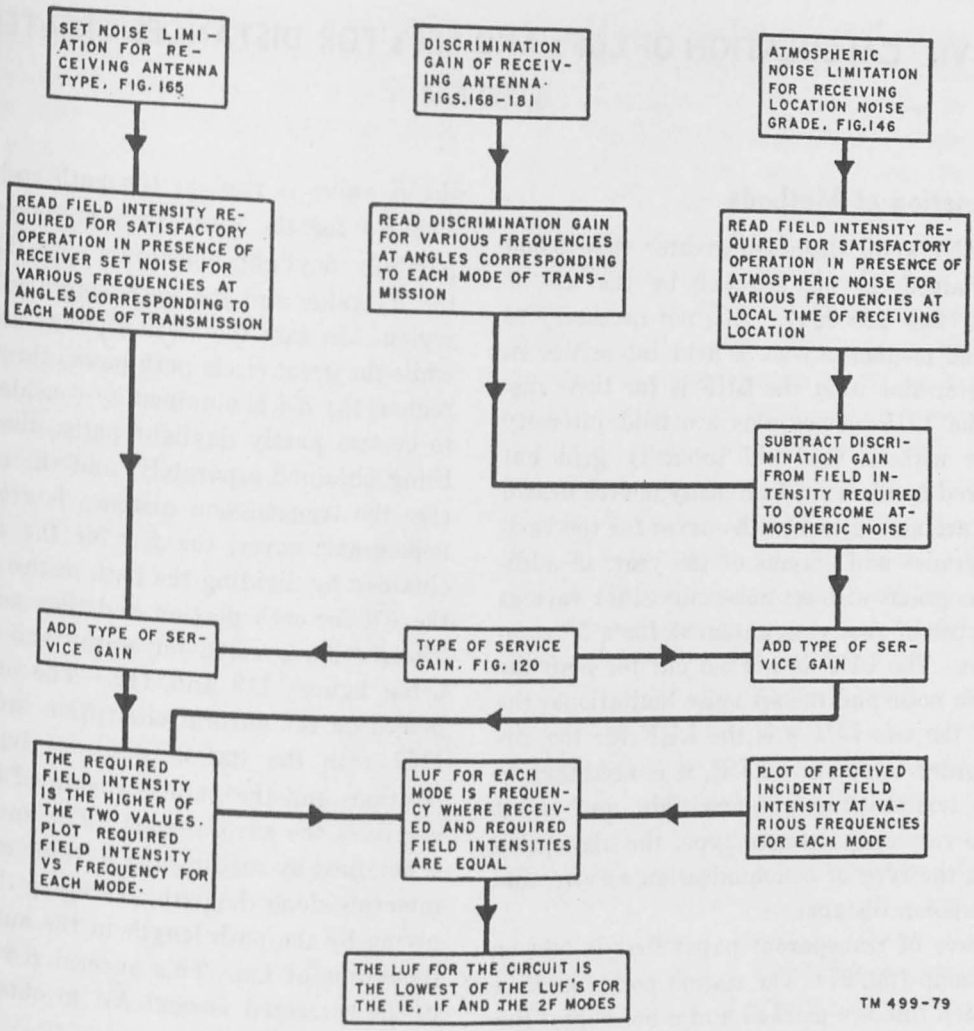


Figure 79. Flow chart, LUF calculation (0 to 3,000 km).

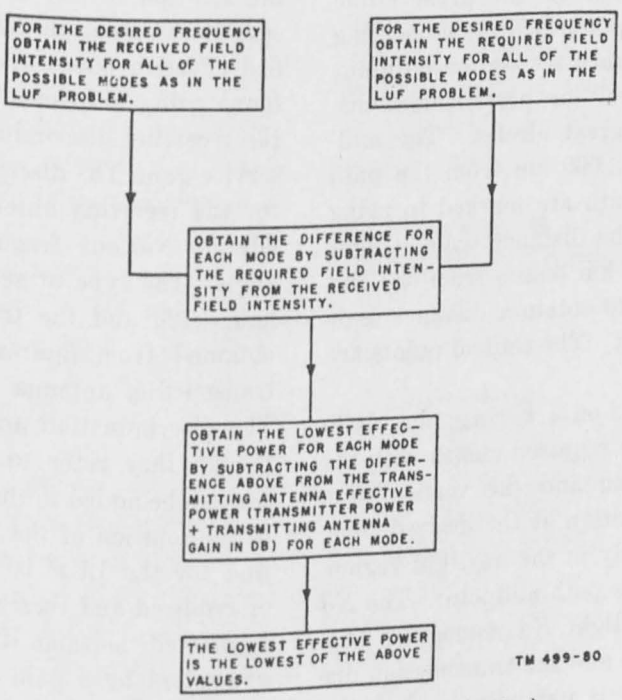


Figure 80. Flow chart, LEP (0 to 3,000 km).

Section VII. CALCULATION OF LUF's AND LEP's FOR DISTANCES GREATER THAN 3,000 KM

92. Explanation of Methods

a. The LUF's for distances greater than 3,000 km are obtained, in this manual, by the use of nomograms (figs. 205–224). It is not necessary to solve for the median sky-wave field intensities in order to determine what the LUF is for these distances. The LUF nomograms are field intensity nomograms without the field intensity grid but with required incident field intensity curves drawn in. These are nomograms with curves for the various noise grades and seasons of the year, in addition to nomograms with set noise curves for various common types of receiving antennas for a 5° radiation angle. The LUF is worked out for both the atmospheric noise and the set noise limitations; the greater of the two LUF's is the LUF for the circuit. In order to obtain a LUF, it is necessary to know the transmitting antenna gain and input power, the receiving antenna type, the absorption index, $\overline{K}d$, the type of communication service, and the transmission distance.

b. A piece of transparent paper first is laid on the world map (fig. 97). The station points and the zone division line are marked and a horizontal line is drawn at the equator and a vertical line at the longitude for which the hours are to be referred. This overlay next is placed on the great circle chart (fig. 98) with the equatorial lines coinciding and it is slid horizontally until the station positions lie on the same great circle or proportional distances between adjacent great circles. The midpoint and control points 2,000 km from the path ends of the great circle path are marked in using the dash-dotted lines as the distance scale. Light marks are placed at 1,000-km points from one end of the transmission path to obtain a distance scale along the great circle path. The control points are labeled.

c. The overlay is placed on a K ring (figs. 103–114) corresponding to the required month with the equatorial lines coinciding and the vertical line through the receiving location at the desired time. In case the path is entirely in the daylight region, the K value is read at the path midpoint. The $\overline{K}d$ is obtained from the daylight $\overline{K}d$ nomogram (fig. 116), using this K_m value and the transmission distance. In case the path is partially in daylight, the K value is read at the path end in daylight. The $\overline{K}d$ for the route then is obtained from the partially daylight nomogram (fig. 117) by using the K_1 value and the path length in the daylight region. In case the station points are in daylight while the great circle path passes through the night region, the $\overline{K}d$ is obtained by considering the path to be two partly daylight paths, the $\overline{K}d$ for each being obtained separately, and the two added. In case the transmission distance is greater than the nomograms cover, the $\overline{K}d$ for the circuit can be obtained by dividing the path in two and obtaining the $\overline{K}d$ for each portion and then adding the two. The $\overline{K}d$ is corrected for season and solar activity, using figures 119 and 118. The overlay next is placed on the auroral absorption index chart (fig. 115) with the station positions lying over their positions and the path is examined to see whether it crosses the auroral zone. The auroral $\overline{K}d$ value is obtained by reading the K value at various short intervals along the path, averaging them and multiplying by the path length in the auroral region in thousands of km. This auroral $\overline{K}d$ then is added to the corrected normal $\overline{K}d$ to obtain the $\overline{K}d$ for the route.

d. The modified effective power is required in the solution of the long-distance LUF's. In the case of the atmospheric noise limitation, the modified effective power includes the transmitting antenna gain, the transmitting antenna input power, the receiving discrimination gain, and the type of service gain. The discrimination gains are obtained for the receiving antenna type from figures 165–201 for various frequencies at the 5° radiation angle. The type of service gain is obtained from figure 120 and the transmitting antenna gain is obtained from figures 182–204 for the type of transmitting antenna at a radiation angle of 5°. The discrimination and type of service gains, although they refer to conditions at the receiving set, can be added to the transmitting antenna gains in the solution of the LUF problem. Since a solution for the LUF is obtained by the comparison of required and received field intensities, the LUF is affected the same if the received field intensities are raised by a gain value instead of subtracting the same gain value from the required field inten-

sity. In the solution of a problem for a particular hour, the antenna gains and discrimination gains are read at various frequencies. The modified effective power used with atmospheric noise nomograms at a particular frequency is equal to the sum of the transmitting antenna gain, the transmitting antenna input power, the discrimination gain, and the type of service gain with its sign changed. These db gains usually are tabulated for various frequencies. The modified effective power then is plotted against frequency. The modified effective power to be used with the set noise nomograms is the same as for the atmospheric noise case except discrimination gains are not added in.

e. The LUF is obtained by using the LUF nomograms (figs. 205–224), the $\overline{Kd}$ value for the circuit, and the relationship between modified effective power and frequency. The LUF is obtained for both atmospheric and receiver noise limitations, the greater of the two being the LUF for the circuit. The noise grade at the receiving location is determined by using figures 142–145 for the month. The LUF for the atmospheric noise limitation is solved by using the nomogram corresponding to the month and noise grade. The LUF for receiver noise limitation is worked out, using the nomogram which has a curve corresponding to the type of receiving antenna used. In order to determine the LUF, it is necessary to prepare frequency strips. Separate frequency strips are prepared for the atmospheric and receiver noise limitations. To make a frequency strip, a blank strip of paper is placed on the modified effective power scale of the power slider (figs. 205–224) and the strip is marked for various frequency values. The frequency values are determined from the relationship between the modified effective power and frequency, as shown previously. With this strip fastened to the power slider with the frequency marks lying over their modified effective powers, the slider is ready for use in the LUF calculations. The power slider is placed vertically with the frequency strip side lying along the effective power reference line. A straightedge is placed from the $\overline{Kd}$ value to the transmission on the power slider. With the straightedge set at these points, the power slider is moved up and down until the straightedge cuts the noise curve for the required local time or the antenna type at the same frequency value that the horizontal reference mark of the effective power reference line cuts the frequency strip. When the frequencies are the same at the intersection of the strip and the index mark, and the noise curve and the straightedge, the LUF is obtained. This value is satisfactory for 90 percent of the days.

f. The LEP for transmission distances greater than 3,000 km are found by using the LUF nomograms. The LEP for a circuit at a given hour and frequency is the greatest of the two LEP values obtained for the atmospheric noise and the receiver noise limitations. The nomograms used correspond to the noise grade and month at the receiving location and the receiving antenna type. It is not necessary to have a frequency strip in order to obtain the LEP. To find the LEP, a straightedge is set on the $\overline{Kd}$ value for the circuit and at the intersection of the wave frequency line and the noise curve. The other end of the straightedge is fastened to the power slider at the transmission distance in km and the modified effective power is read at the point where the horizontal index mark of the effective power reference line cuts the power scale. This value is the lowest modified effective power for the circuit. The LEP for a circuit is obtained from the lowest modified effective power by removing the discrimination and type of service gains. The modified effective power used in the atmospheric noise limitation was shown to be the sum of the transmitting antenna effective power, the discrimination gain, and the type of service gain with the sign changed. Thus, the LEP for the atmospheric noise limitation is equal to the lowest modified effective power, as obtained above, with the discrimination gain subtracted and the type of service gain added. The LEP for the receiver noise limitation is the lowest modified effective power, obtained from the nomographic solution above, with the type of service gain added.

93. Example of Calculation for LUF and LEP for Distances Greater than 3,000 km

The LUF is required at New York for New York receiving on the following circuit:

Station locations:	
New York, New York	40.8° N, 74.0° W
Berlin, Germany	52.6° N, 13.2° E
Transmission distance	6,400 km
Transmitter power	10 kw
Transmitting antenna	Type A rhombic over poor ground
Receiving antenna	Same as above
Month and year	June 1946
Type of service	Manual cw
Time of day	1200 New York mean time

a. Place a piece of transparent paper over the world map (g. 97) and place marks at the station points, New York and Berlin. Draw in a horizontal line at the equator and a vertical line through the longitude of New York, the LUF being required for 1200 local time at New York. Place this overlay on the great circle chart (fig. 98), with the equatorial lines coinciding, and slide horizontally until the station positions lie at proportional distances between adjacent circles. Draw in the great circle path. The dash-dotted scale of the chart shows the path length to be 6,400 km. Mark control points at 2,000 km from the path ends and label the W zone point "A" and the I zone point "B." Also mark a point at the center of the great circle path and points at 1,000 km from the New York end of the great circle path. Place this overlay on the F2 4000 MUF for June 1946 prediction chart and read the MUF for control point A on the W chart, and on the I chart for control point B at 1200 local hour. The MUF's are 20.1 and 20.9 mc. Wave frequencies greater than the MUF, 20.1 mc, will penetrate the ionosphere and are not usable. Place the overlay on the K ring for June with the equatorial lines coinciding and the time reference line set at 1200. In this case, the path lies entirely in the daylight region because K is greater than zero for all points along the path. Read the K at the midpoint of the path; this is 0.76. Using a nomogram (fig. 116), obtain the $\overline{K}d$ values for the transmission distance of 6,400 km and the K_m value of 0.76. The $\overline{K}d$ is 4.65 for the circuit. Multiply this value by the seasonal correction factor 0.7, and the solar activity factor, 1.46, as obtained from figures 119 and 118. The corrected $\overline{K}d$ is 4.75. Place the overlay on the auroral absorption index chart with the station points coinciding with their positions on the chart; read the K_a values every 500 km along the path, average these values, and estimate the path length in the auroral region, using the 1,000 km points along the great circle path as a scale. The auroral $\overline{K}d$ is the product of the average of the K_a and the transmission distance in the auroral region in thousands of km. The auroral $\overline{K}d$ is 0.27 times 3.5. The $\overline{K}d$ for the path is the sum of the auroral $\overline{K}d$ and the corrected normal $\overline{K}d$, or 5.68 for 1200 local time at New York during June 1946. See figures 81–84 for the reading of the MUF's, the absorption index, K, and the normal $\overline{K}d$.

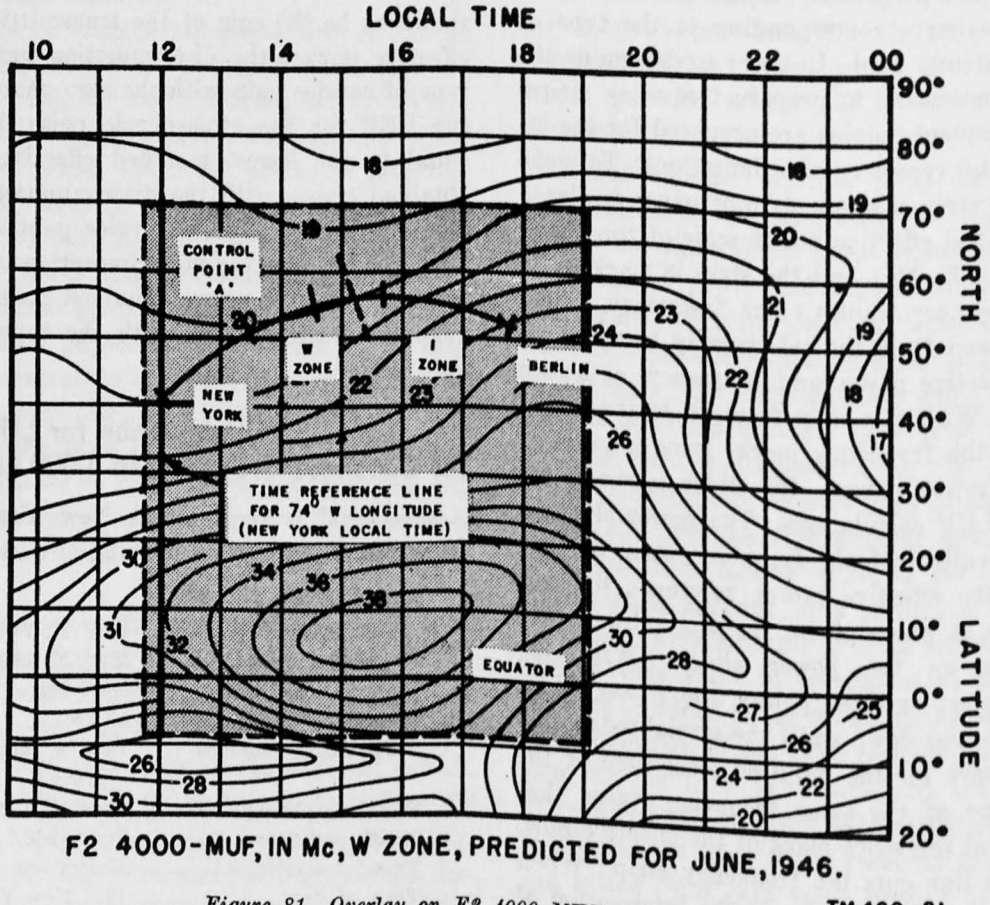


Figure 81. Overlay on F2 4000 MUF, W zone, chart. TM 499-81

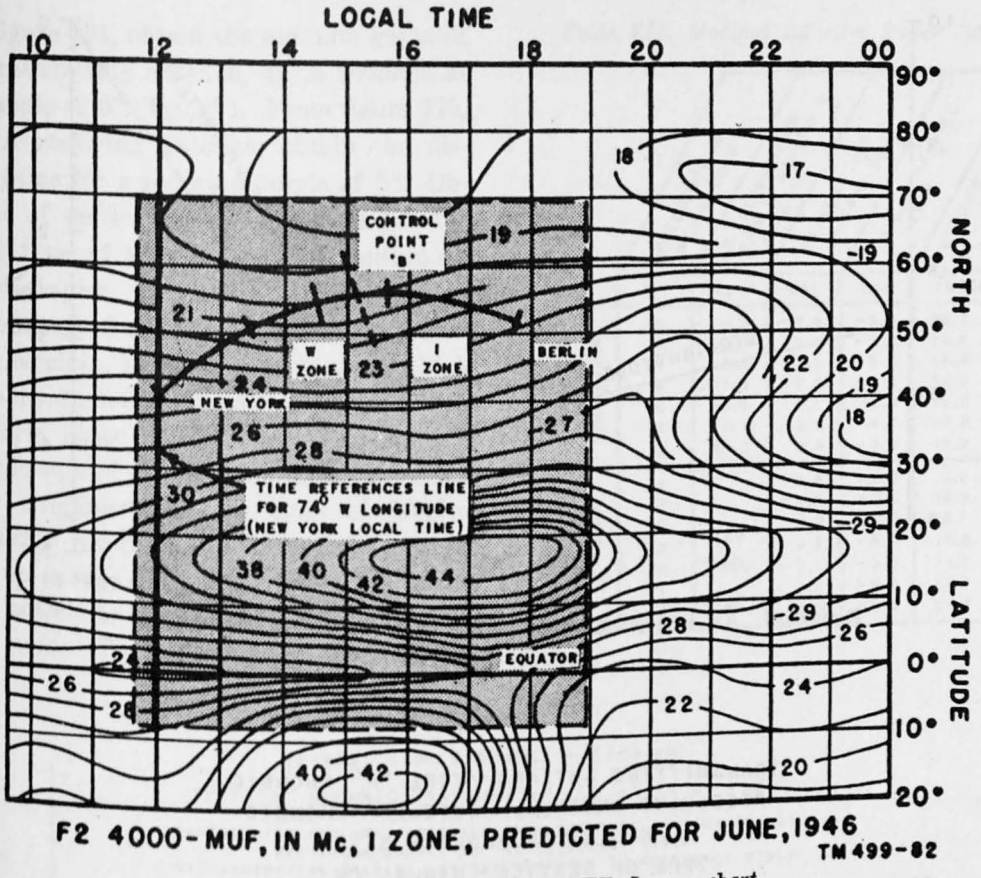


Figure 82. Overlay on F2 4000 MUF, I zone, chart.

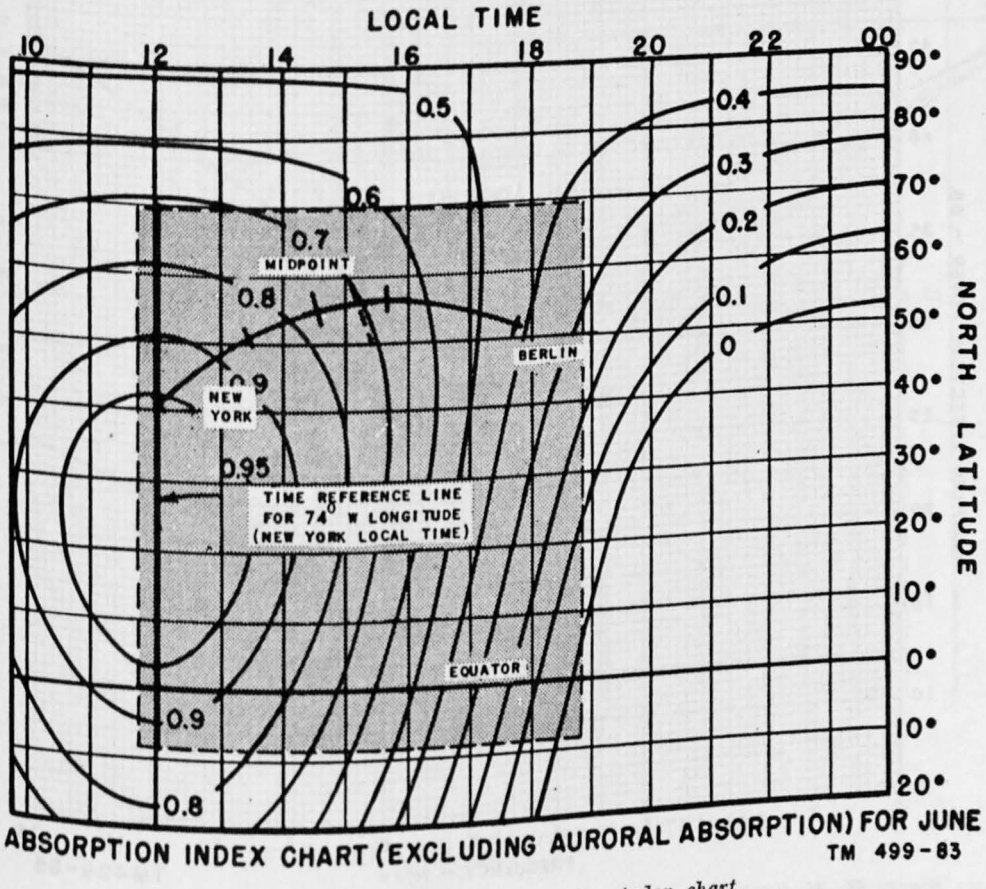


Figure 83. Overlay on absorption index chart.

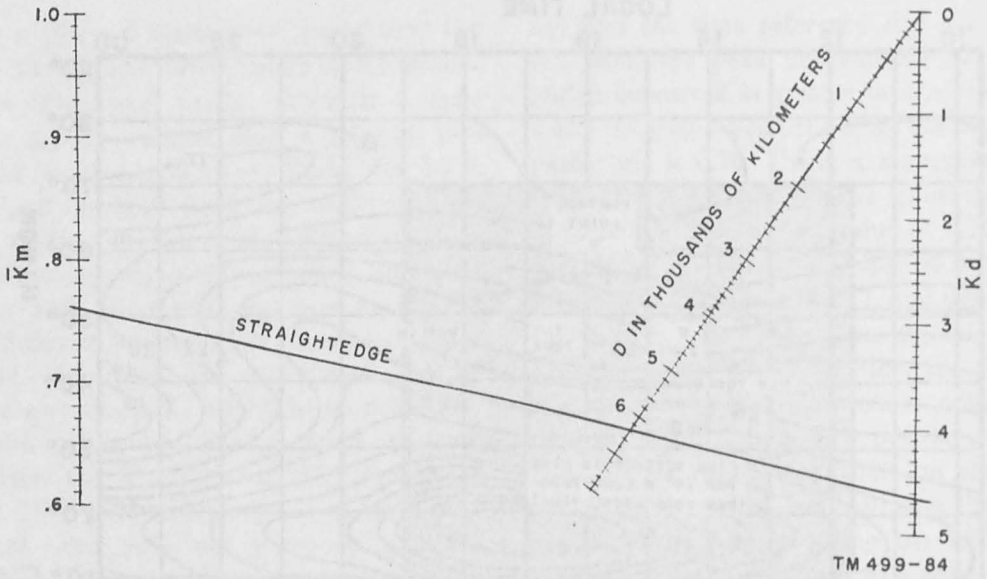


Figure 84. $\bar{K}d$ nomogram, transmission path entirely in day region.

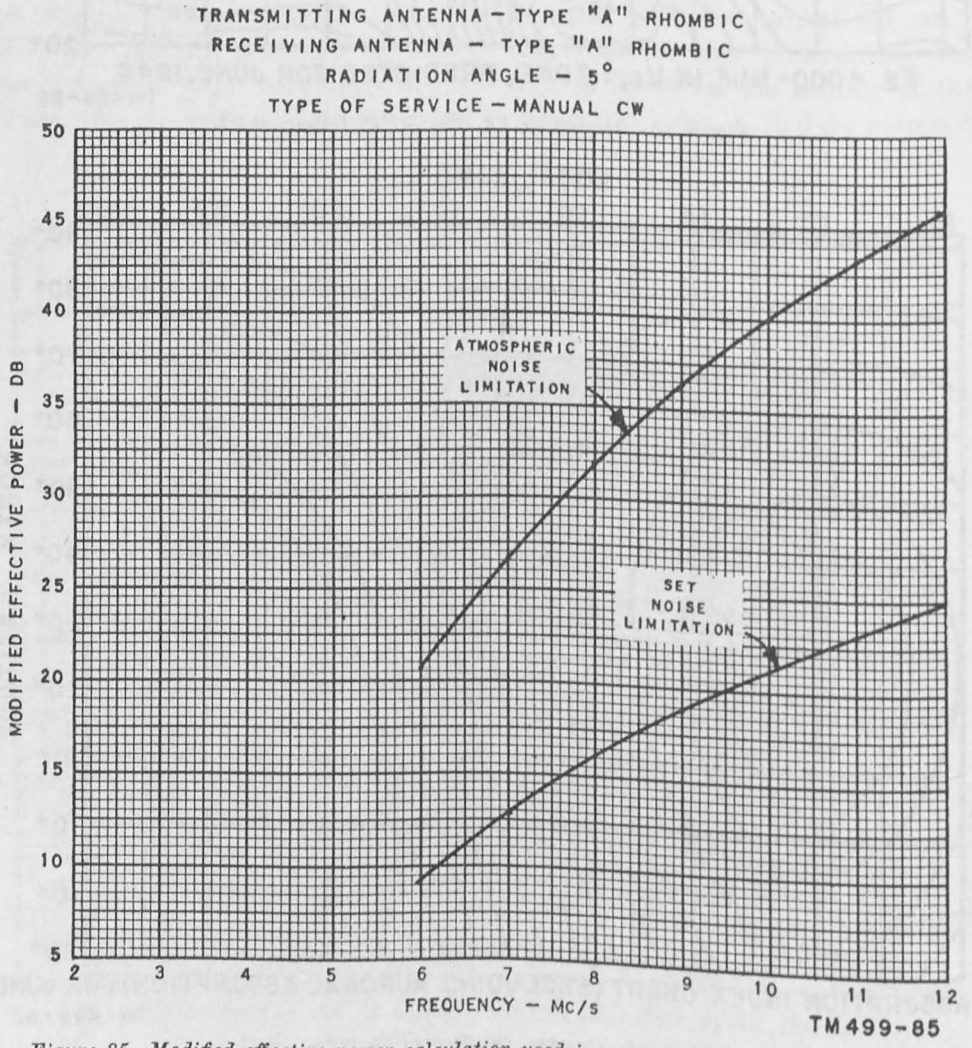


Figure 85. Modified effective power calculation used in preparing a "frequency strip."

b. From figure 191, obtain the antenna gains in db for the transmitting antenna, an A rhombic at a radiation angle of 5° (fig. 99). From figure 175, for a type A receiving antenna, obtain the discrimination gains for a radiation angle of 5°. Obtain the type of service gain from figure 120 for the required type of service, manual continuous wave radiotelegraphy. These gain values are listed in various columns of table VII for various transmission frequencies. There is one column which gives the modified effective power to be used with the atmospheric noise curve. The values in this column are the sum of the discrimination gain, the transmitting antenna gain, the type of service gain with its sign reversed, and the input power in db. There also is a column which gives the modified effective powers to be used with the nomograms for receiver noise. These values are the same as

Table VII. Modified Effective Power Calculations

	Frequency in megacycles	Discrimination gain of receiving antenna	Transmitting antenna gain	Type of service gain	Modified effective power (2)+(3)−(4)+10 db
	(1)	(2)	(3)	(4)	(5)
Atmospheric noise limitation	6	11.5	−9.8	−9.0	20.7
	7	13.8	−6.2	−9.0	26.6
	8	15.8	−2.9	−9.0	31.9
	9	17.5	−0.2	−9.0	36.3
	10	18.9	2.1	−9.0	40.0
	11	20.0	4.2	−9.0	43.2
	12	21.0	5.9	−9.0	45.9
Set noise limitation	6	Not used	−9.8	−9.0	9.2
	7		−6.2	−9.0	12.8
	8		−2.9	−9.0	16.1
	9		−0.2	−9.0	18.8
	10		2.1	−9.0	21.1
	11		4.2	−9.0	23.2
	12		5.9	−9.0	24.9

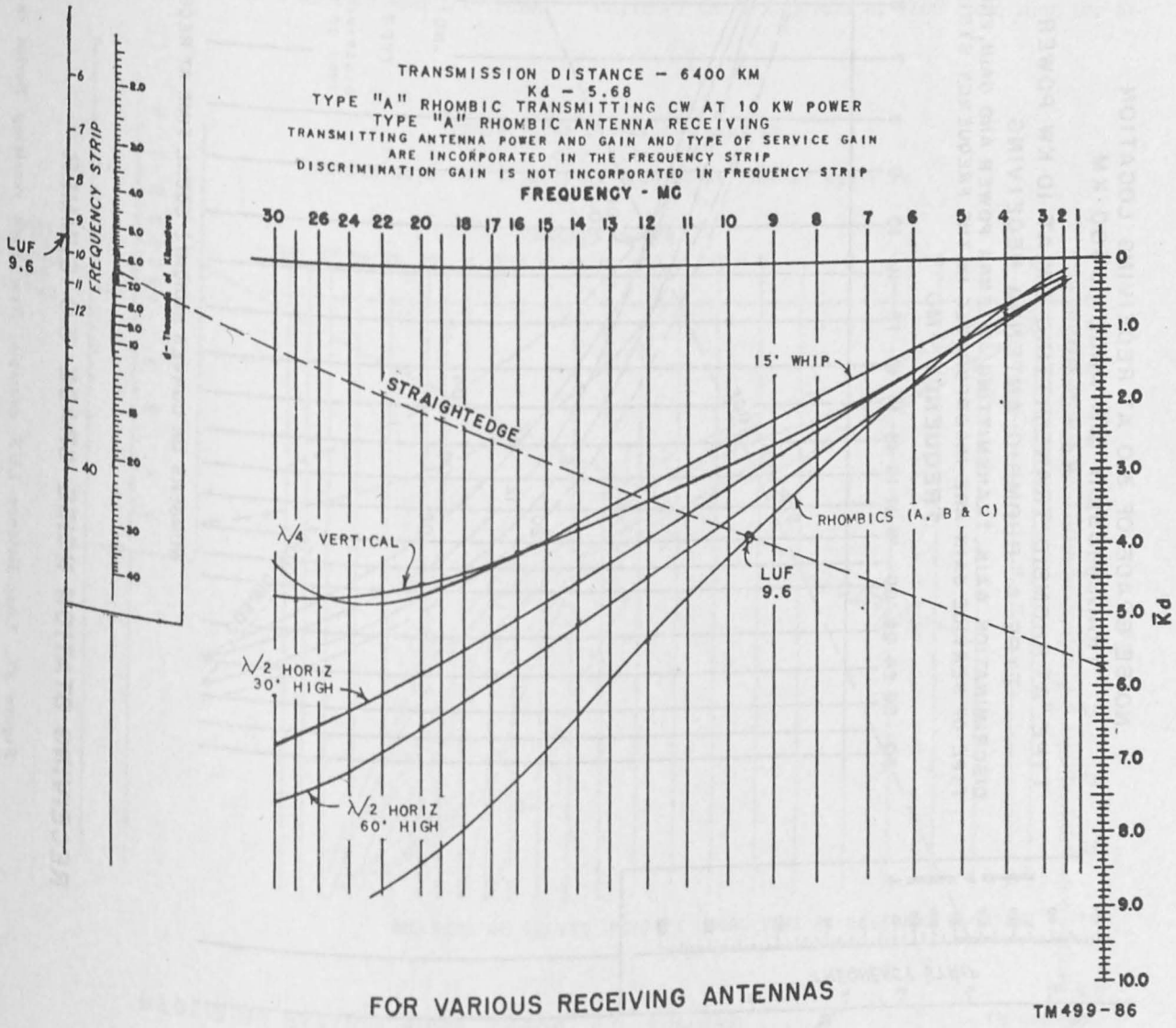
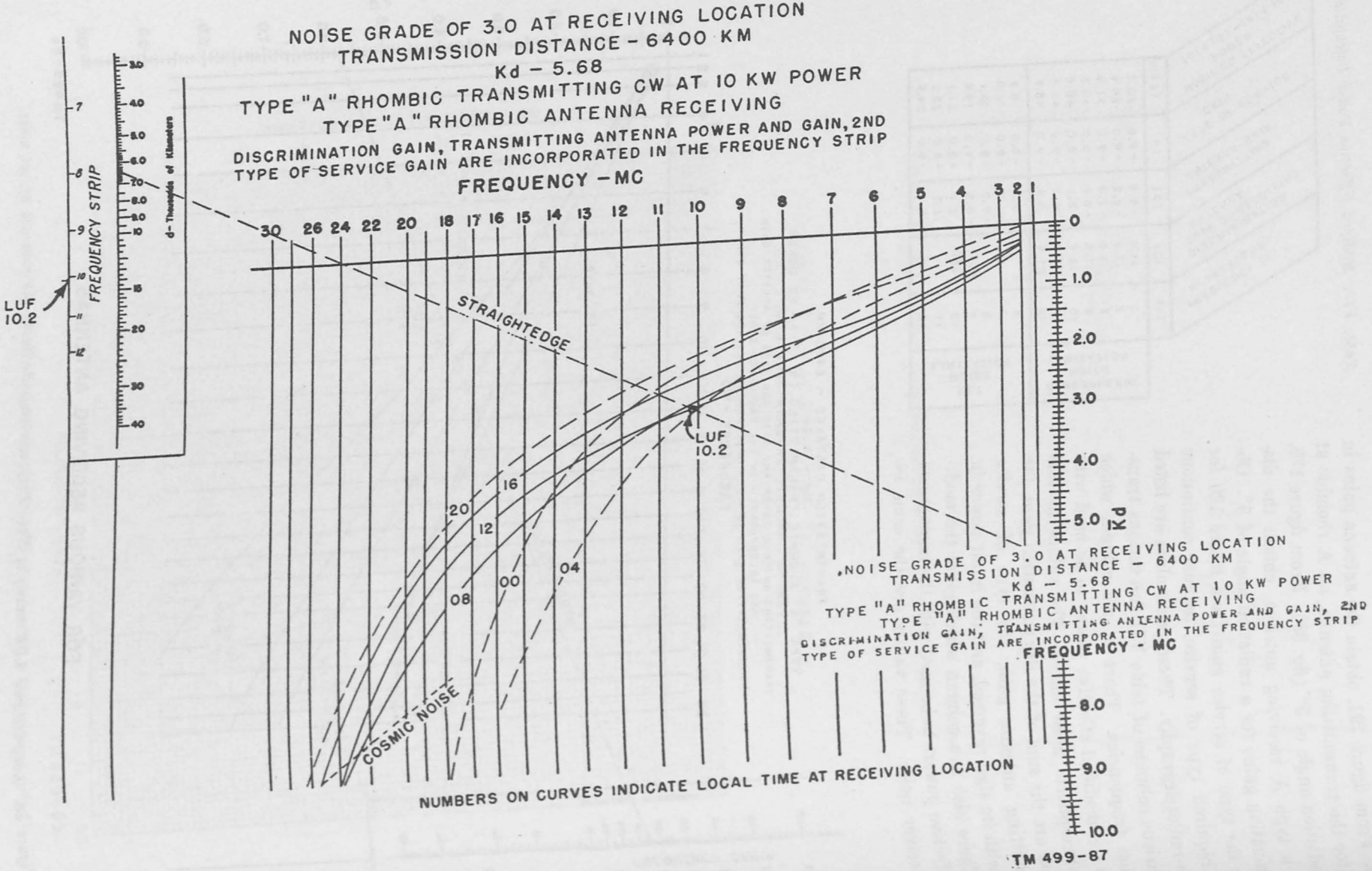


Figure 86. Long-distance LUF example, New York receiving Berlin in the presence of set noise.



RECEIVING STATION NOISE GRADE 3.0 SUMMER

Figure 87. Long-distance LUF example, New York receiving Berlin in the presence of atmospheric noise.

those to be used with the atmospheric noise nomogram with the exception that the discrimination gains are not included. These modified effective powers are plotted against frequency in figure 85.

c. Using the modified effective values from the curves, prepare a frequency strip by laying a piece of paper over the modified effective power scale of the power slider of the LUF nomogram and mark frequency values corresponding to effective power values. The power sliders are prepared for use with the nomograms which determine the LUF's, based both on atmospheric noise and on receiver noise limitations. Attach the frequency strips on the power slider with frequency values laying over their modified effective powers. Place the power slider, which has the frequency strip fastened to it, along the effective power reference line on the extreme left of the nomograms. Place a straightedge between the $\overline{K}d$ value of 5.68 and the transmission distance of 6,400 km on the power slider and move the power slider vertically up and down until the horizontal index line on the effective power reference line is at the same frequency value on the frequency strip as at the point where the straightedge intersects the required field intensity curve of the nomogram at 1200 local time for at-

Table VIII. Lowest Effective Power Calculations, New York Recruiting Berlin (1200 Local Time in New York, Manual CW—10 KW—11 Mc).

FREQUENCY IN MC	MOD EFF POWER BASED ON ATMOS NOISE FIG. 88	DISC GAIN OF RECG ANTENNA	(2) − (3)	MOD EFF POWER BASED ON SET NOISE FIG 89	LARGER OF (5) OR (6)	LOWEST EFFECTIVE POWER (6) + (−9 DB TOS GAIN)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
11.0	28.5	20.0	8.5	7.2	8.5	−.5

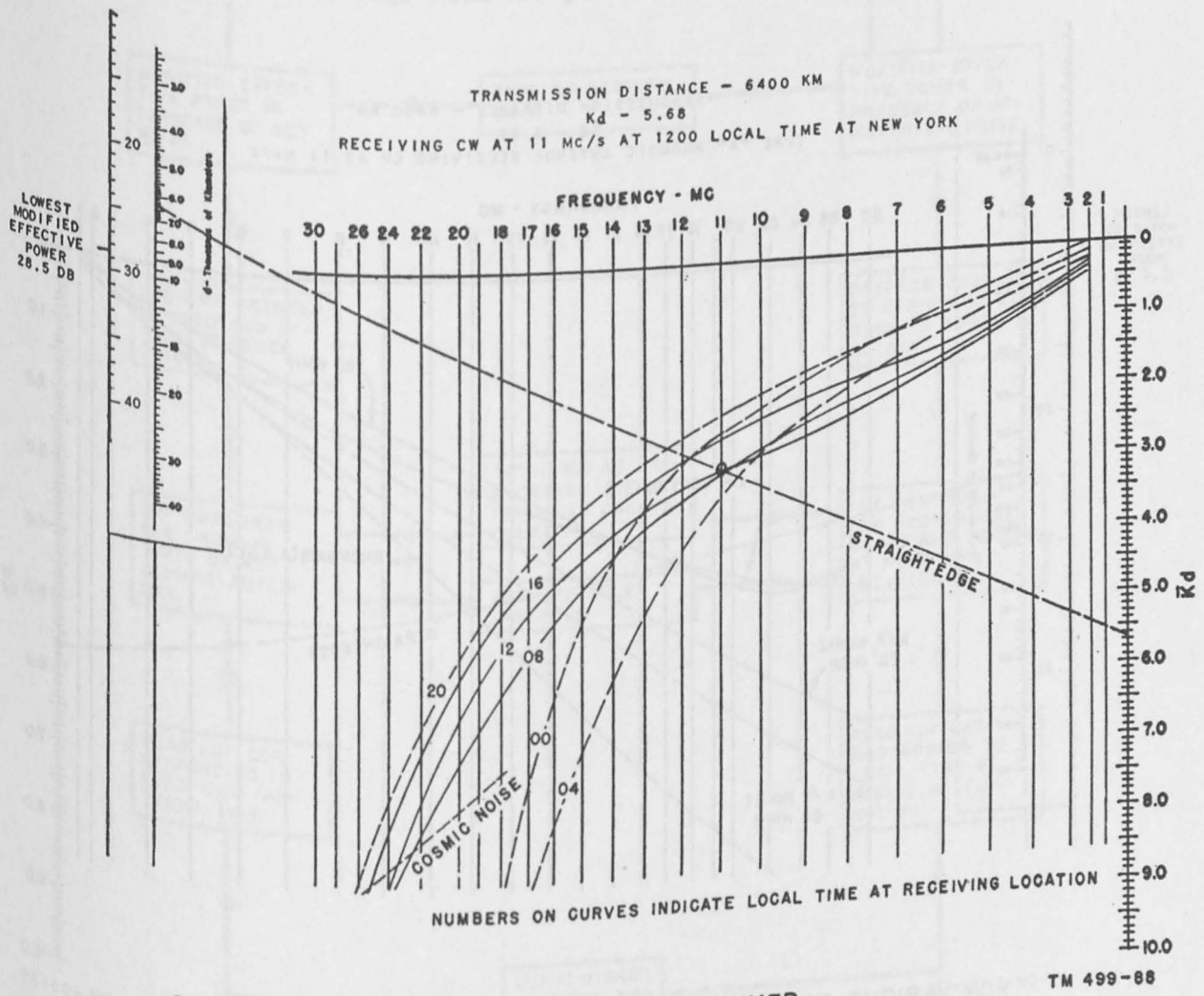


Figure 88. LEP example, New York receiving Berlin in the presence of atmospheric noise.

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mospheric noise. The nomogram used for atmospheric noise is figure 158 (noise grade 3.0, summer), the noise grade value being obtained from figure 144 at the location of New York for June. In the case of set noise, the straightedge must intersect the noise curve (fig. 175) corresponding to the receiving antenna used, which is an A rhombic. The LUF from the atmospheric noise nomogram is 10.2, while the LUF from the set noise nomogram is 9.6. The LUF at 1200 local time New York, for New York receiving Berlin, in June 1946 is 10.2 mc.

d. As a sample problem, assume that it is required to find the LEP for this New York receiving Berlin circuit for a wave frequency of 11 mc. To find the LEP for the atmospheric noise limitation, use figure 158, corresponding to the noise grade at the receiving location for June. This nomogram corresponds to a noise grade of 3.0 for summer. The lowest modified effective power is obtained from the nomogram by setting the straightedge at the $\overline{K}d$ value of 5.68, corresponding to the desired time (1200 local time at New York) and the intersection of the atmospheric noise curve for 1200 local time and the wave frequency of 11 mc. Place the movable power slider vertically so that the transmission distance of 6,400 km intersects the straightedge, and read the lowest modified effective power from the power scale at the point where the horizontal index mark of the modified effective power reference line cuts the modified effective power scale of the power slider (fig. 88). This value is 28.5 db for the atmospheric noise limitations. To obtain the lowest modified effective power for the receiver noise limitation, set the straightedge on figure 89 at the $\overline{K}d$ value of 5.68 and at the intersection of the wave frequency of 11 mc, with the curve corresponding to the receiving type A rhombic antenna (fig. 89). The movable power slider again is set in the vertical position

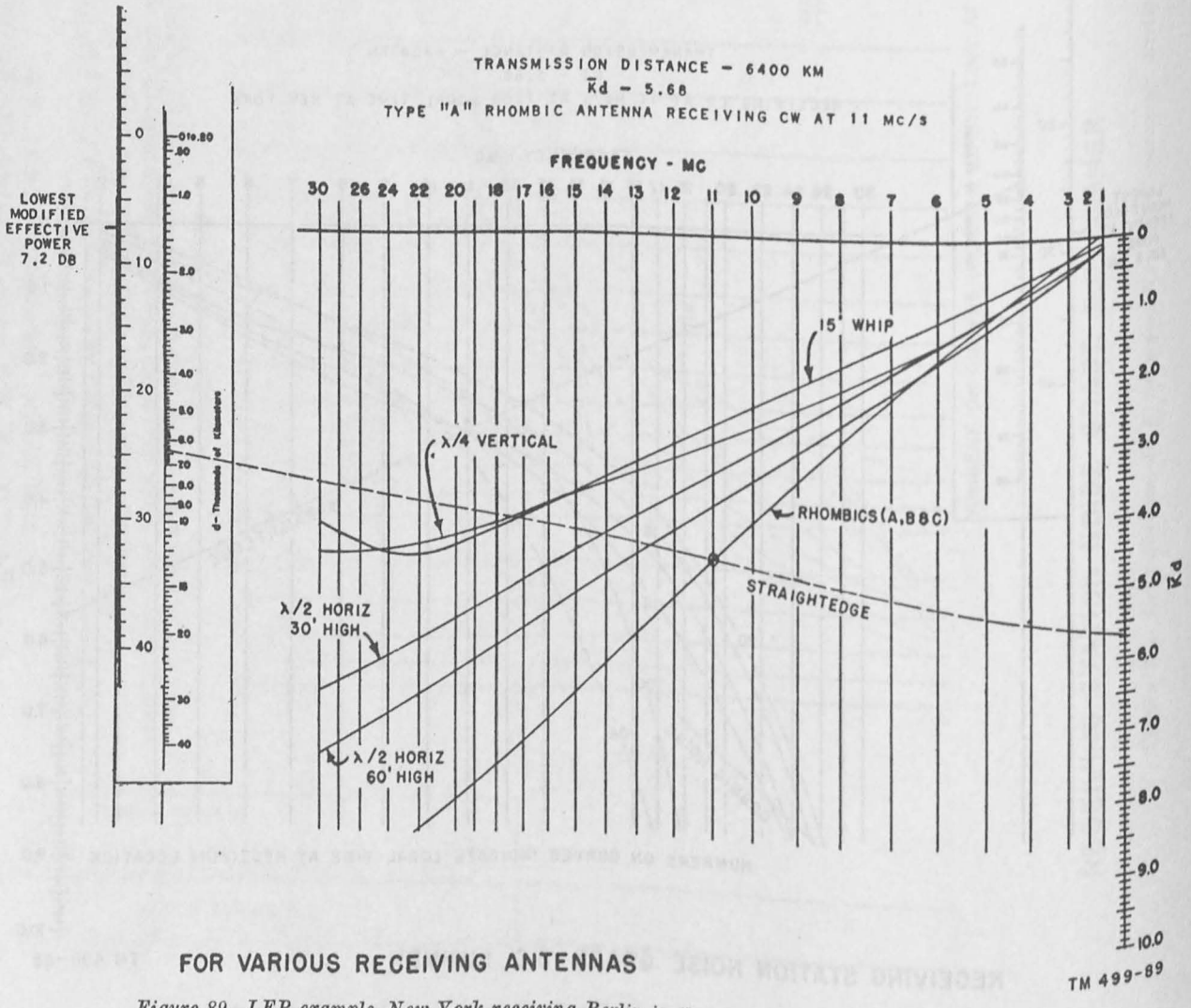


Figure 89. LEP example, New York receiving Berlin in the presence of receiver set noise only.

with the straightedge intersecting the distance scale at the transmission distance at 6,400 km and the lowest modified effective power (7.2 db) is read at the horizontal index mark from the modified effective power scale. The lowest modified effective power for the receiver noise limitation is 7.2 db. The LEP for the atmospheric noise limitation is equal to the lowest modified effective power (28.5 db) minus the discrimination gain (20 db) plus the type of service gain (—9.0 db). The LEP for the receiver noise limitation is equal to the lowest modified effective power (7.2 db) plus the type of service gain (—9.0 db). The LEP for the transmission circuit is equal to the greater of these two values, or —0.5 db. At 1200 local time, New York, it is possible to receive Berlin with an effective transmitter power of at least --0.5 db in June 1946.

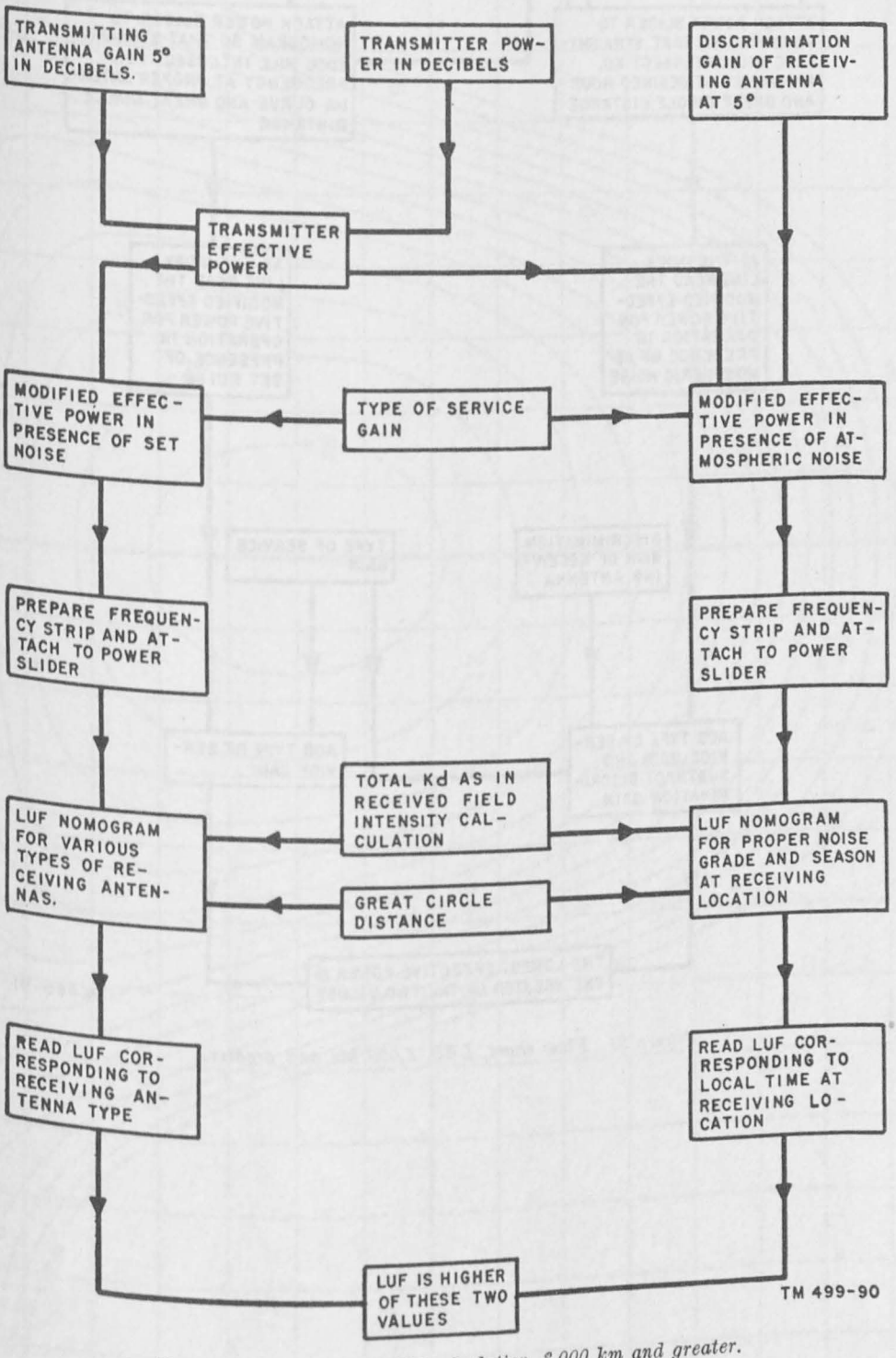


Figure 90. Flow chart, LUF calculation, 3,000 km and greater.

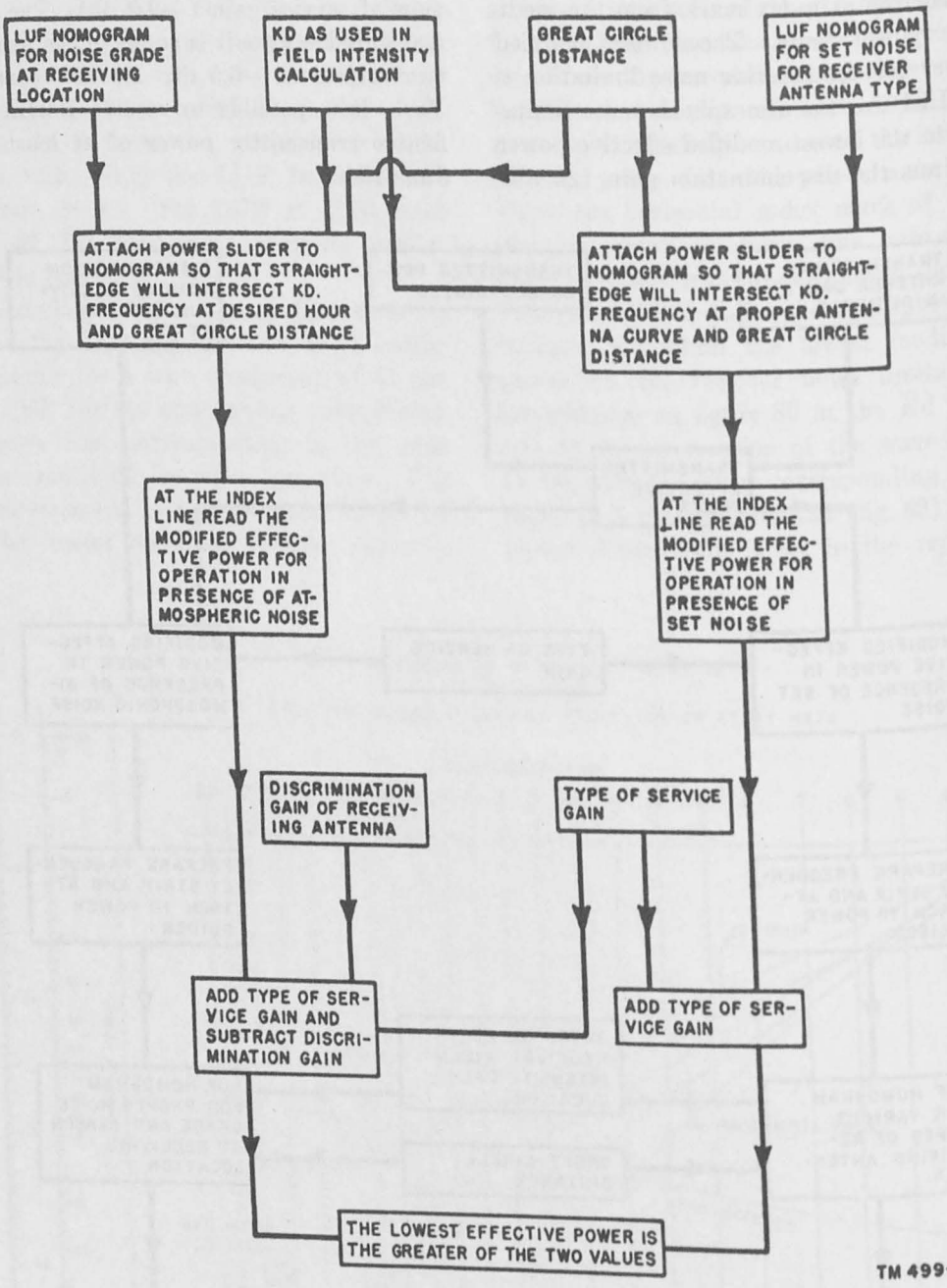


Figure 91. Flow chart, LEP, 3,000 km and greater.

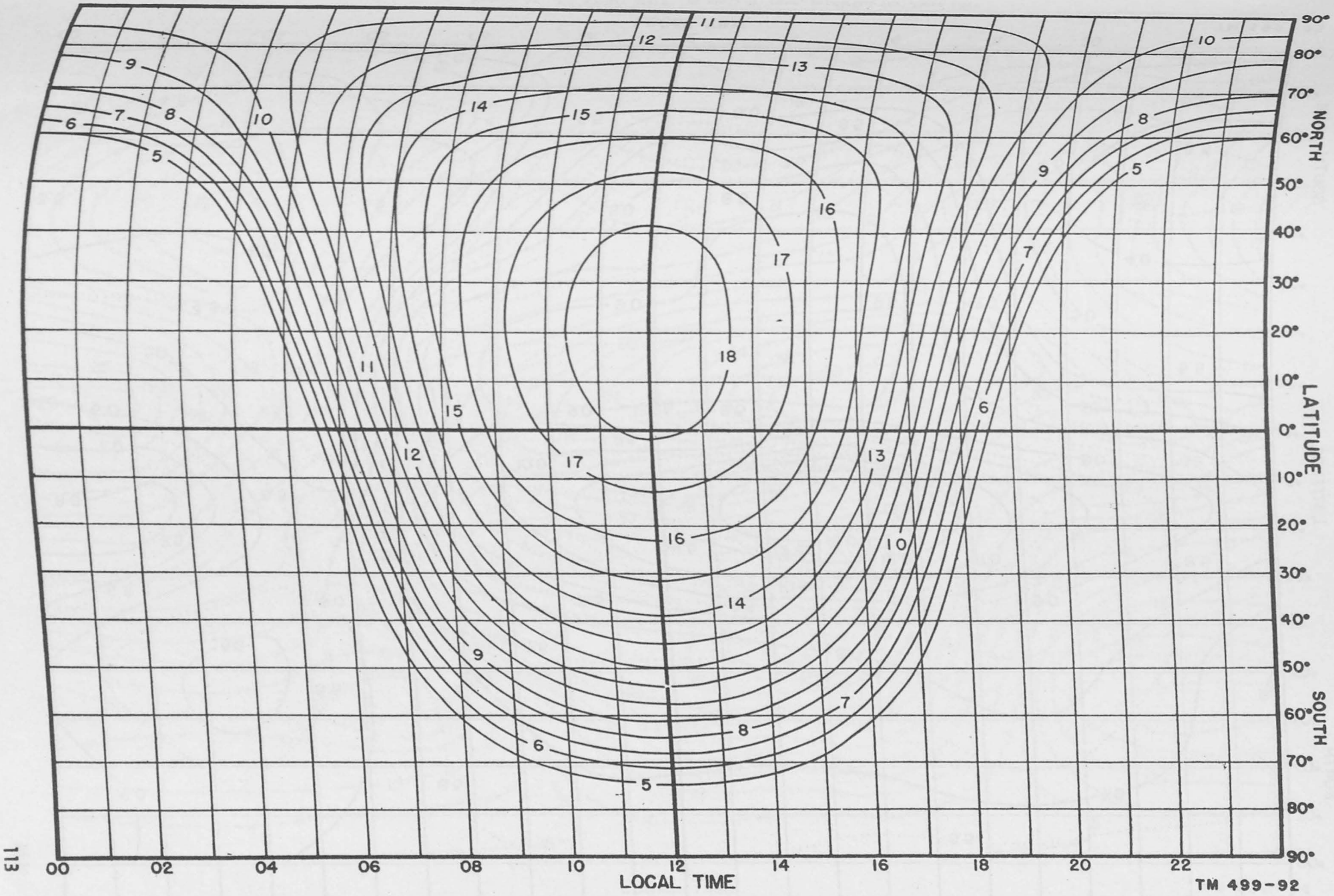


Figure 92. E 2000 MUF (in mc) predicted for June 1946.

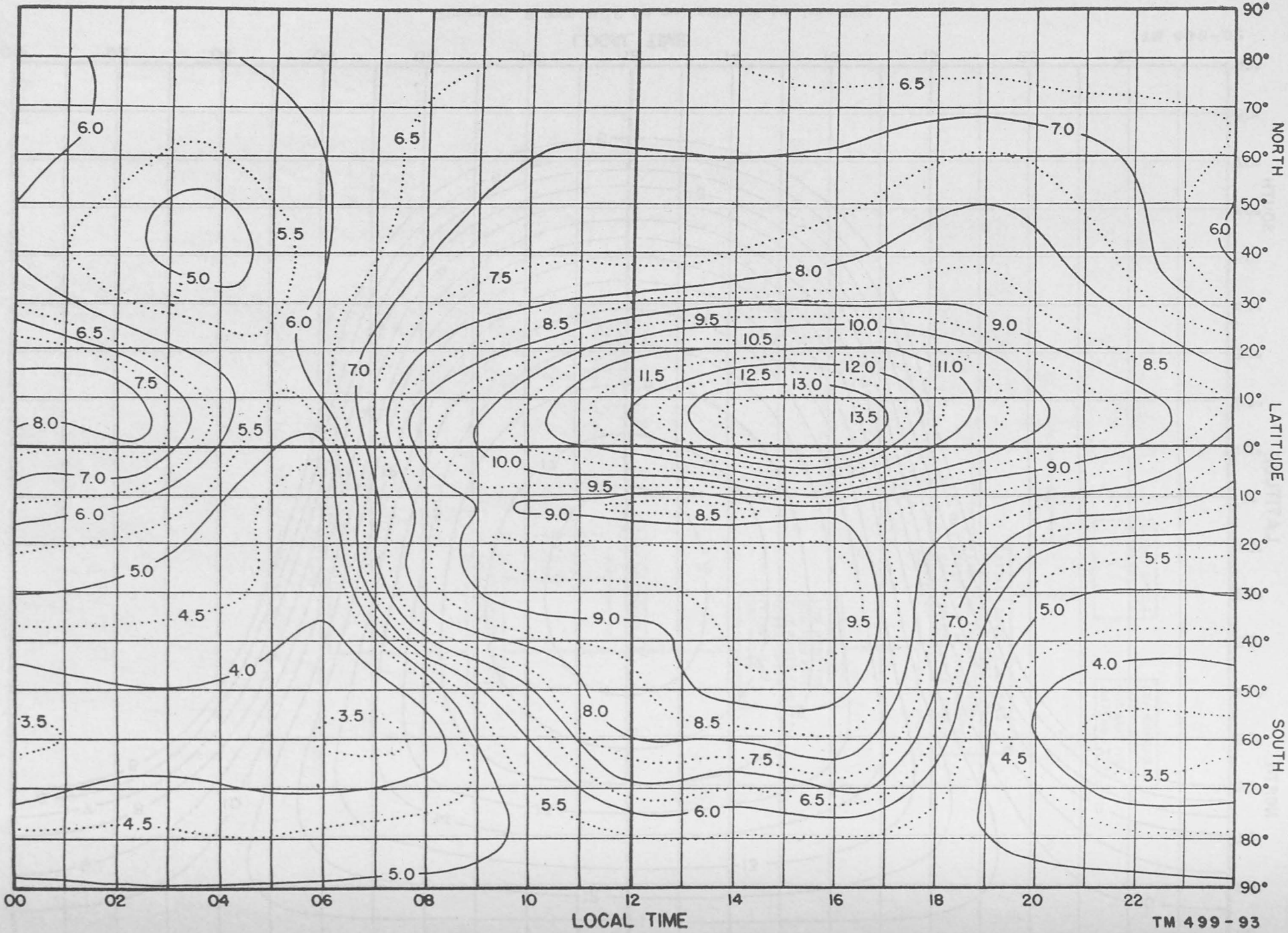


Figure 93. F2 ZERO MUF (in mc), W zone, predicted for June 1946.

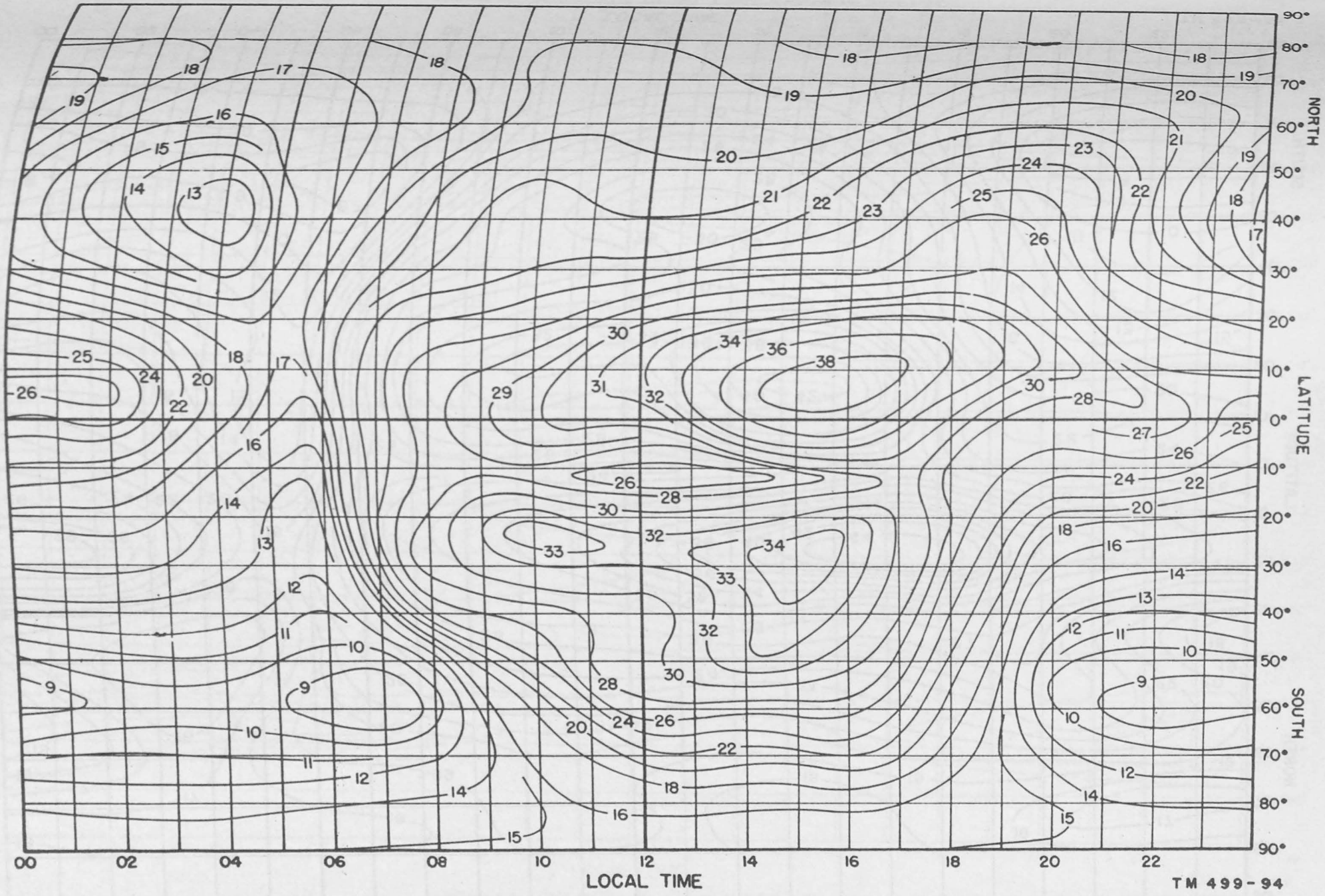


Figure 94. F2 4000 MUF (in mc), W zone predicted for june 1946.

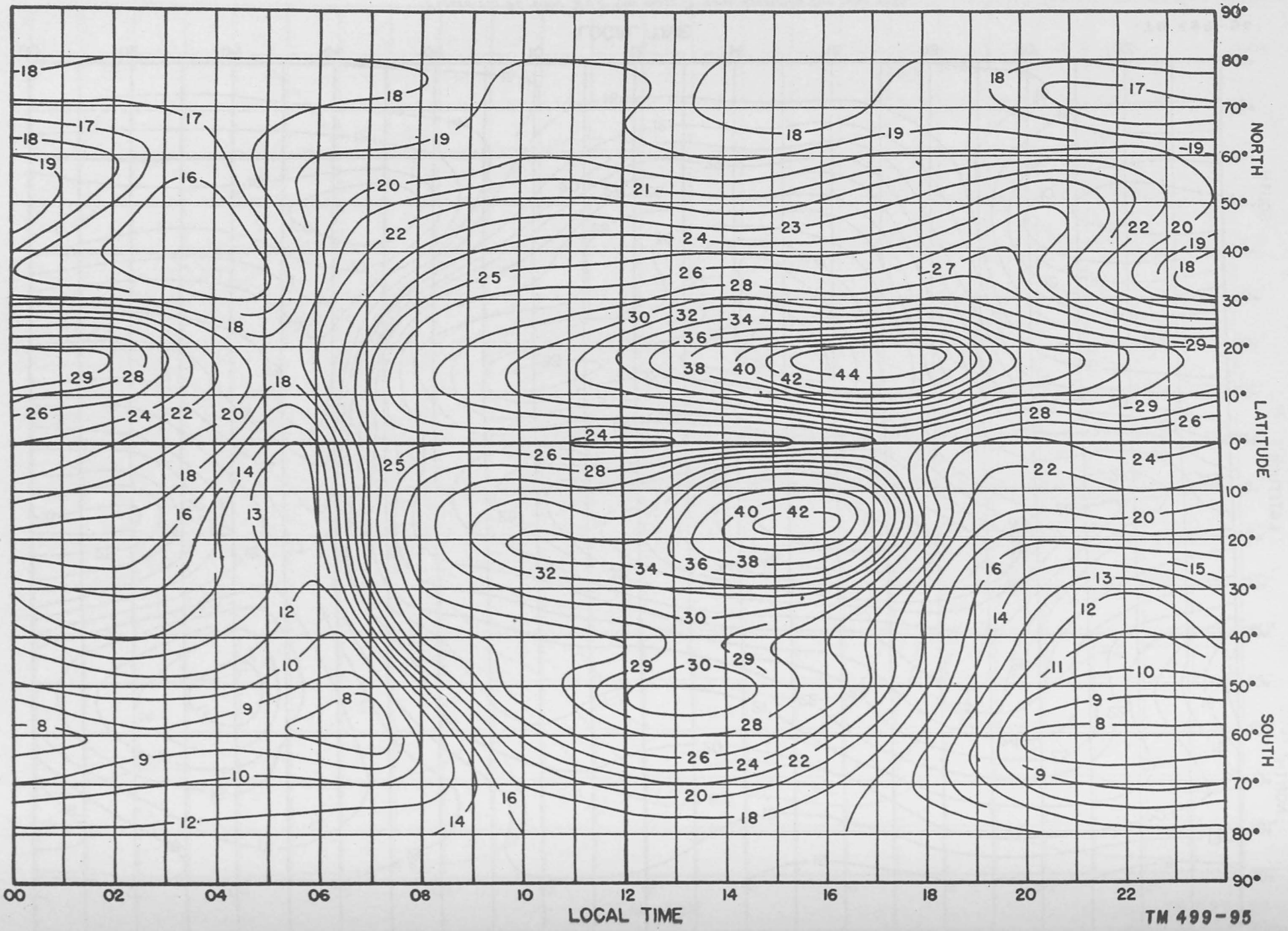


Figure 95. F2 4000 MUF (in mc), I zone, predicted for June 1946.

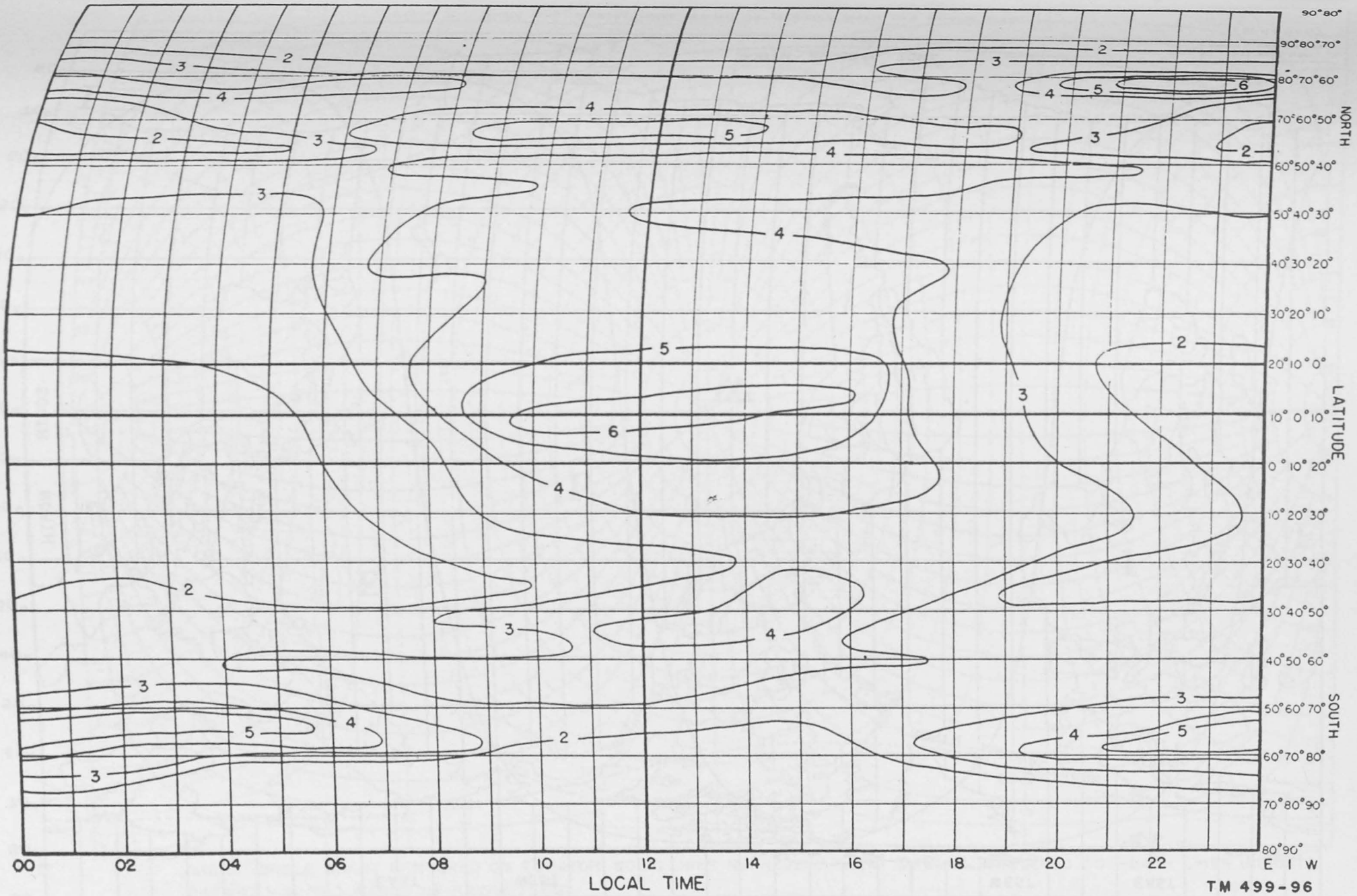
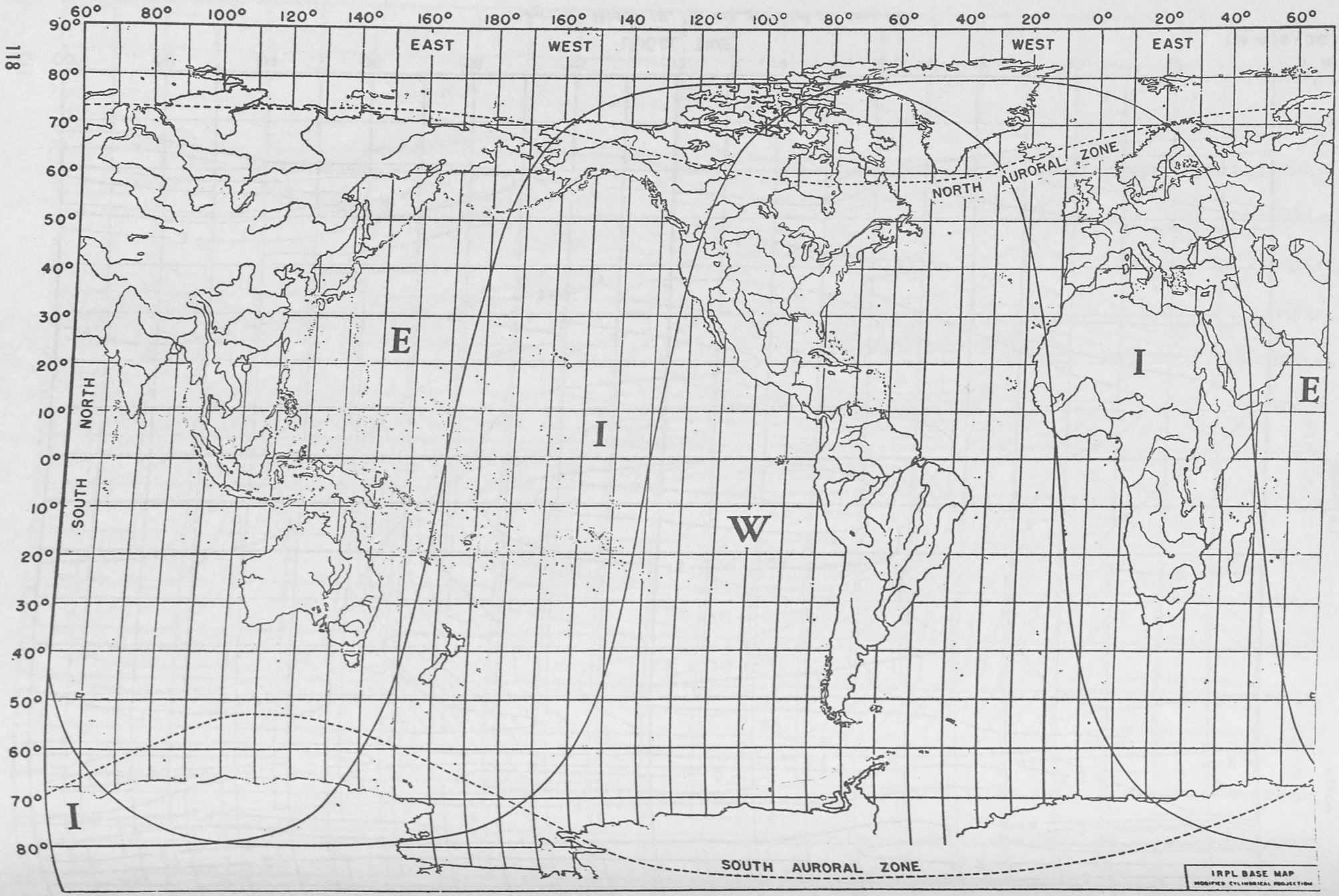


Figure 96. Median fE. (in mc), predicted for June 1946.



TM 499-97

Figure 97. World map, showing zones covered by predicted charts and auroral zones.

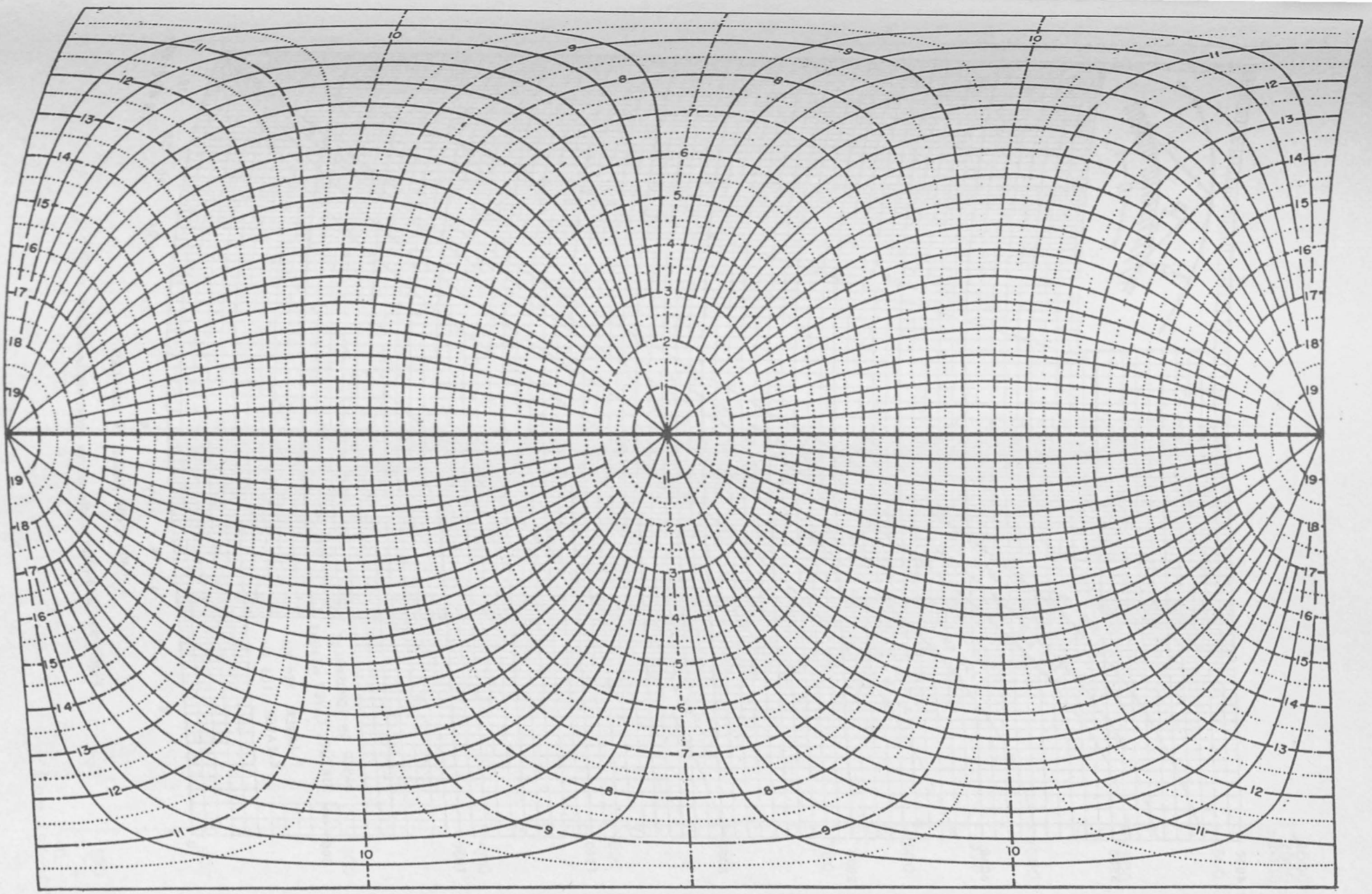


Figure 98. Great circle distance chart.

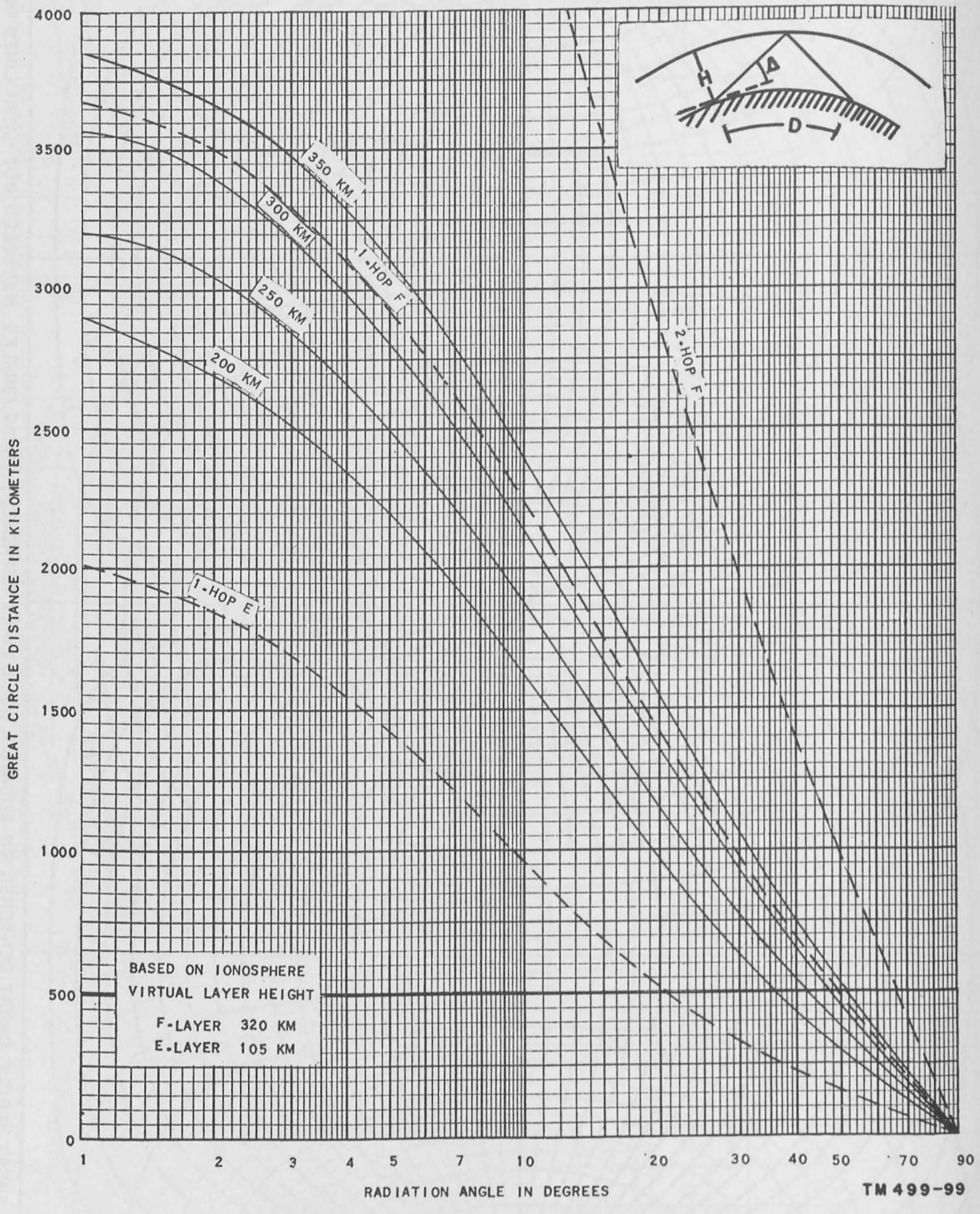
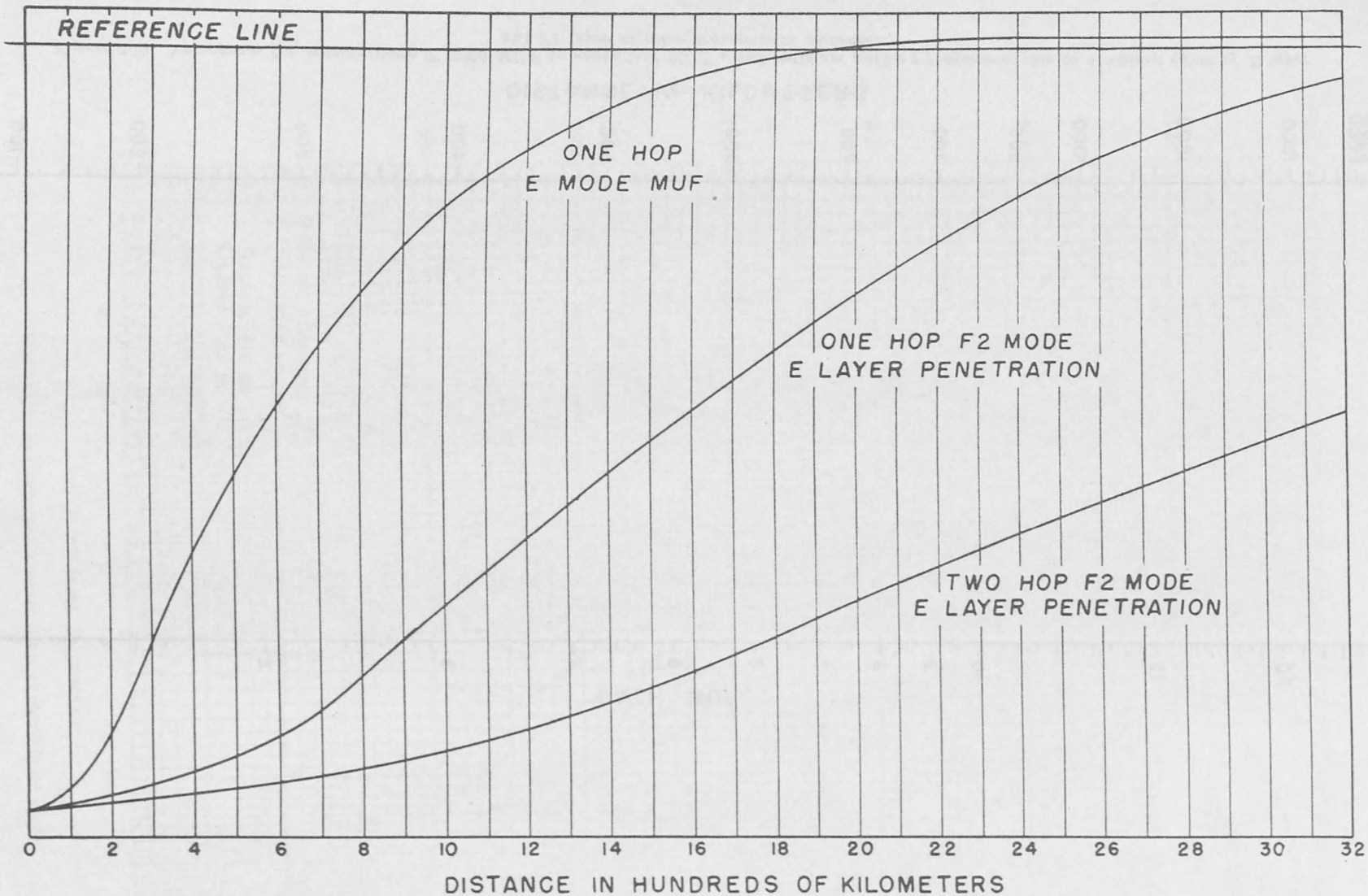
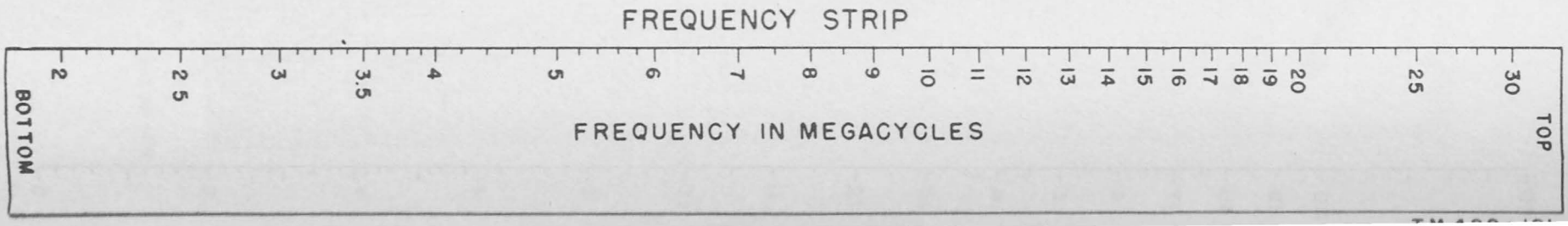


Figure 99. Radiation angle versus great circle distance curves.

Figure 100. Nomogram for transforming E 2000 MUF to equivalent MUF's and optimum working frequencies due to combined effect of E layer and F1 layer at other transmission distances.


REFERENCE LINE
ONE HOP
E MODE MUF
ONE HOP F2 MODE
E LAYER PENETRATION
TWO HOP F2 MODE
E LAYER PENETRATION
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
DISTANCE IN HUNDREDS OF KILOMETERS


FREQUENCY STRIP
BOTTOM
2 2.5 3 3.5 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 25 30
TOP
FREQUENCY IN MEGACYCLES

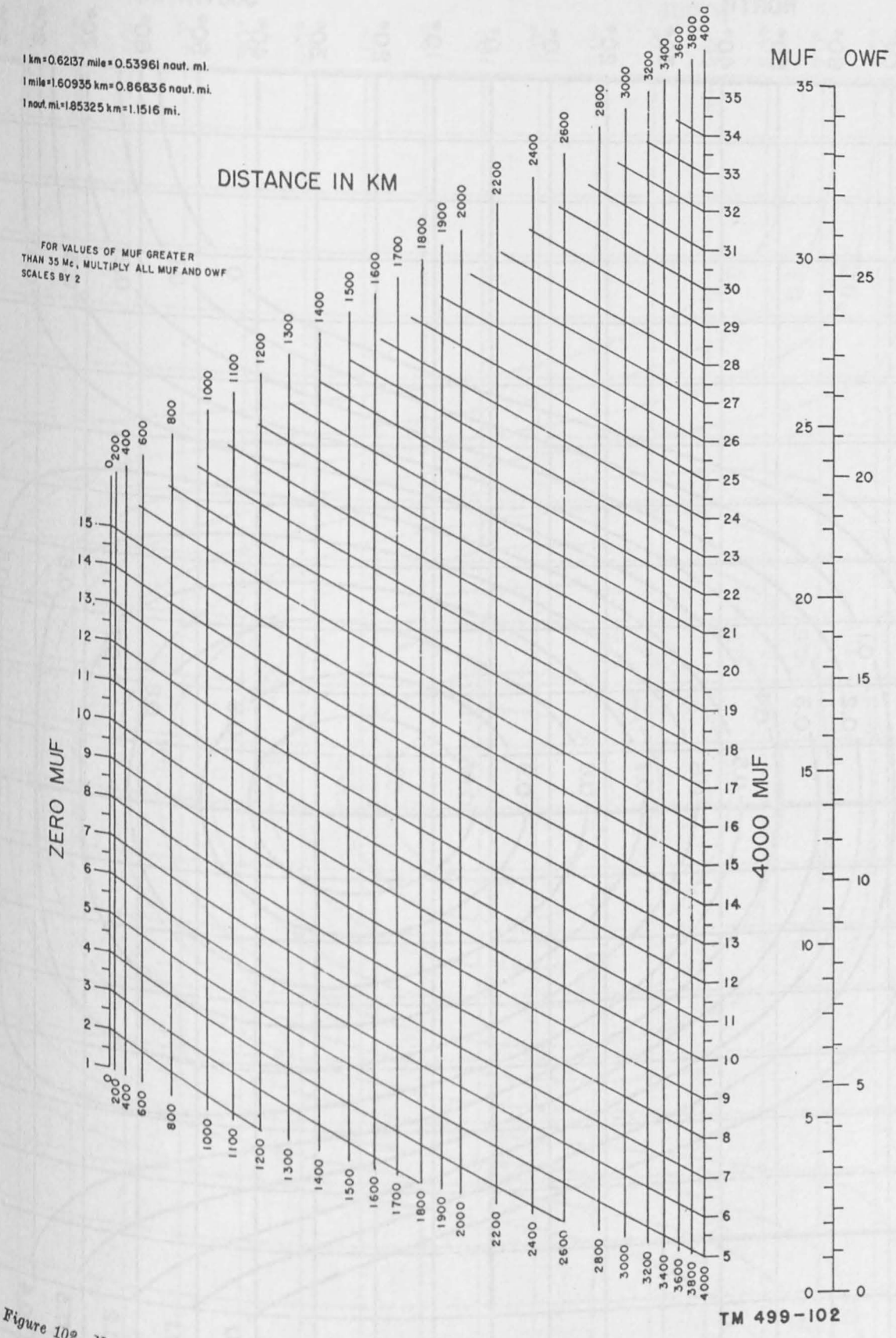
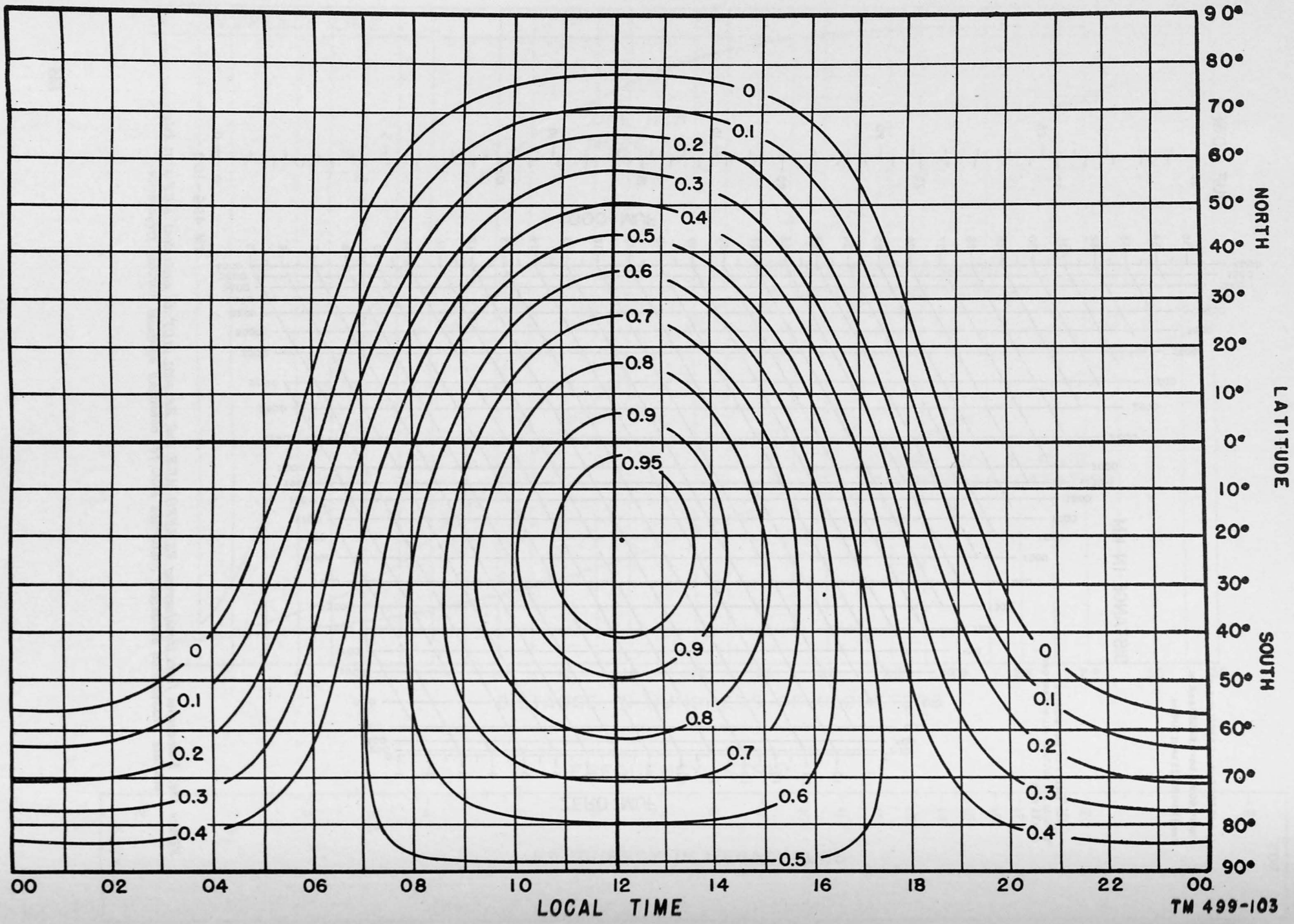
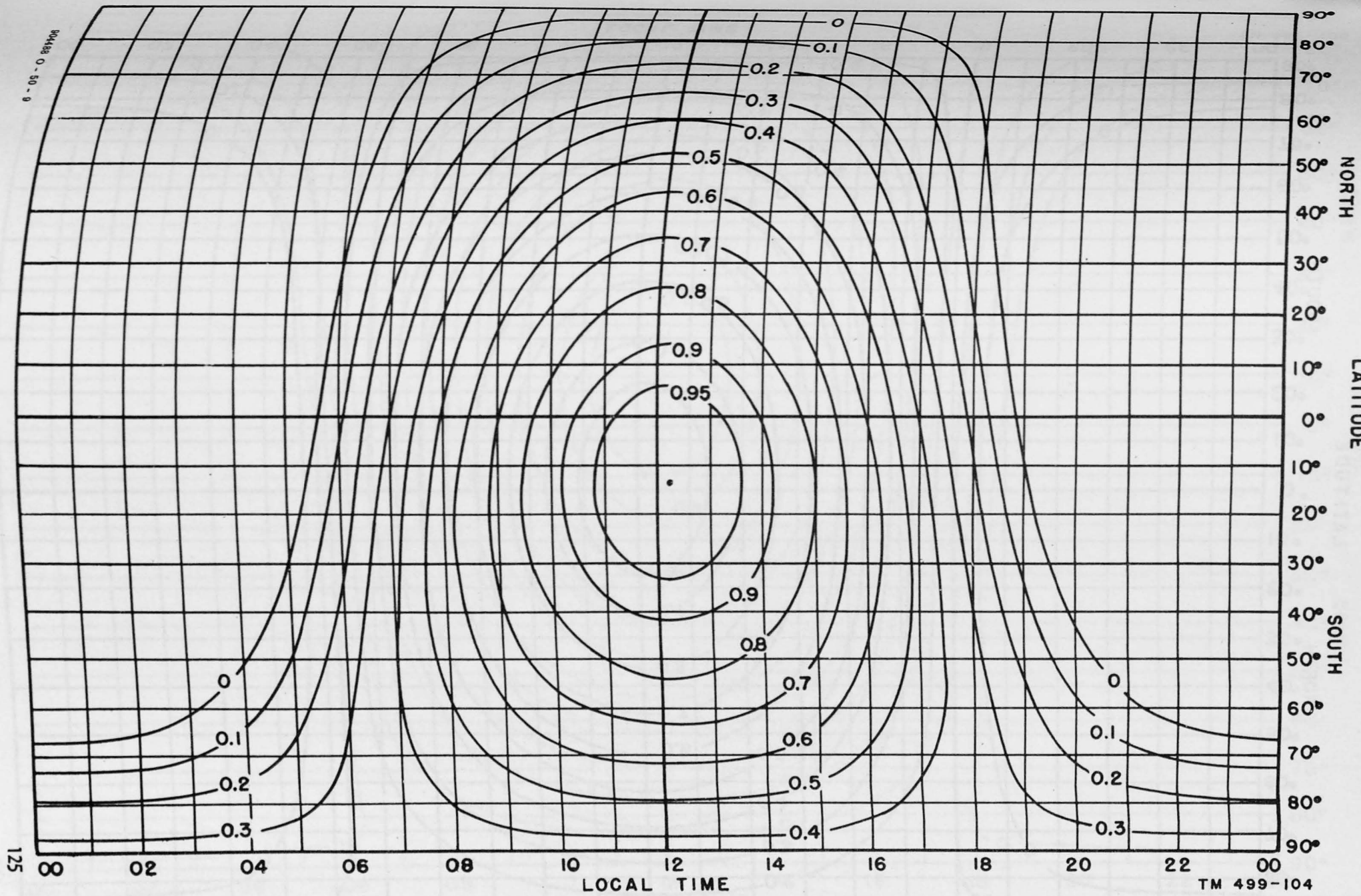


Figure 102. Nomogram from transforming F2 ZERO MUF and F2 4001 MUF to equivalent MUF's at intermediate transmission distances; conversion scale for obtaining optimum working frequencies


0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.95
0.9
0.8
0.7
0.6
0.5
0
0.1
0.2
0.3
0.4
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
NORTH
LATITUDE
SOUTH
00
02
04
06
08
10
12
14
16
18
20
22
00
LOCAL TIME
TM 499-103


0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.95
0
0.1
0.2
0.3
0.9
0.8
0.7
0.6
0.5
0.4
0
0.1
0.2
0.3
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
NORTH
LATITUDE
SOUTH
00
02
04
06
08
10
12
14
16
18
20
22
00
LOCAL TIME
TM 499-104

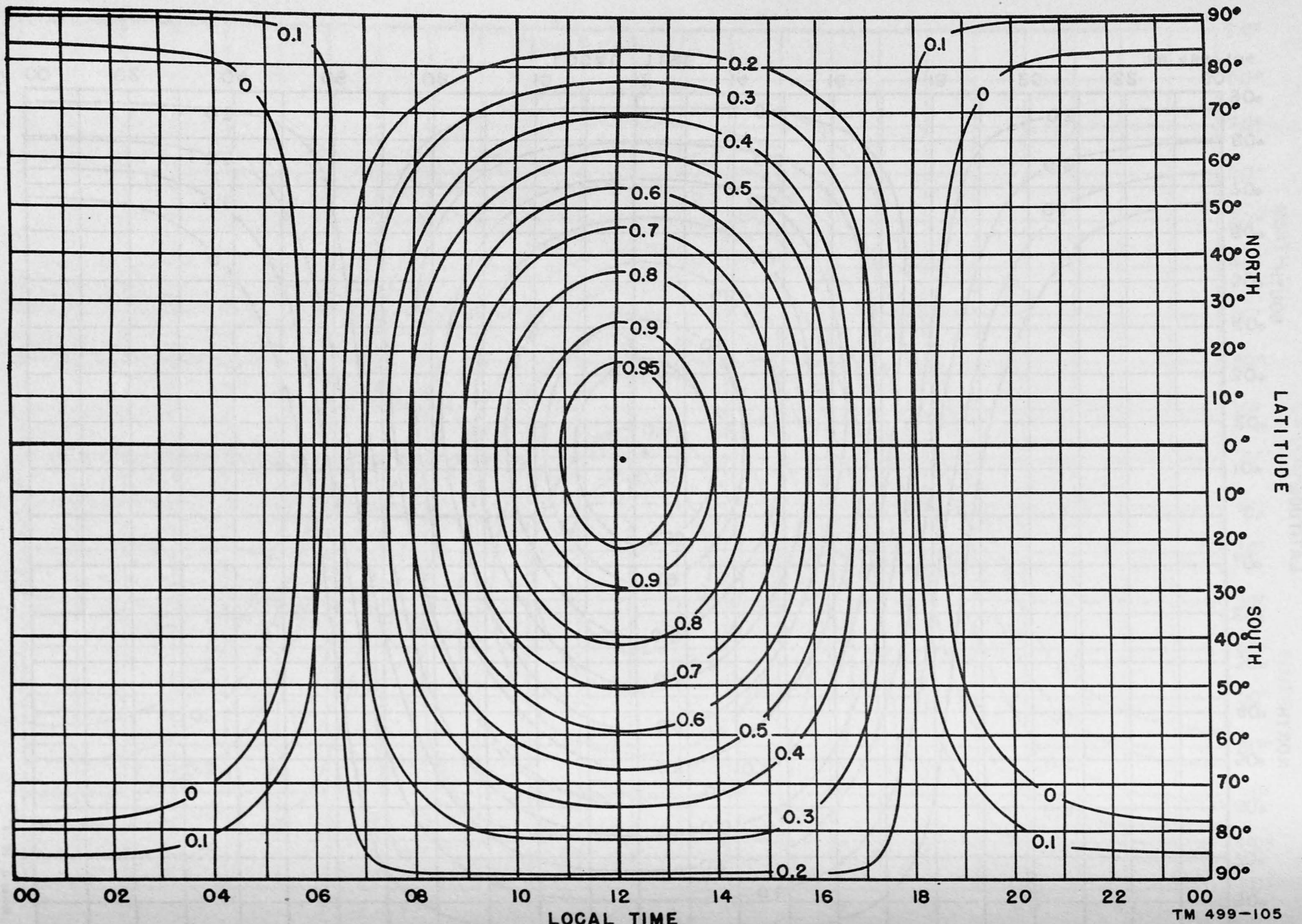
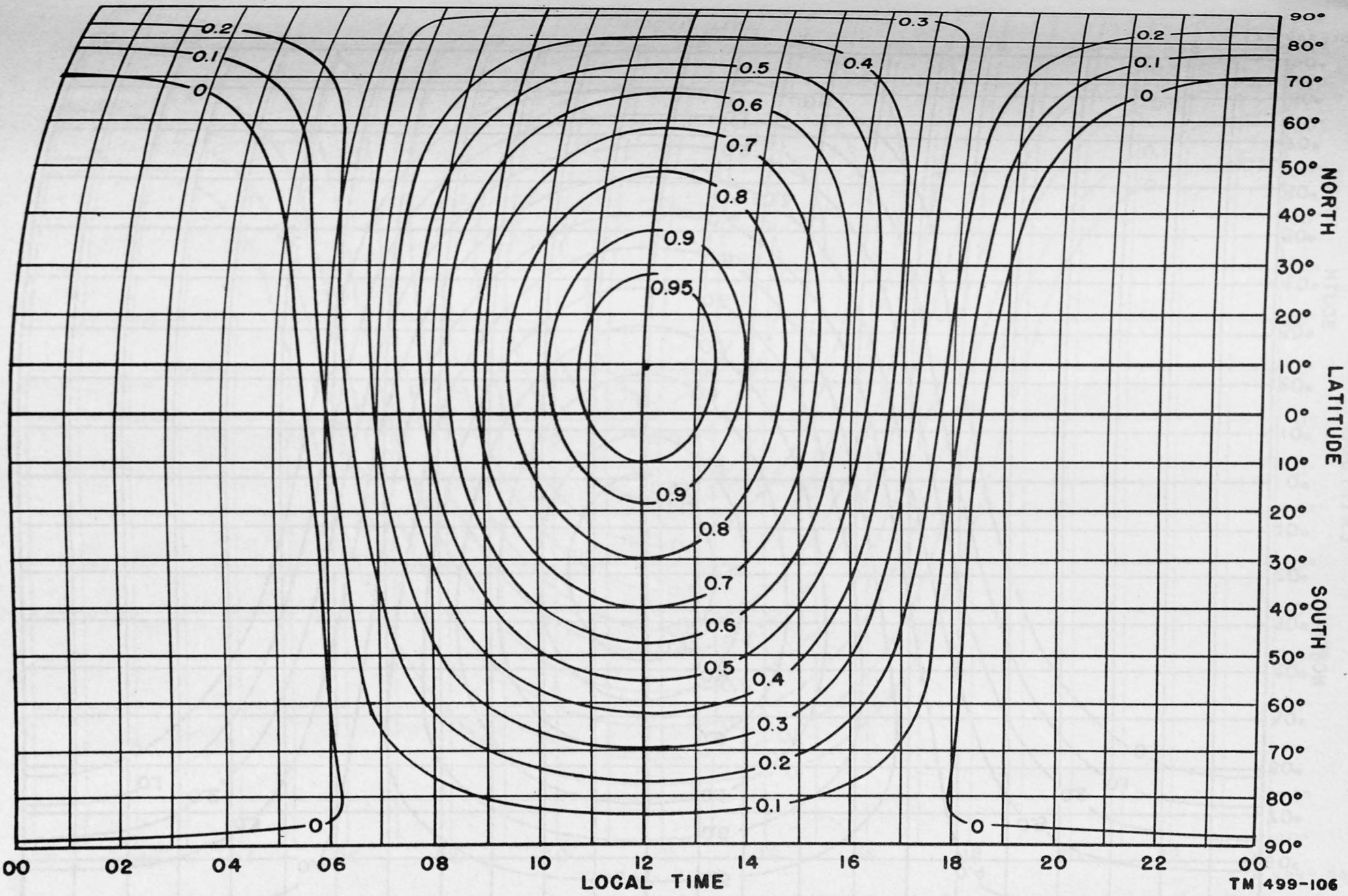


Figure 105. Absorption index chart (excluding auroral absorption) for March.


0.2
0.1
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.95
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.1
0
0
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
NORTH
LATITUDE
SOUTH
00
02
04
06
08
10
12
14
16
18
20
22
00
LOCAL TIME
TM 499-106

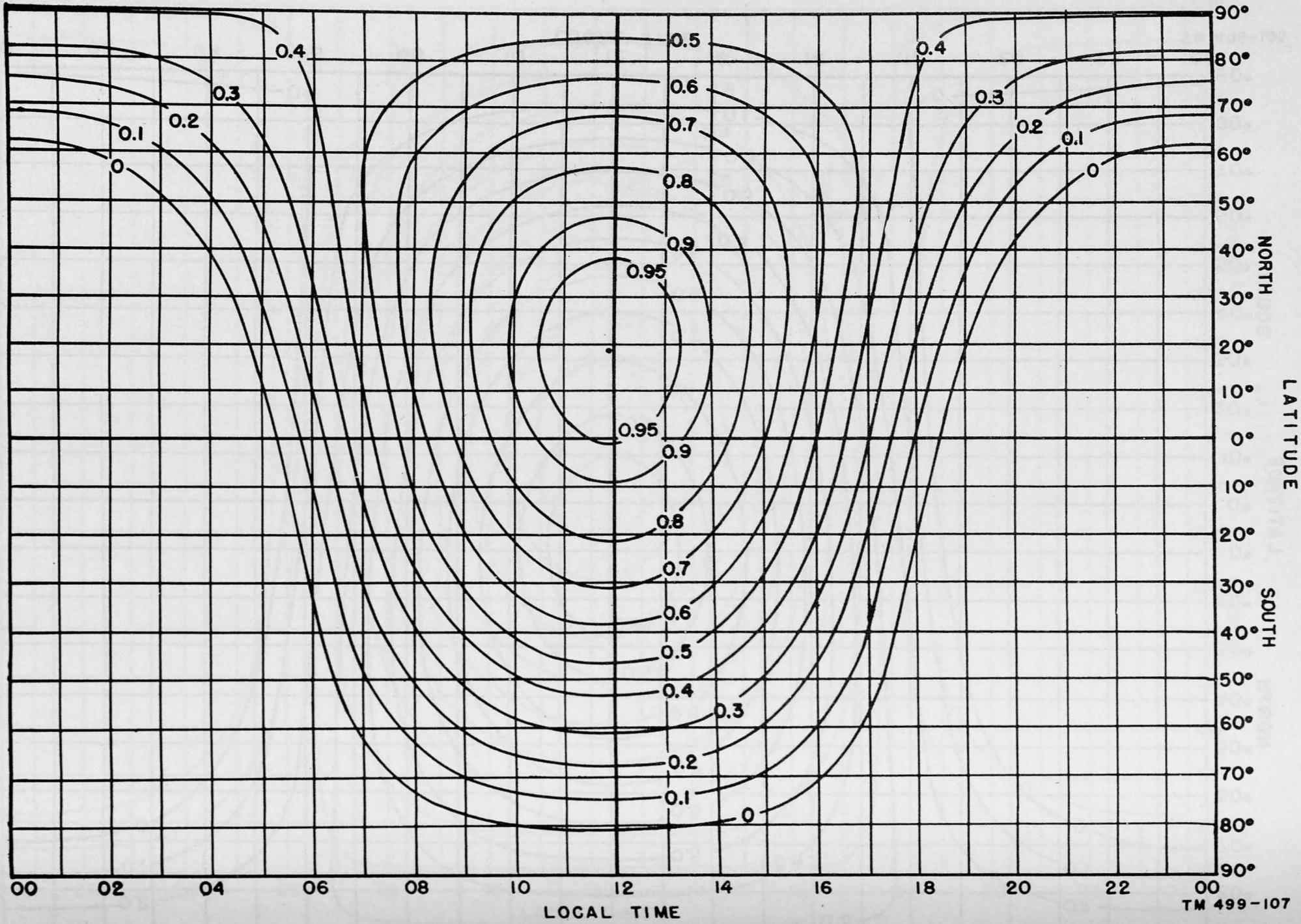


Figure 107. Absorption index chart (excluding auroral absorption) for May.

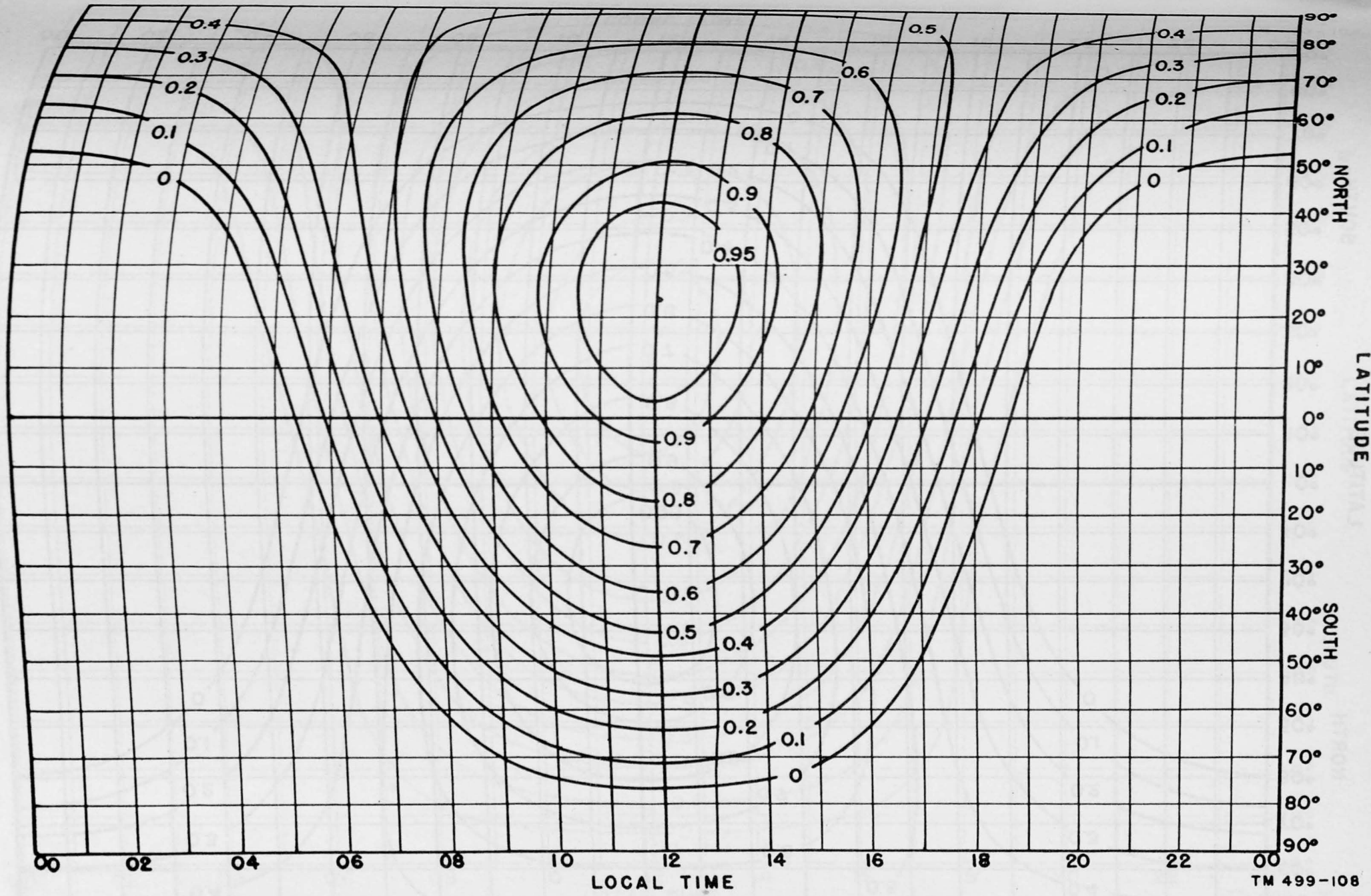


Figure 108. Absorption index chart (excluding auroral absorption) for June.

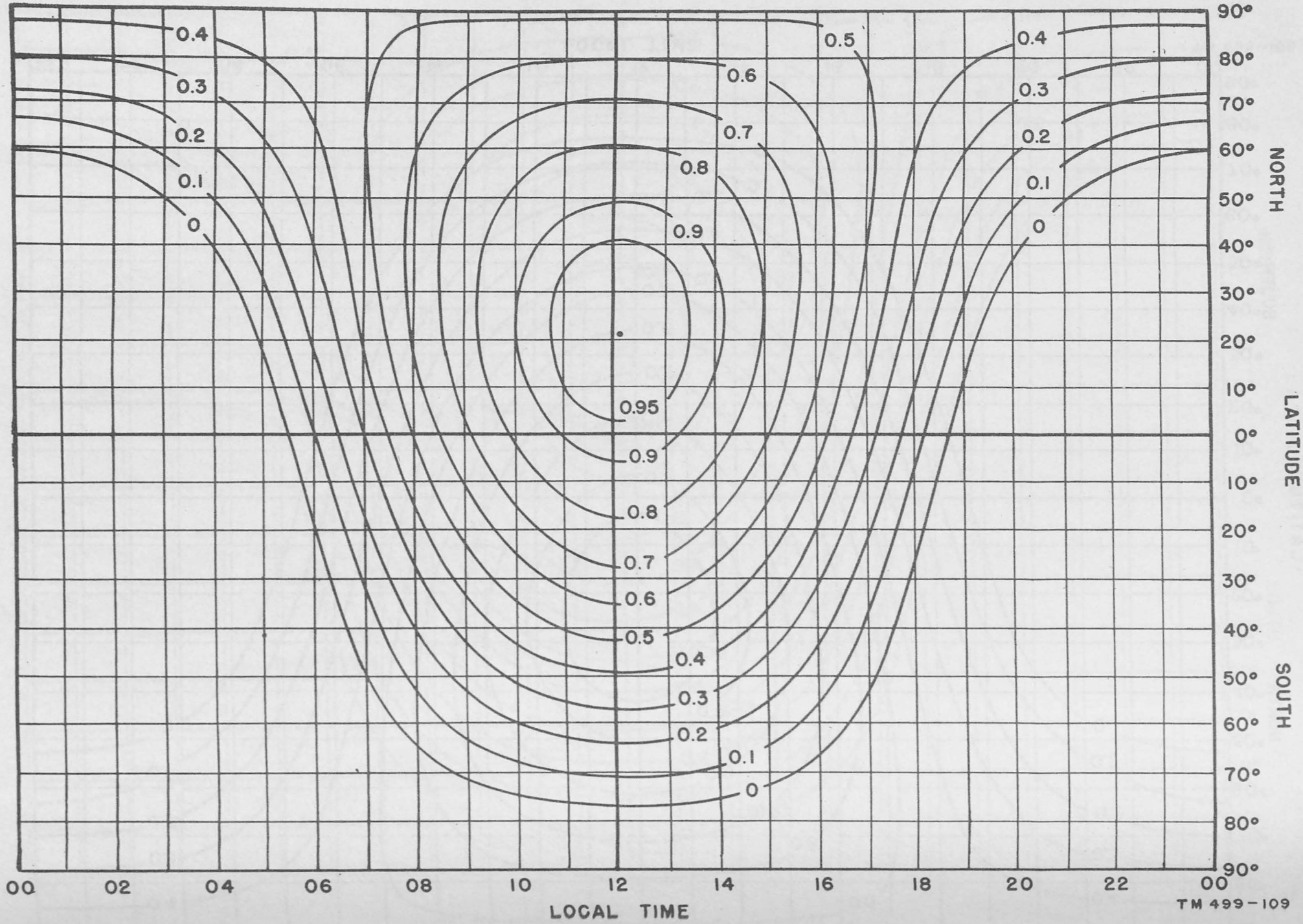


Figure 109. Absorption index chart (excluding auroral absorption) for July.

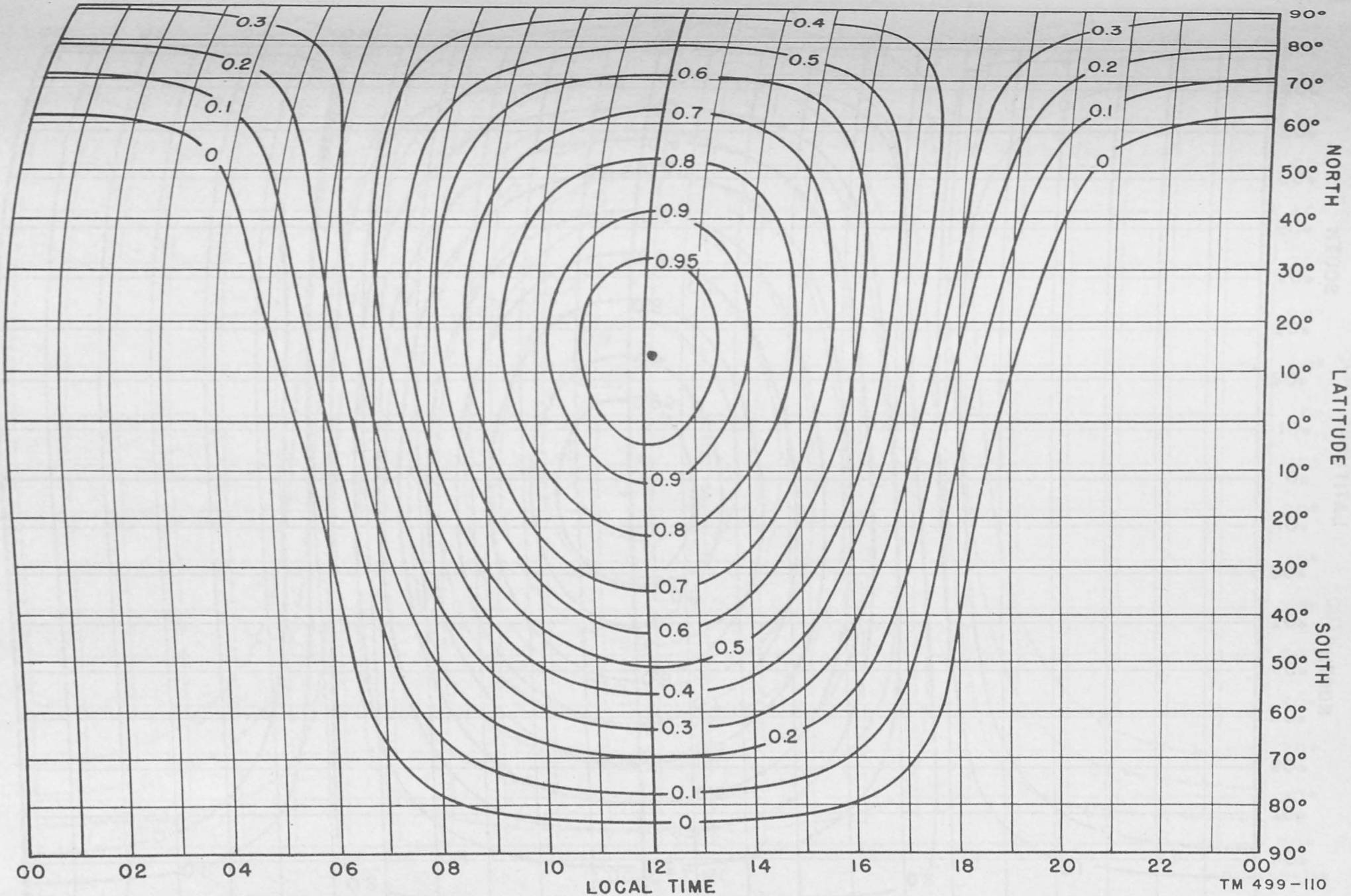


Figure 110, Absorption index chart (excluding auroral absorption) for August.

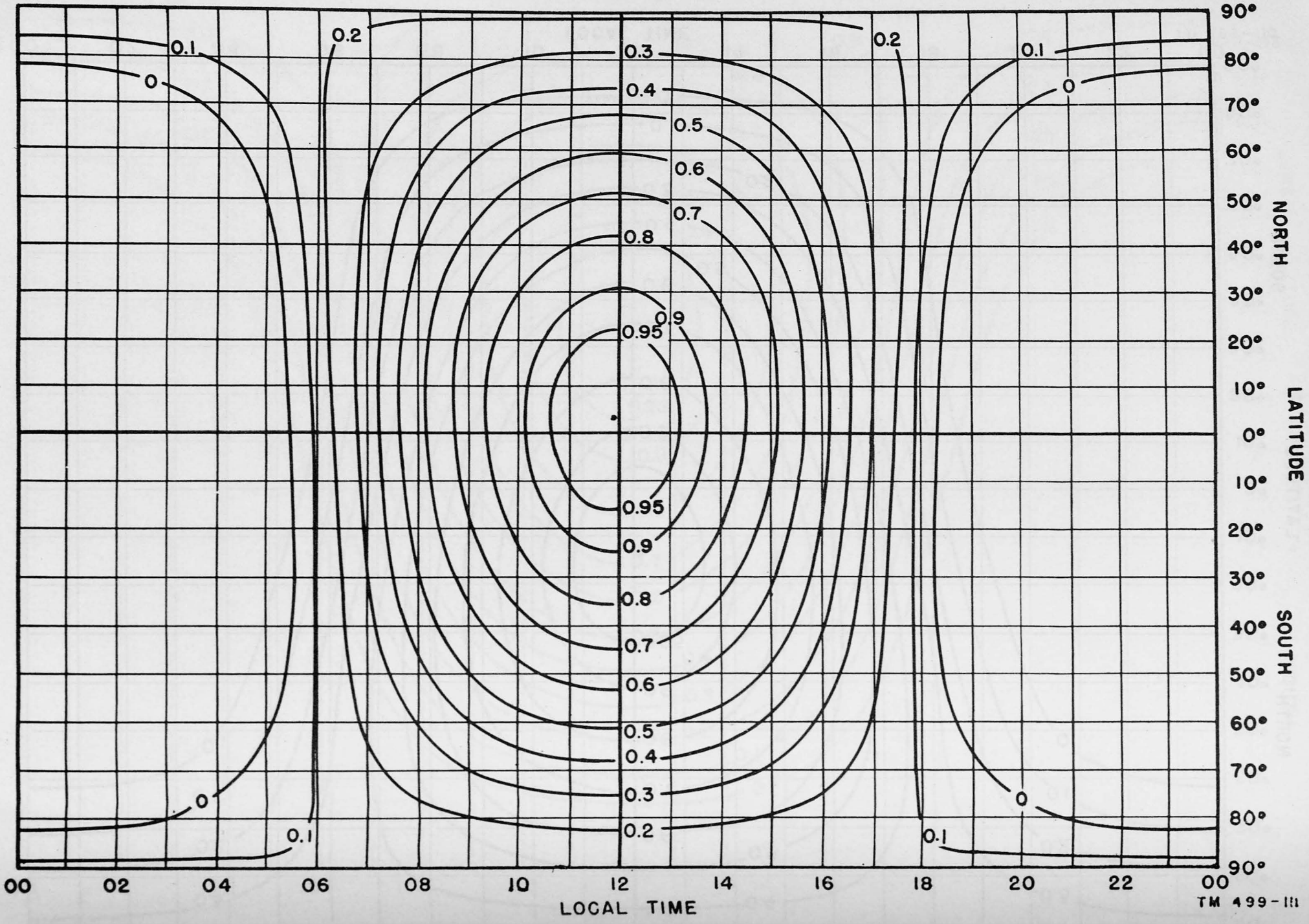


Figure 111. Absorption index chart (excluding auroral absorption) for September.

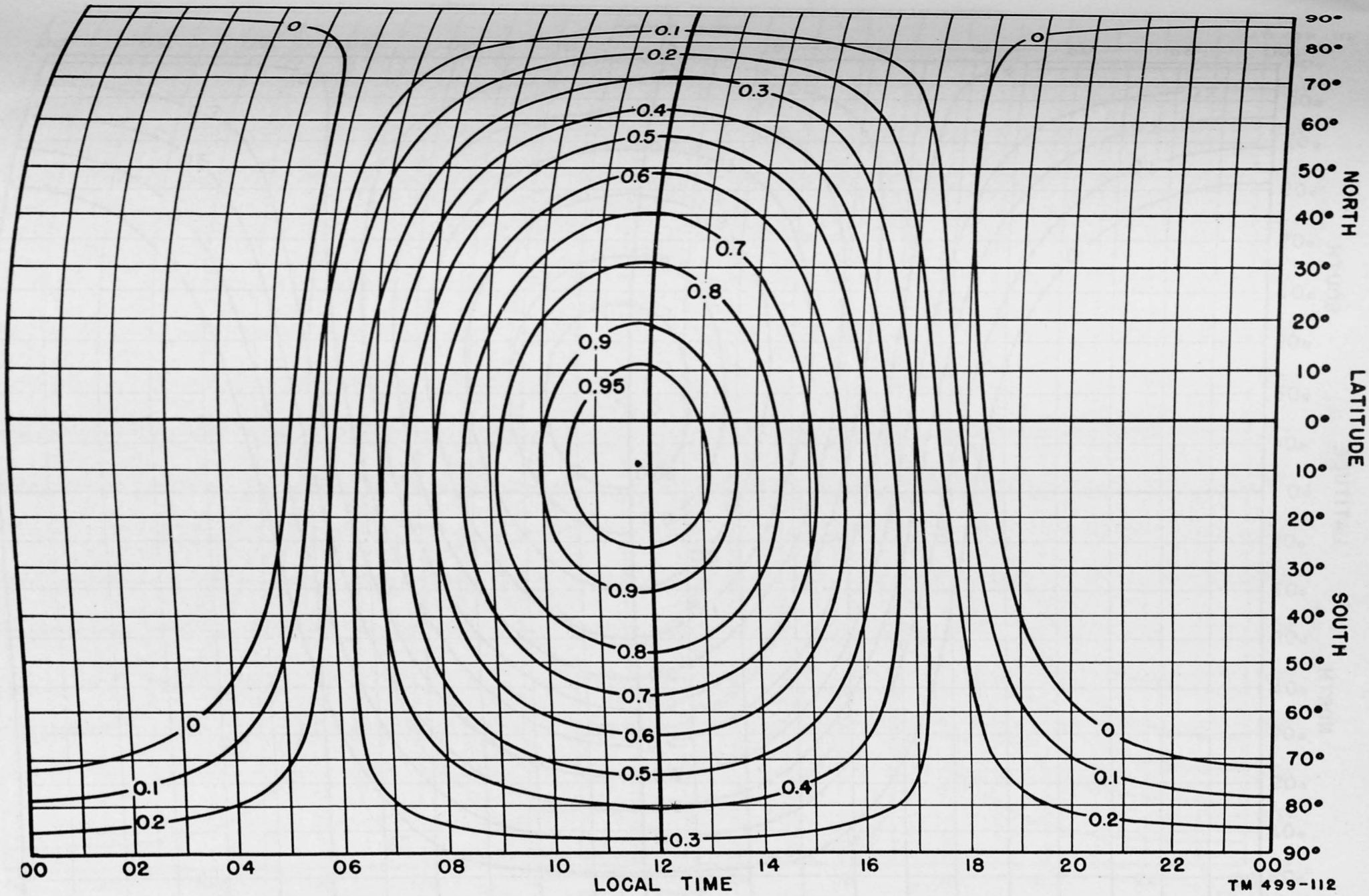


Figure 112. Absorption index chart (excluding auroral absorption) for October.

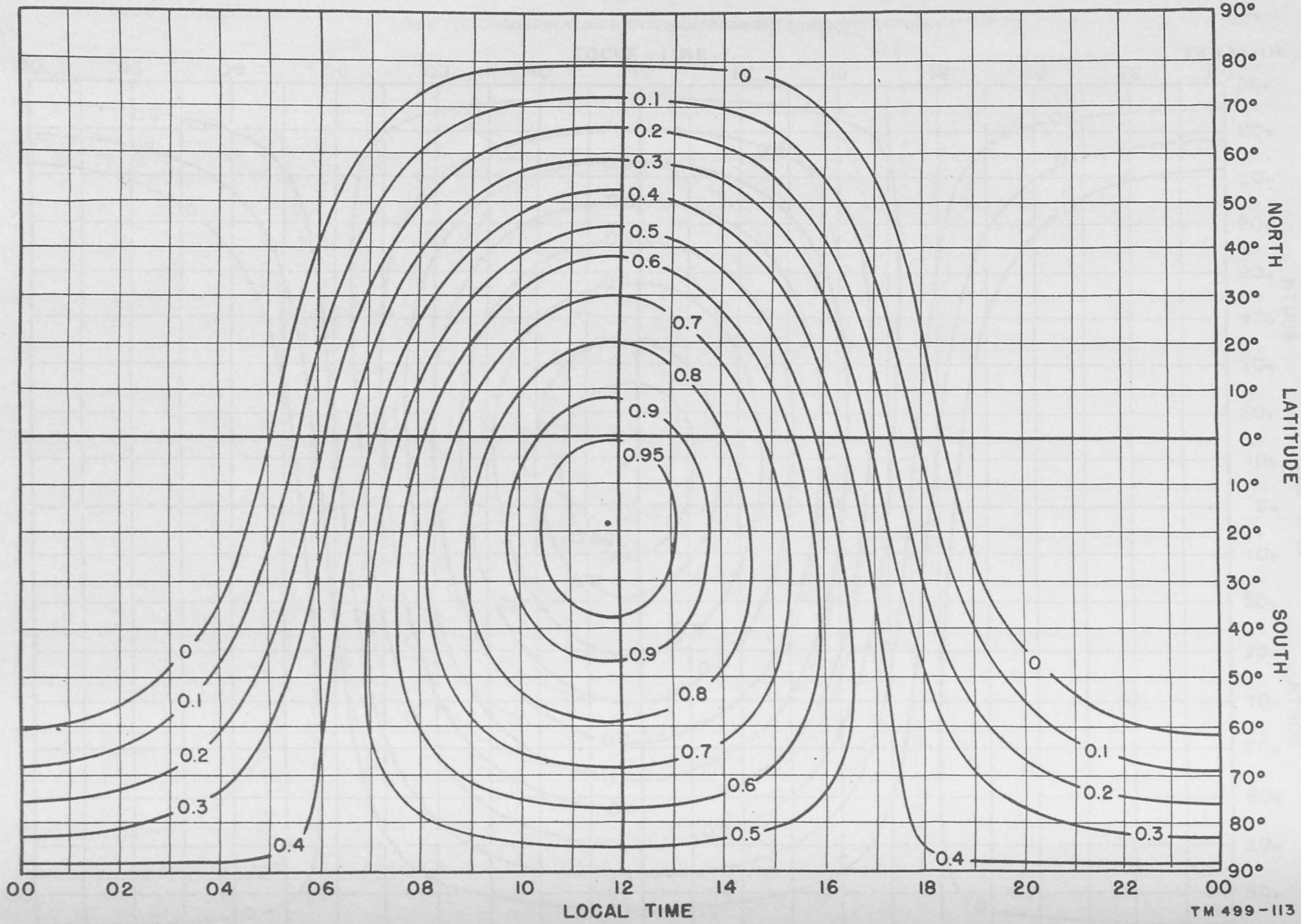
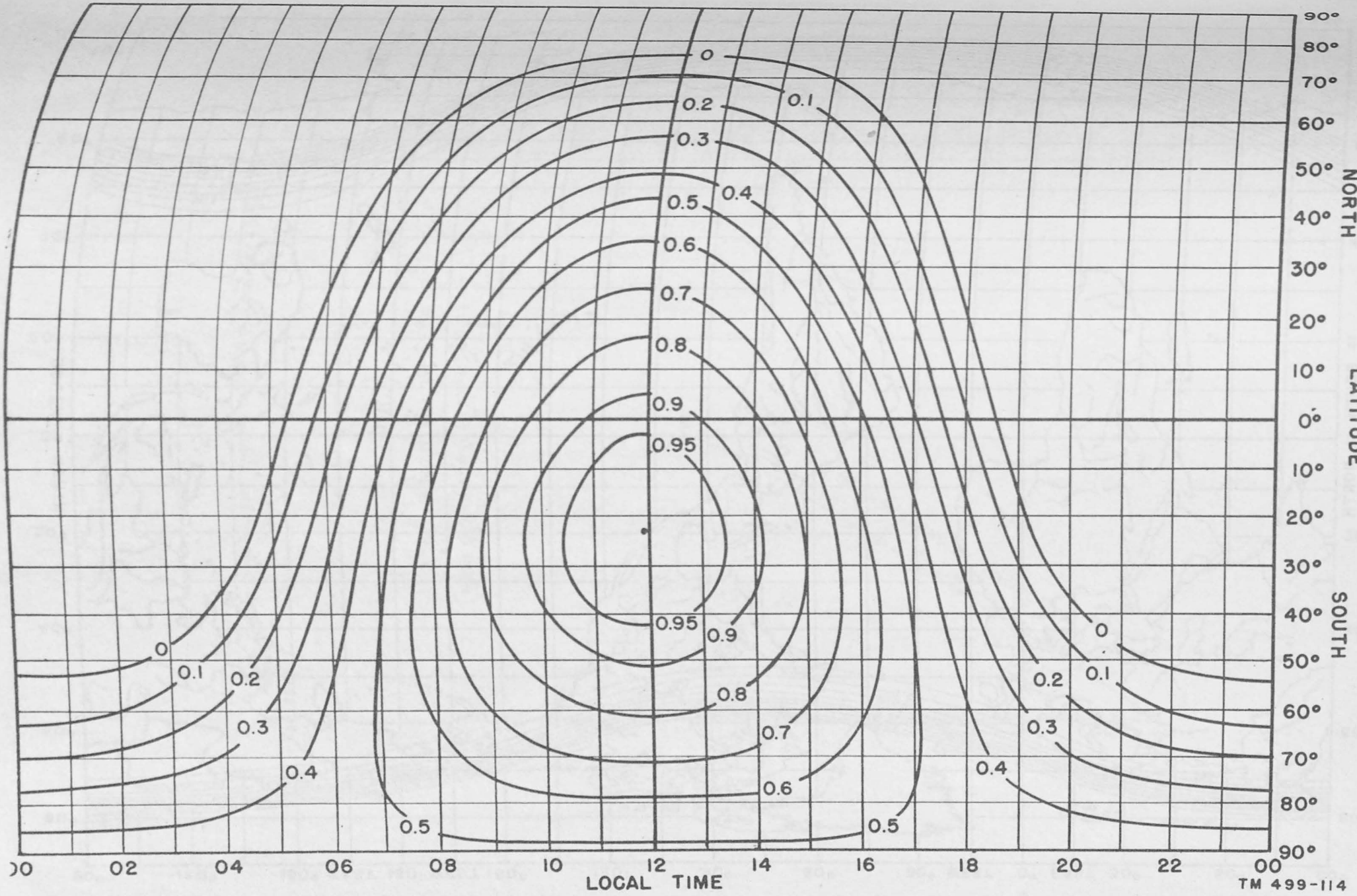


Figure 113. Absorption index chart (excluding auroral absorption) for November.


0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.95
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
NORTH
LATITUDE
SOUTH
00
02
04
06
08
10
12
14
16
18
20
22
00
LOCAL TIME
TM 499-114

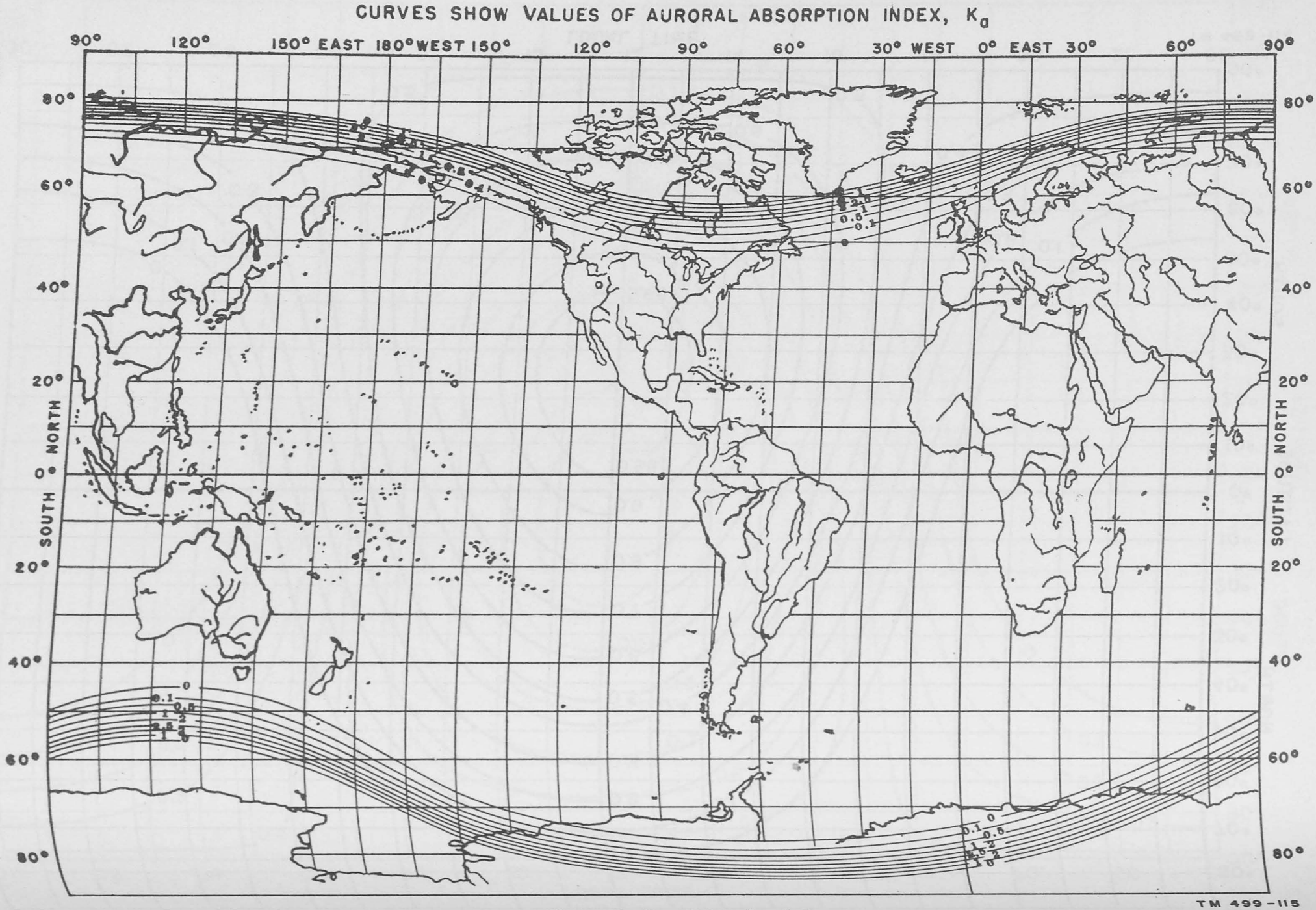


Figure 115. Auroral absorption chart.

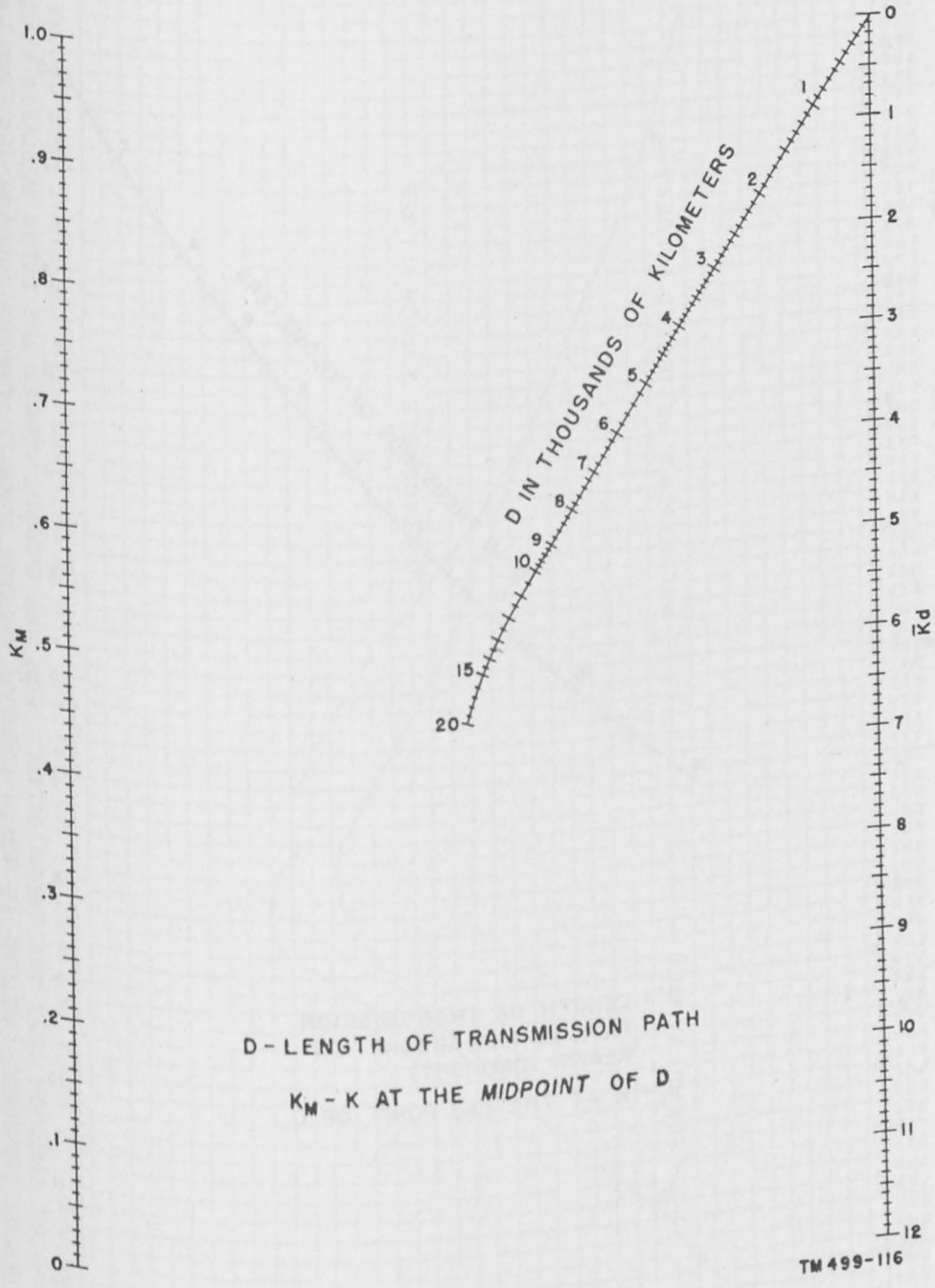


Figure 116. $\overline{K}d$ nomogram, transmission path entirely in the day region.

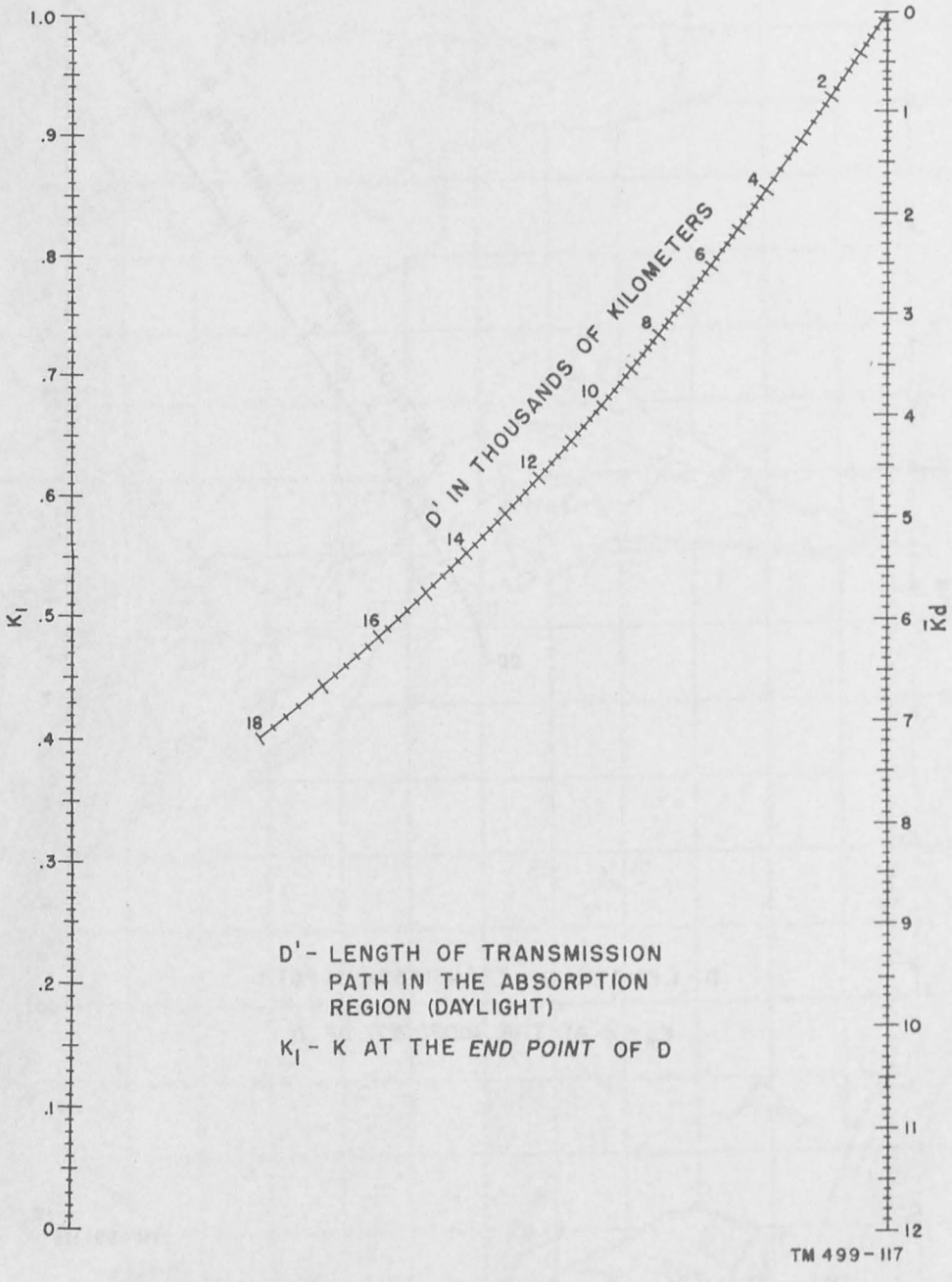


Figure 117. $\overline{Kd}$ nomogram, transmission path entirely in the day region.

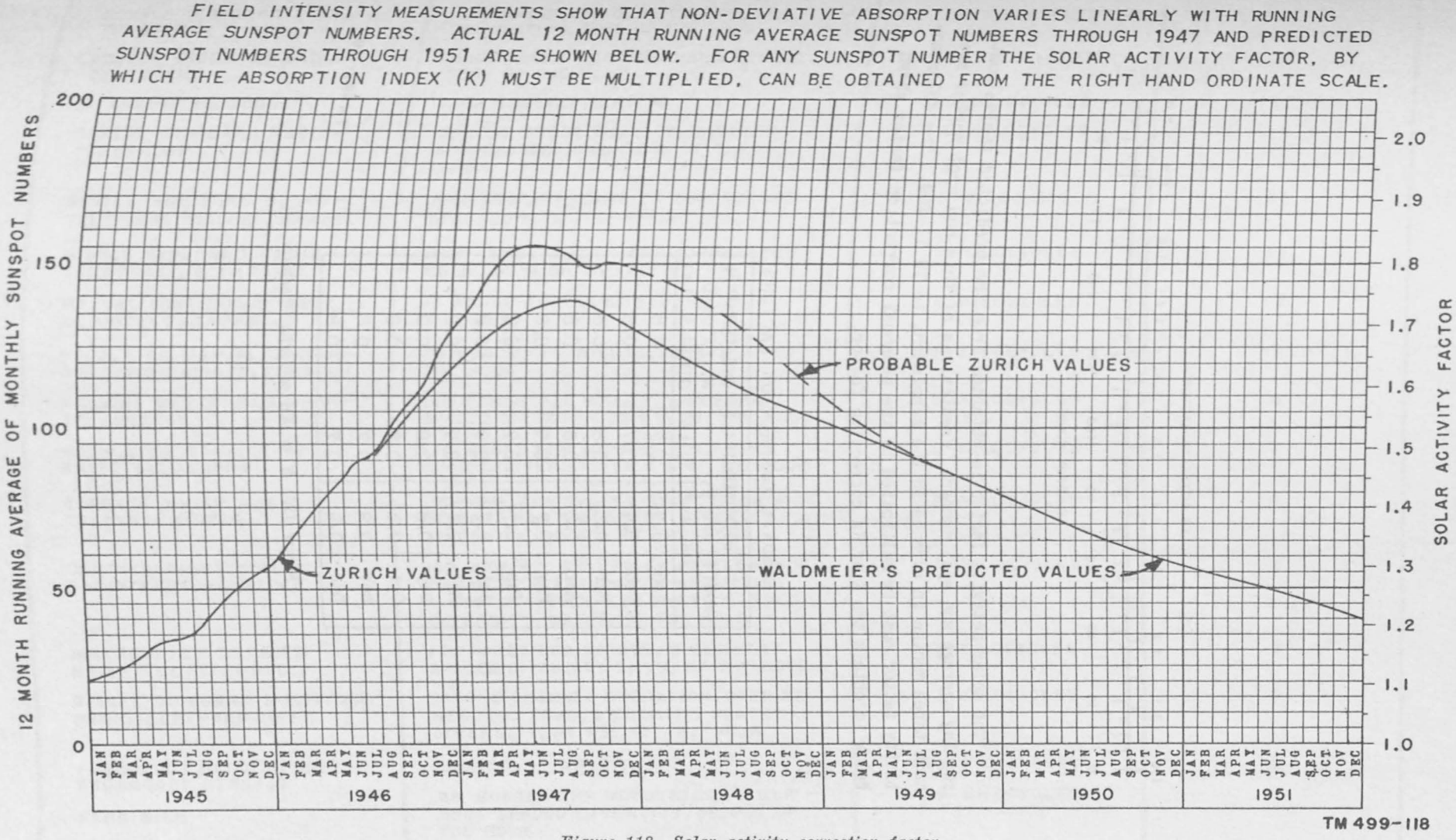
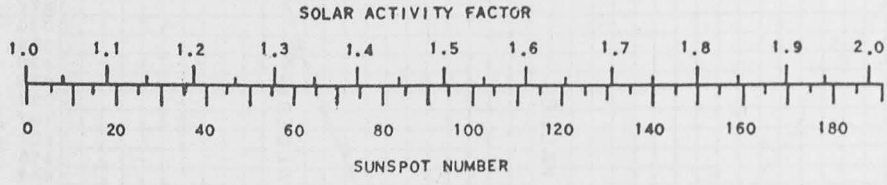


Figure 118. Solar activity correction factor.



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 in the supplement to TB 11-499. 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

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Figure 119. K or Kd correction factors.

TYPE OF SERVICE	CONDITIONS	BANDWIDTH	SIGNAL STRENGTH IN DECIBELS ABOVE REFERENCE LEVEL
DOUBLE SIDEBAND RADIO - TELEPHONY	SPEECH GRADE QUALITY AT 100% MODULATION. 90% OF THE HOUR	6 KILOCYCLES	8
DOUBLE SIDEBAND RADIO - TELEPHONY	HIGH QUALITY COMMERCIAL SERVICE. 90% OF THE HOUR	6 KILOCYCLES	33
STANDARD BROADCAST	HIGH QUALITY SERVICE	10 KILOCYCLES	27
SINGLE SIDEBAND RADIO - TELEPHONY	SPEECH GRADE QUALITY, CARRIER SUPPRESSED 10 db, 90% OF THE HOUR	3 KILOCYCLES	-1
SINGLE SIDEBAND RADIO - TELEPHONY SINGLE CHANNEL	HIGH QUALITY, CARRIER SUPPRESSED 10 db, 90% OF THE HOUR	3 KILOCYCLES	24
SINGLE SIDEBAND RADIO - TELEPHONY, 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 RADIOTELEGRAPHY	30 WORDS PER MINUTE, 90% OF THE HOUR	2 KILOCYCLES	-5
MACHINE SPEED RADIO - TELEGRAPHY	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 RADIO - TELETYPEWRITER	150 WPM, 425 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

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Figure 120. Table of service gains, sky-wave communications, fading signal.

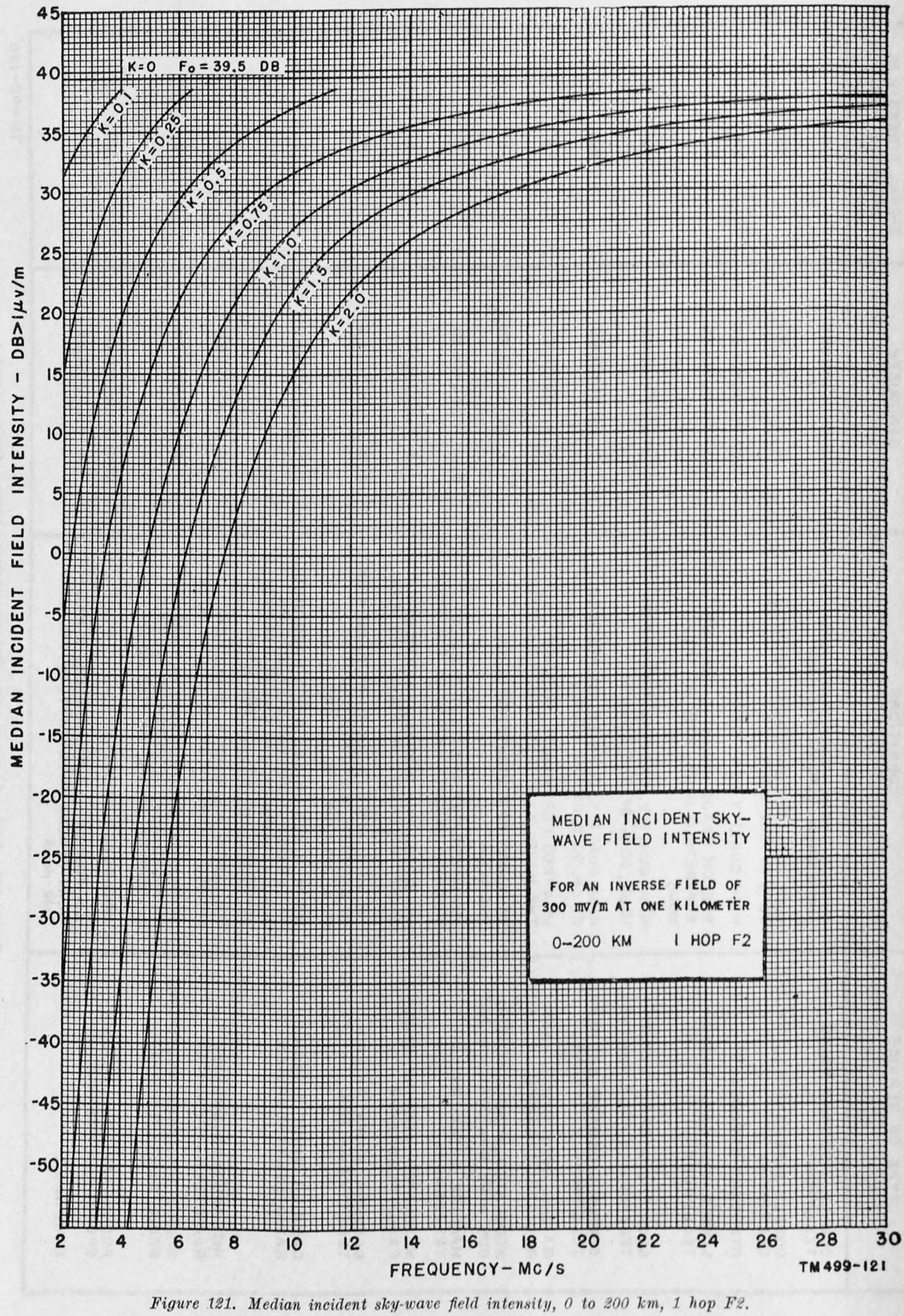


Figure 121. Median incident sky-wave field intensity, 0 to 200 km, 1 hop F2.

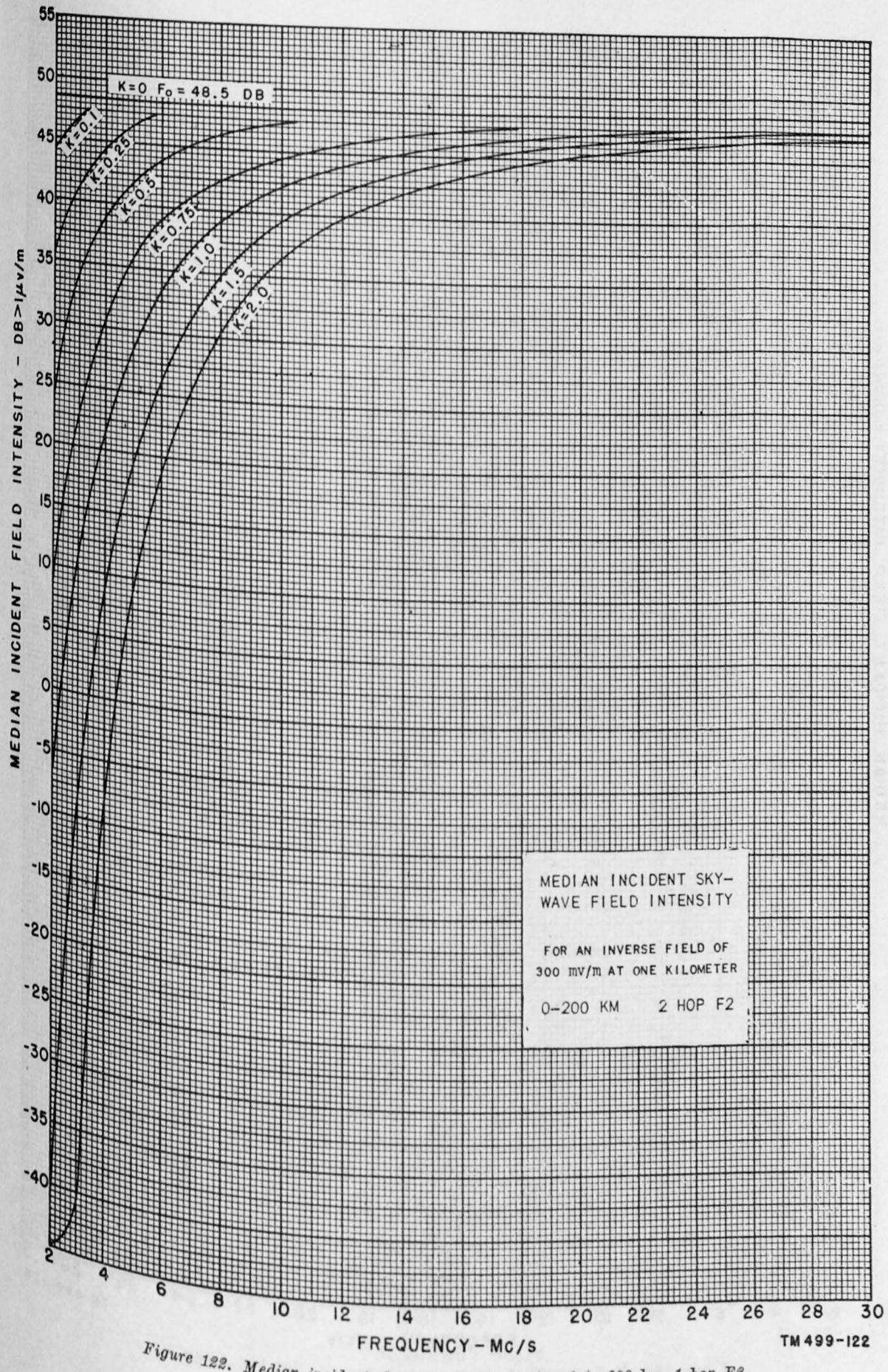


Figure 122. Median incident sky-wave field intensity, 0 to 200 km, 1 hop F2.

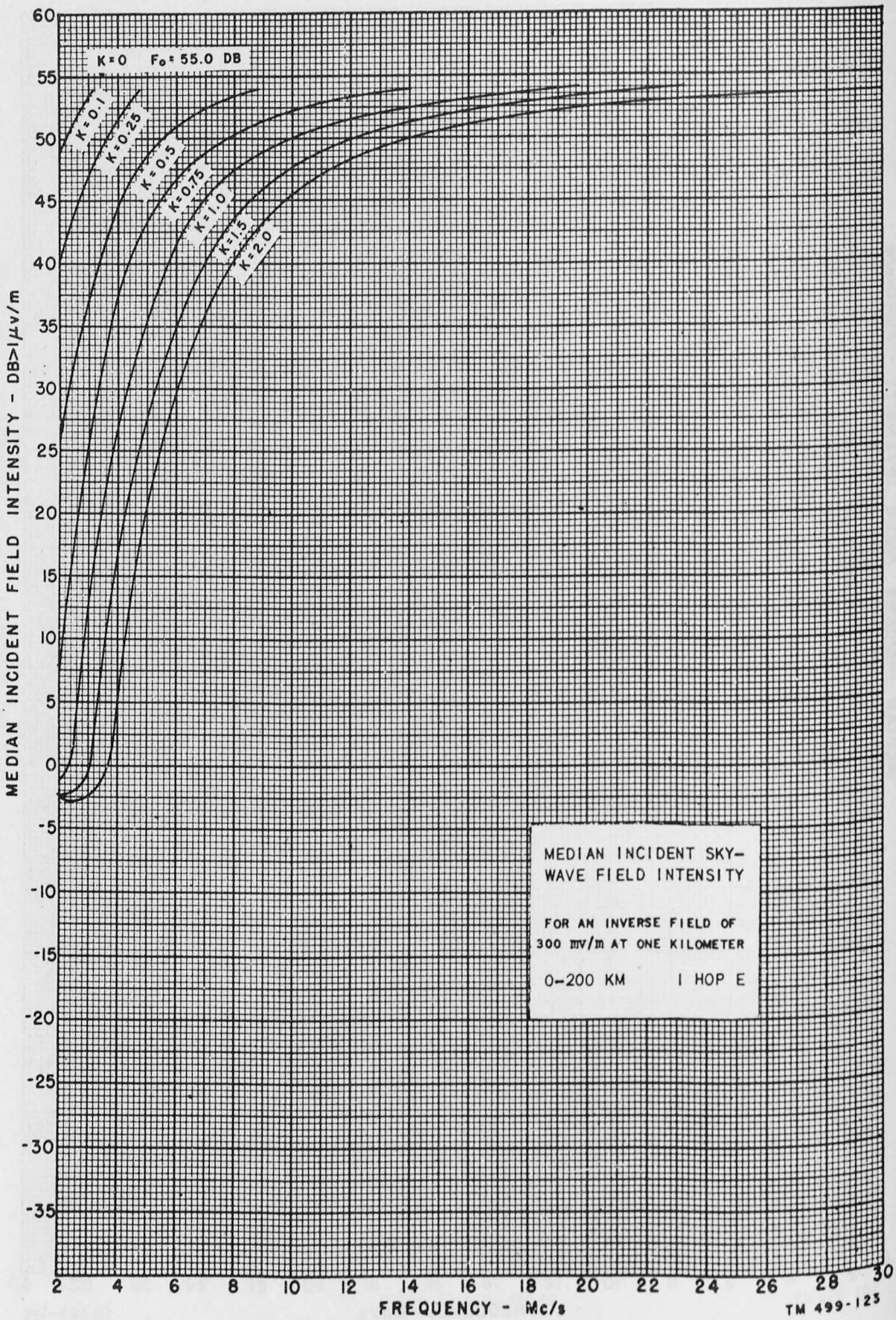


Figure 123. Median incident sky-wave intensity, 0 to 200 km, 2 hop E.

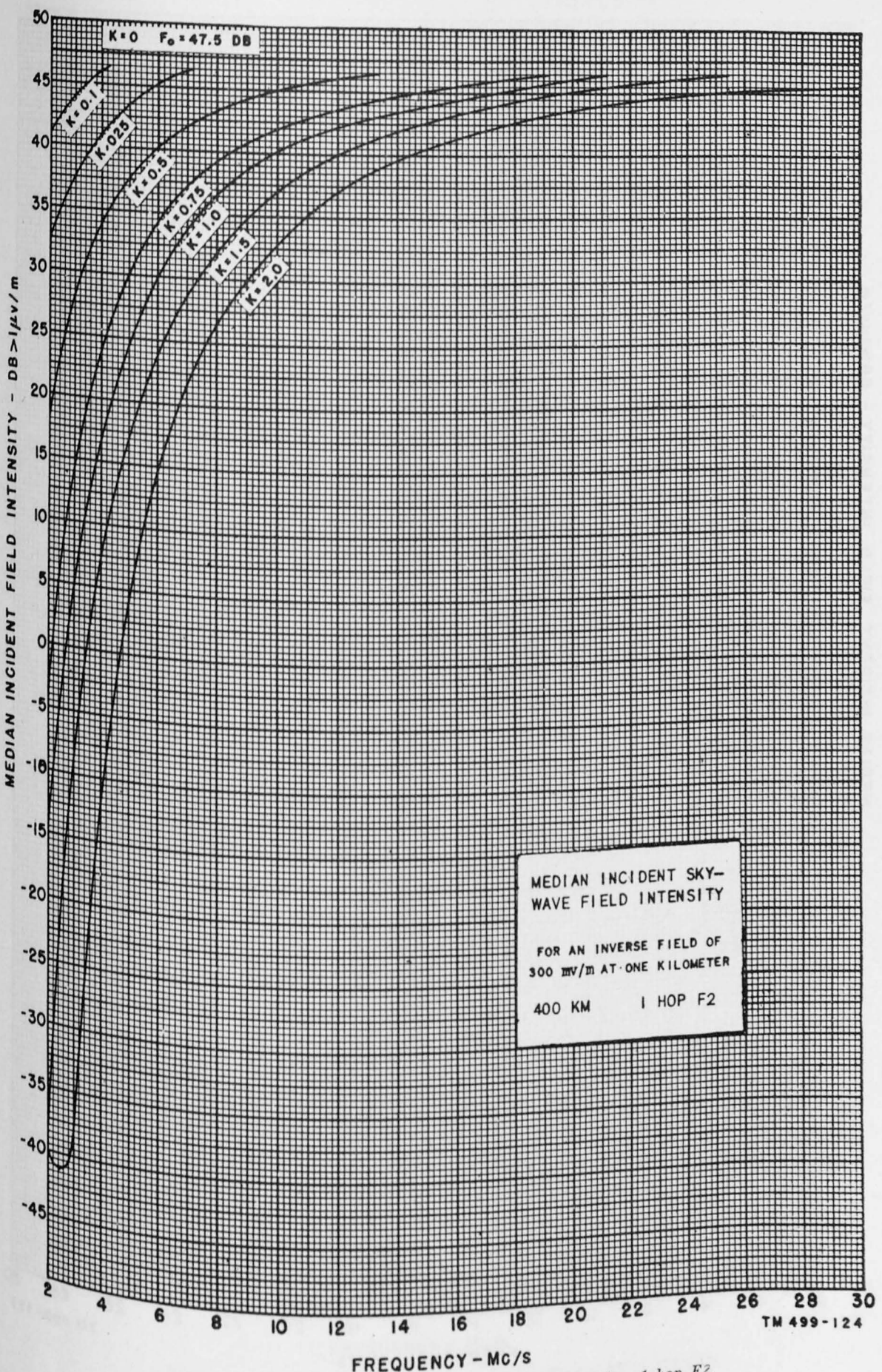


Figure 124. Median incident sky-wave field intensity, 400 km, 1 hop F2.

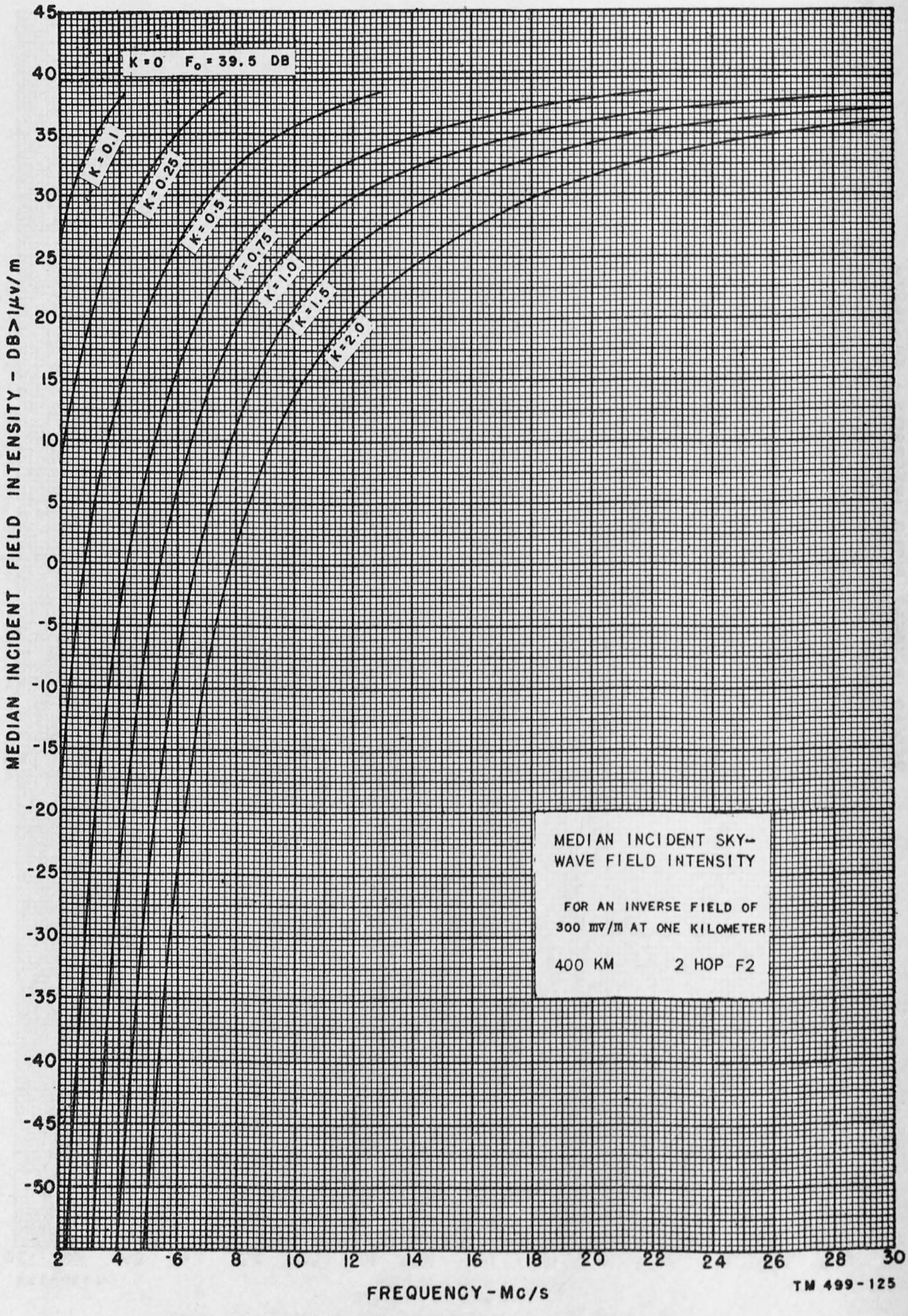


Figure 125. Median incident sky-wave field intensity, 400 km, 2 hop F2.

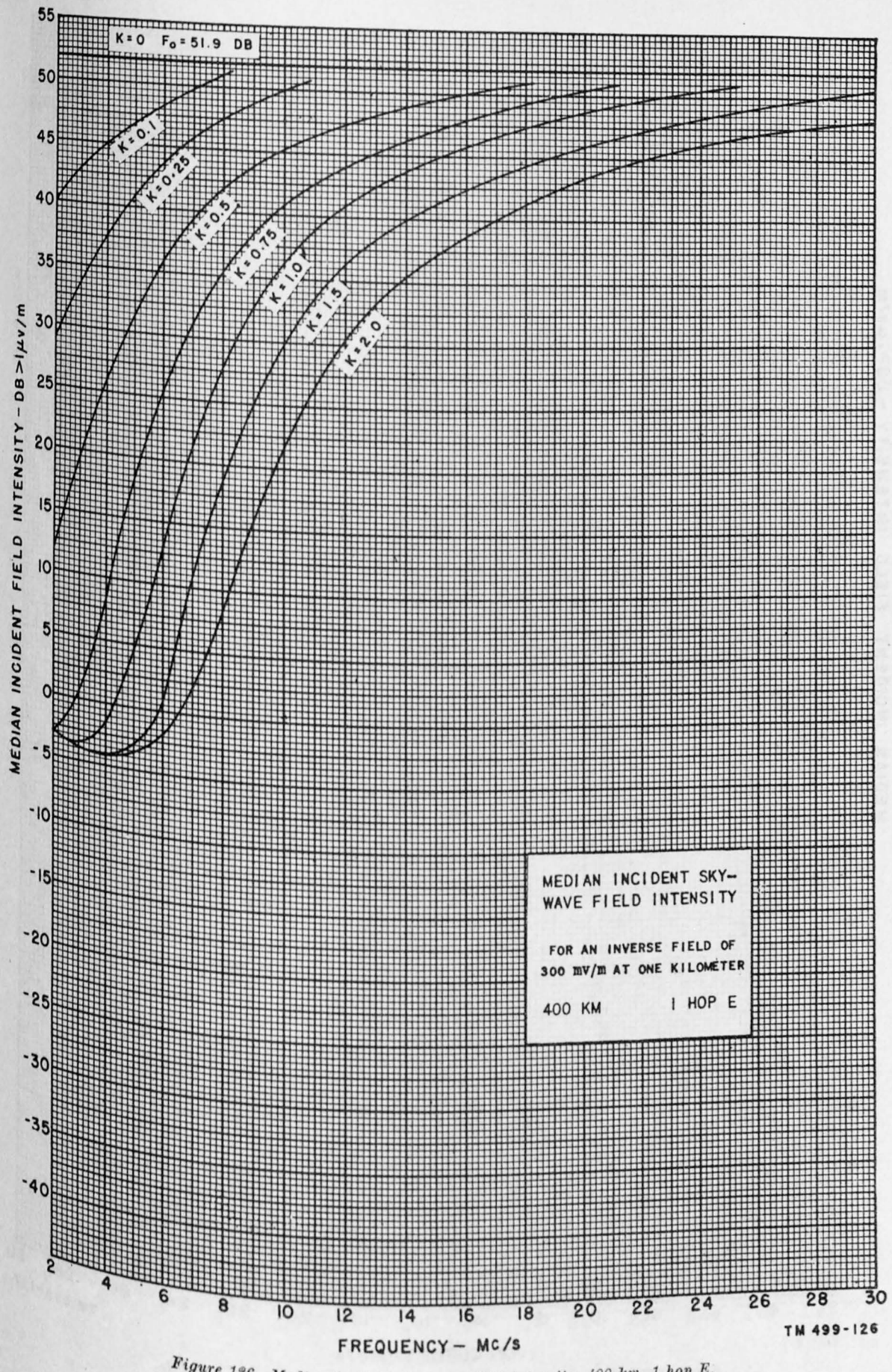


Figure 126. Median incident sky-wave field intensity, 400 km, 1 hop E.

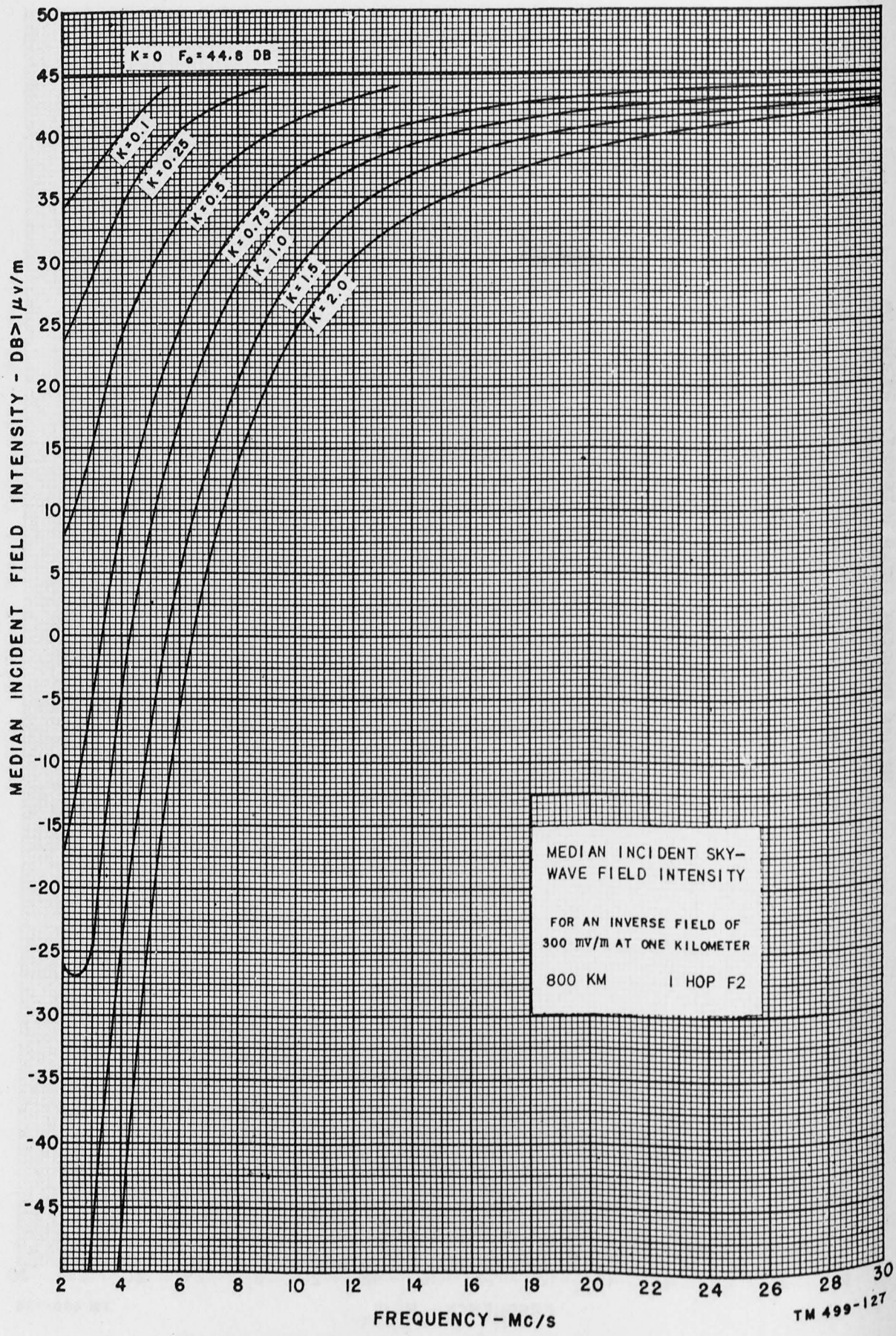


Figure 127. Median incident sky-wave field intensity, 800 km, 1 hop F2.

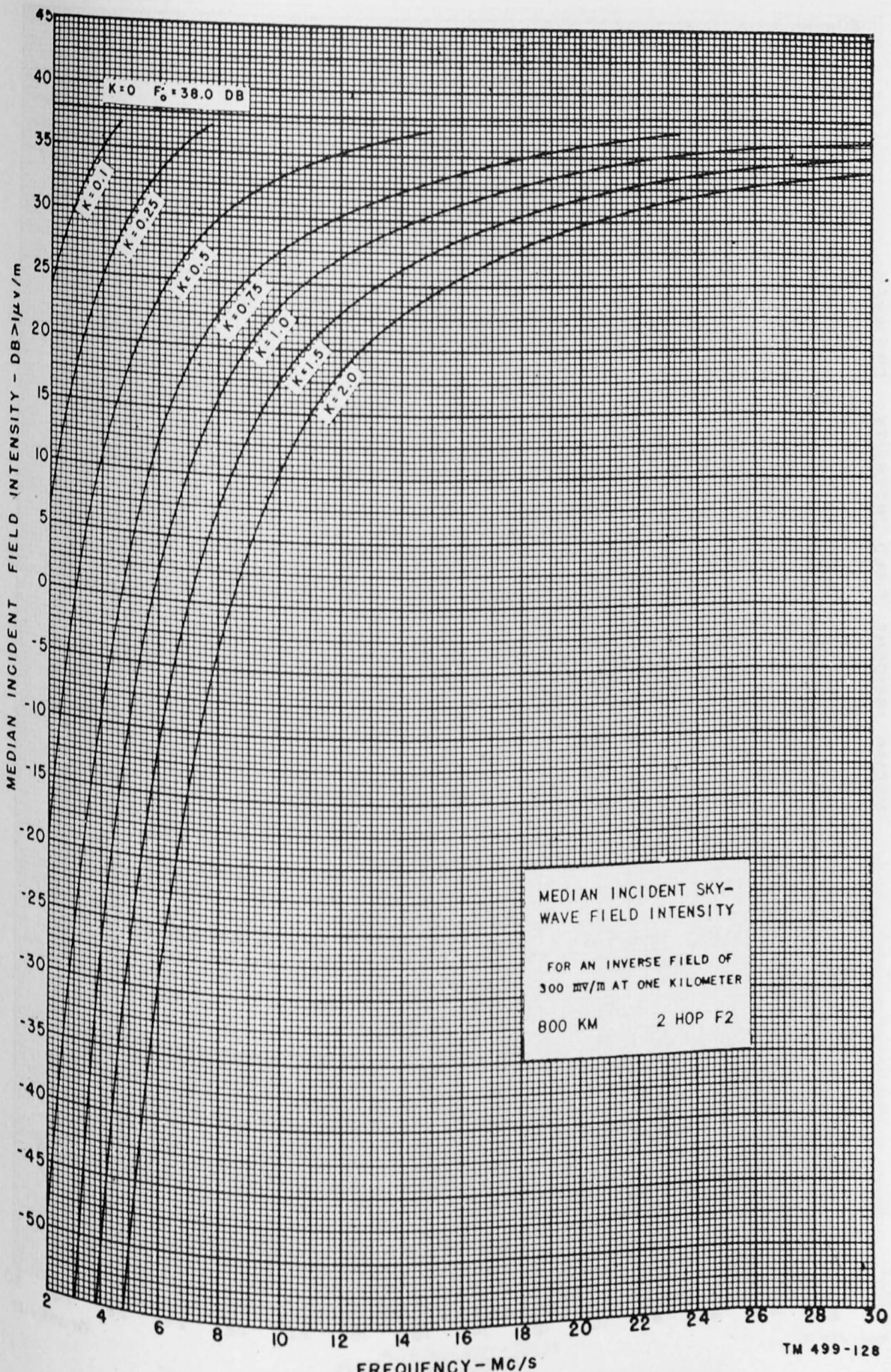


Figure 128. Median incident sky-wave field intensity, 800 km. 2 hop F2.

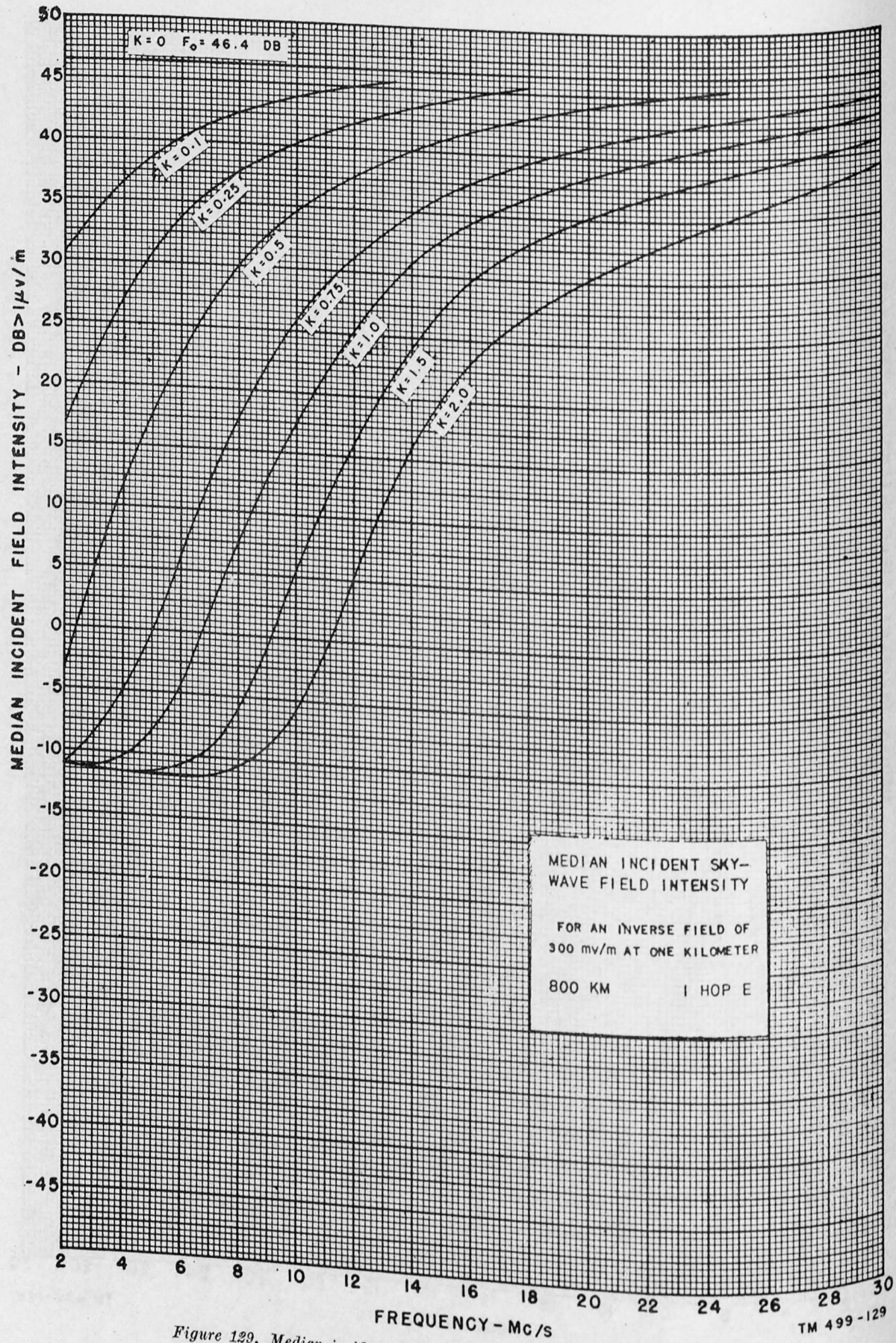


Figure 129. Median incident sky-wave field intensity, 800 km, 1 hop E.

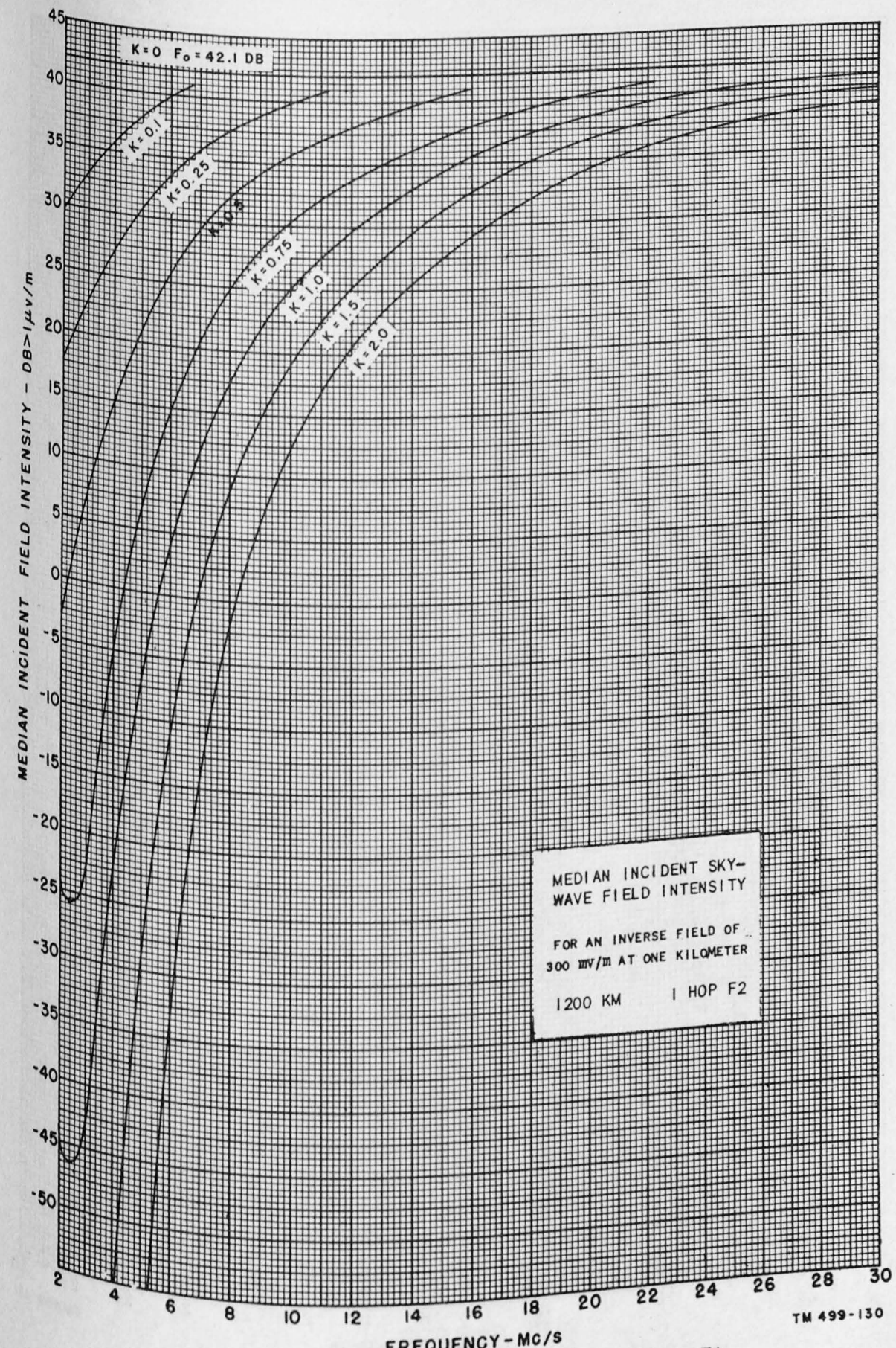


Figure 130. Median incident sky-wave field intensity, 1,200 km, 1 hop F2.

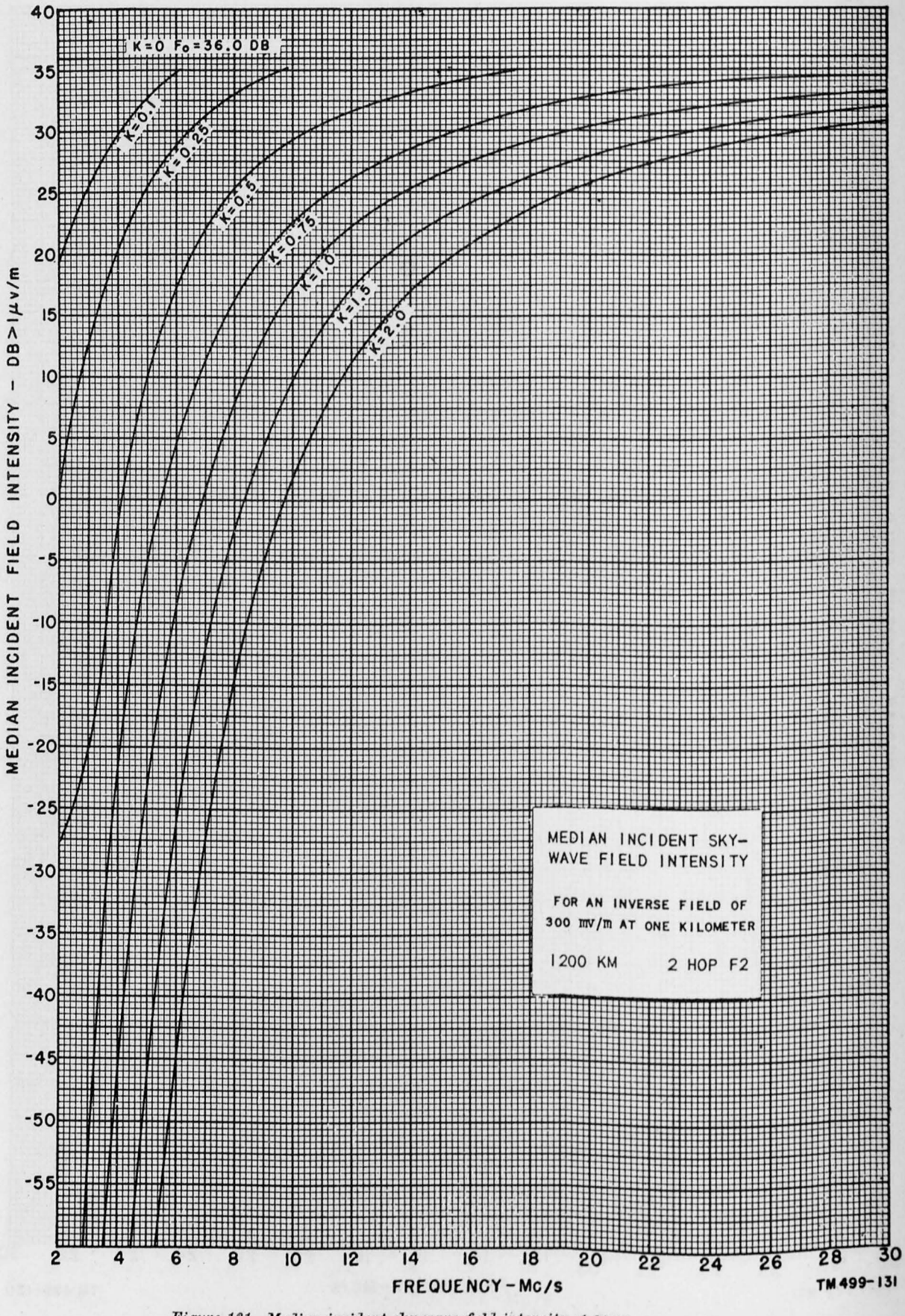


Figure 131. Median incident sky-wave field intensity, 1,200 km, 2 hop F2.

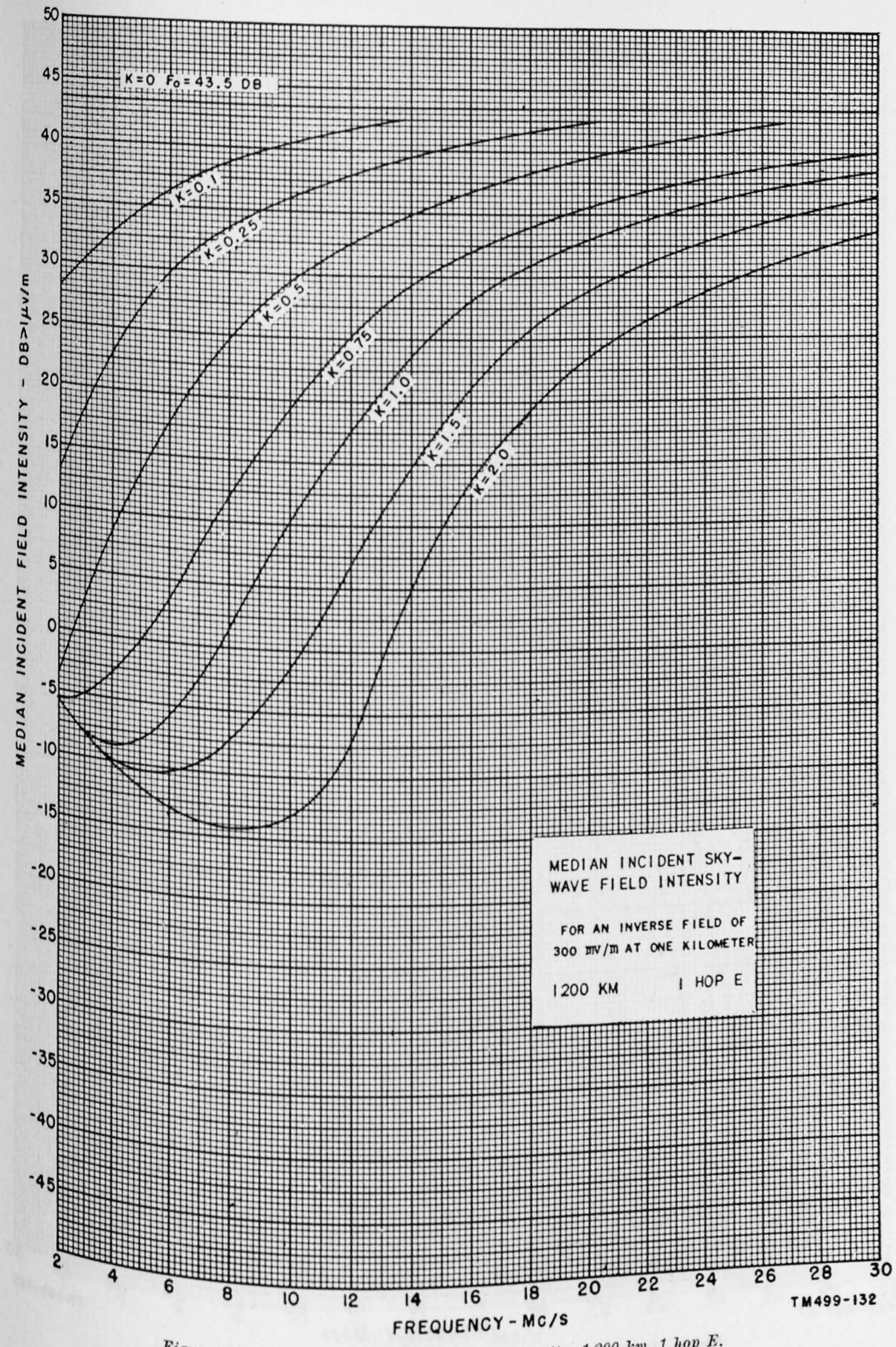


Figure 132. Median incident sky-wave field intensity, 1,200 km, 1 hop E.

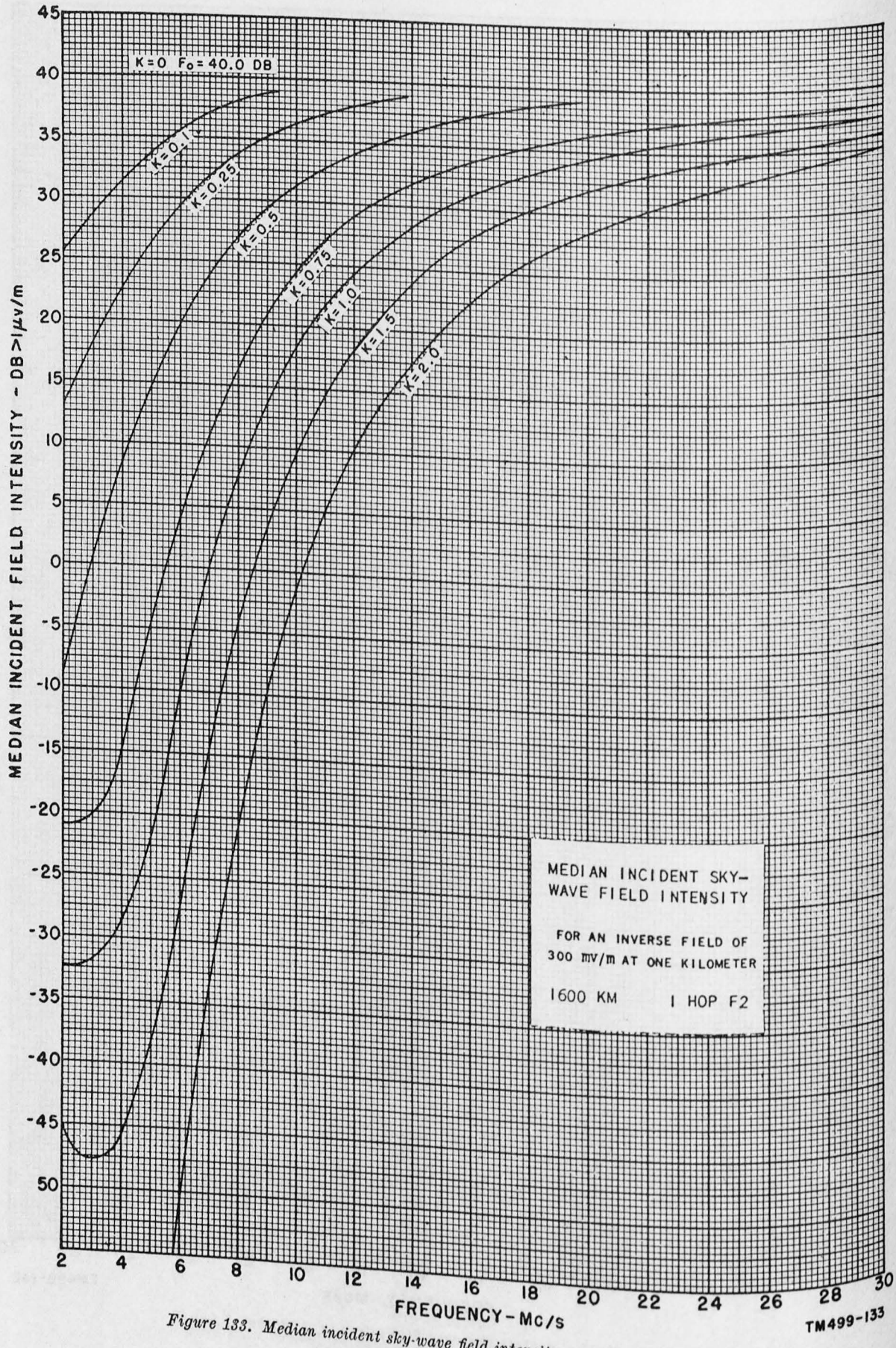


Figure 133. Median incident sky-wave field intensity, 1,600 km, 1 hop F2.

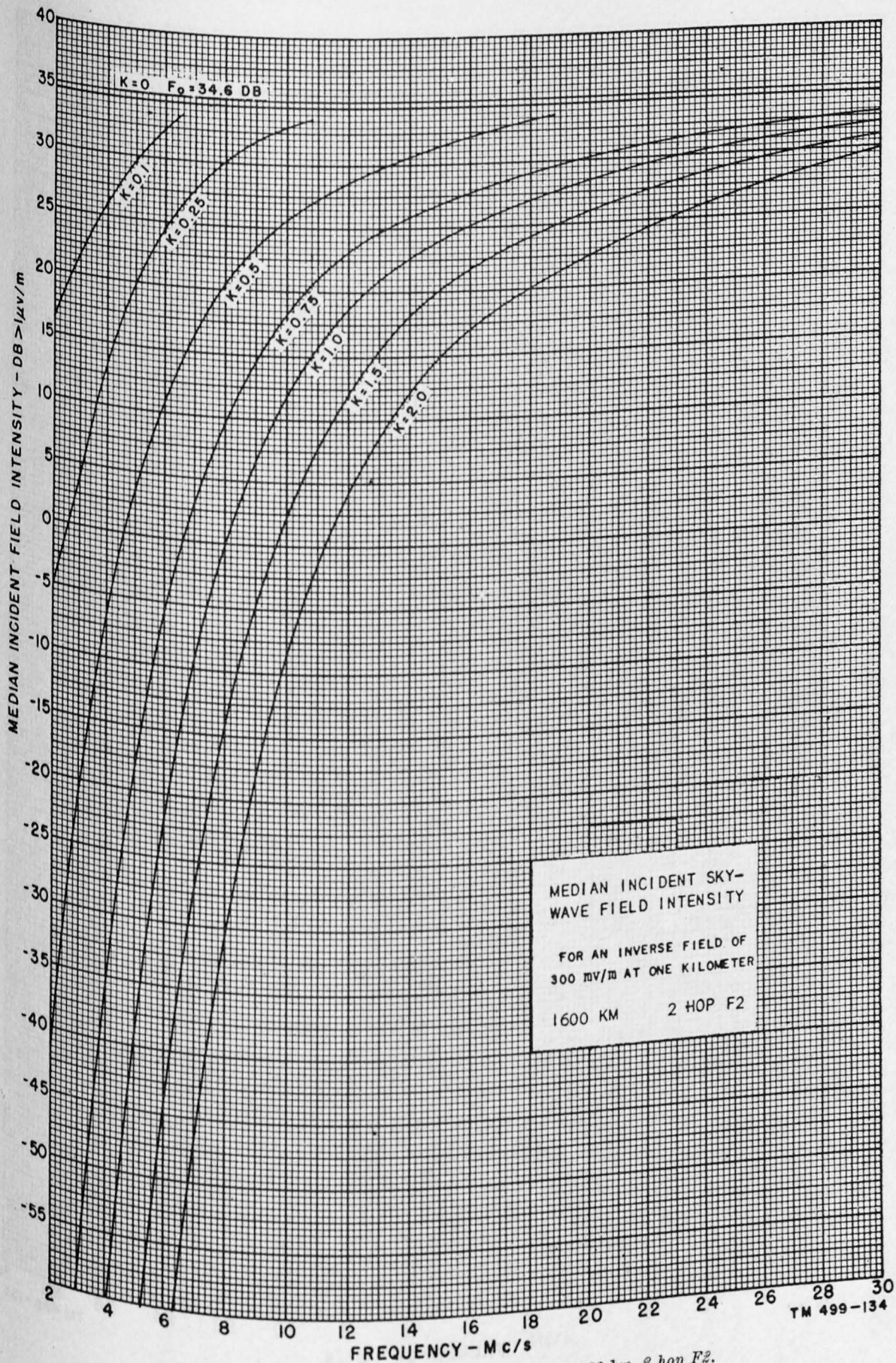


Figure 134. Median incident sky-wave field intensity, 1,600 km, 2 hop F2.

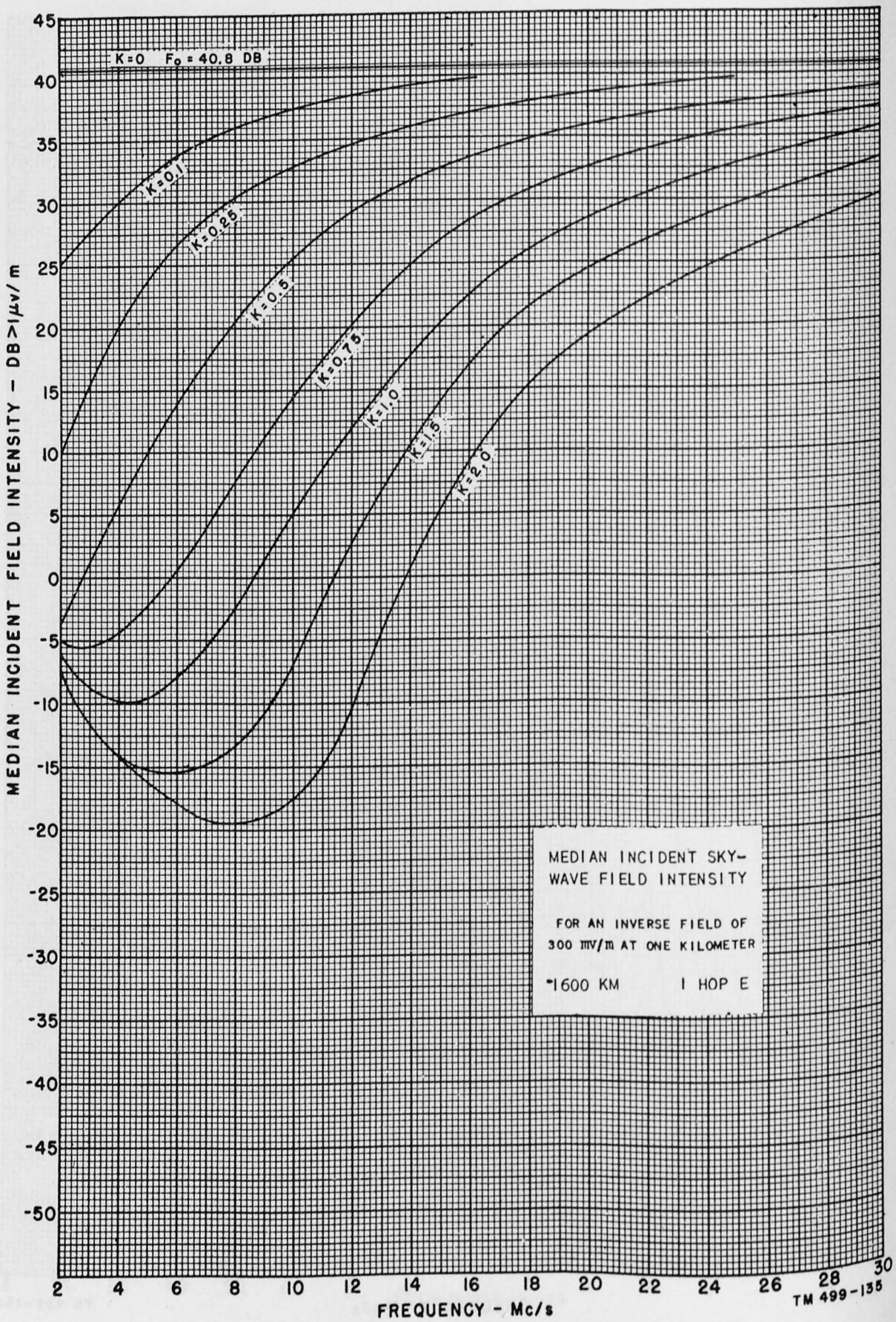


Figure 135. Median incident sky-wave field intensity, 1,600 km, 1 hop E.

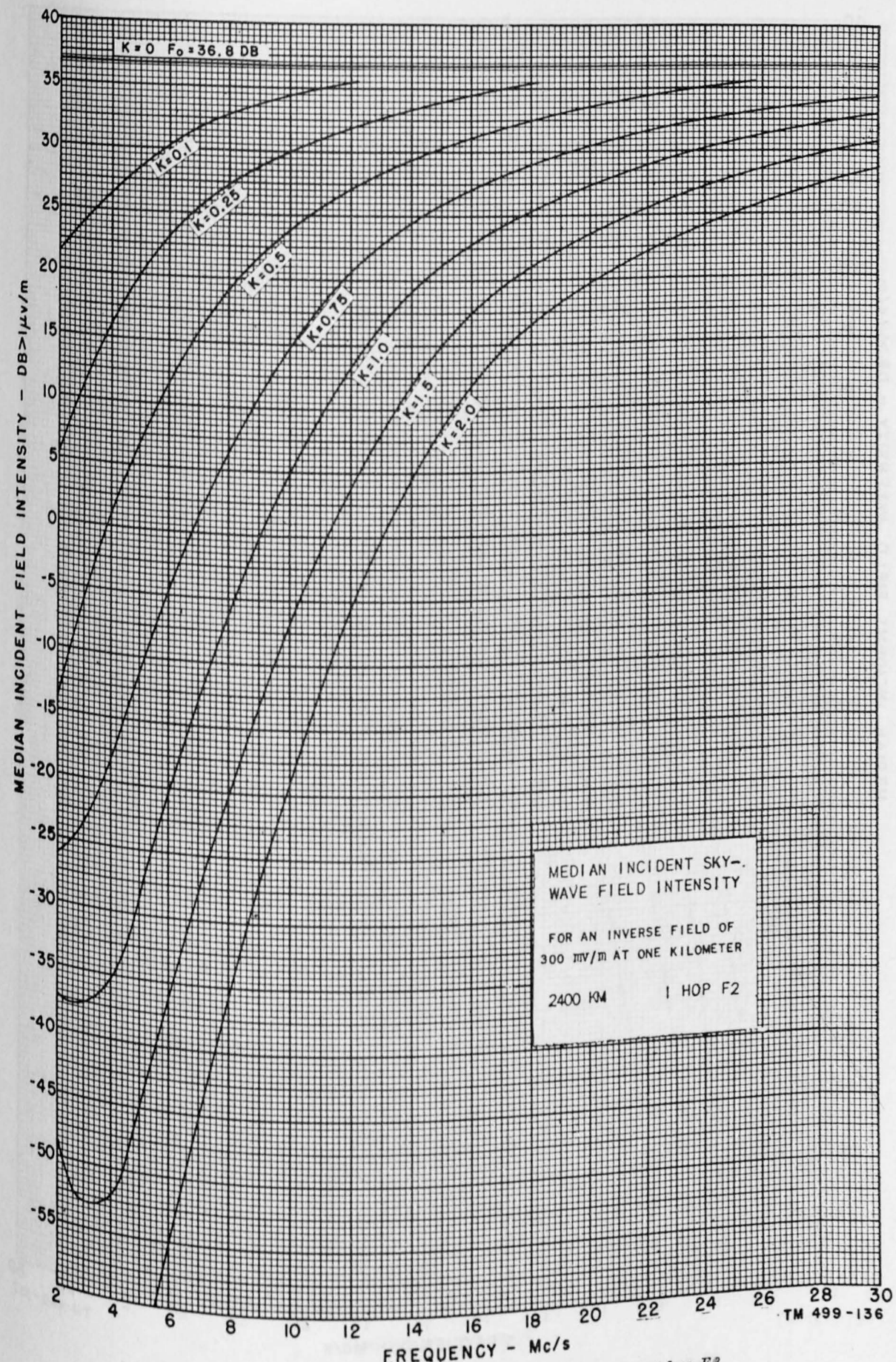


Figure 136. Median incident sky-wave field intensity, 2,400 km, 1 hop F2.

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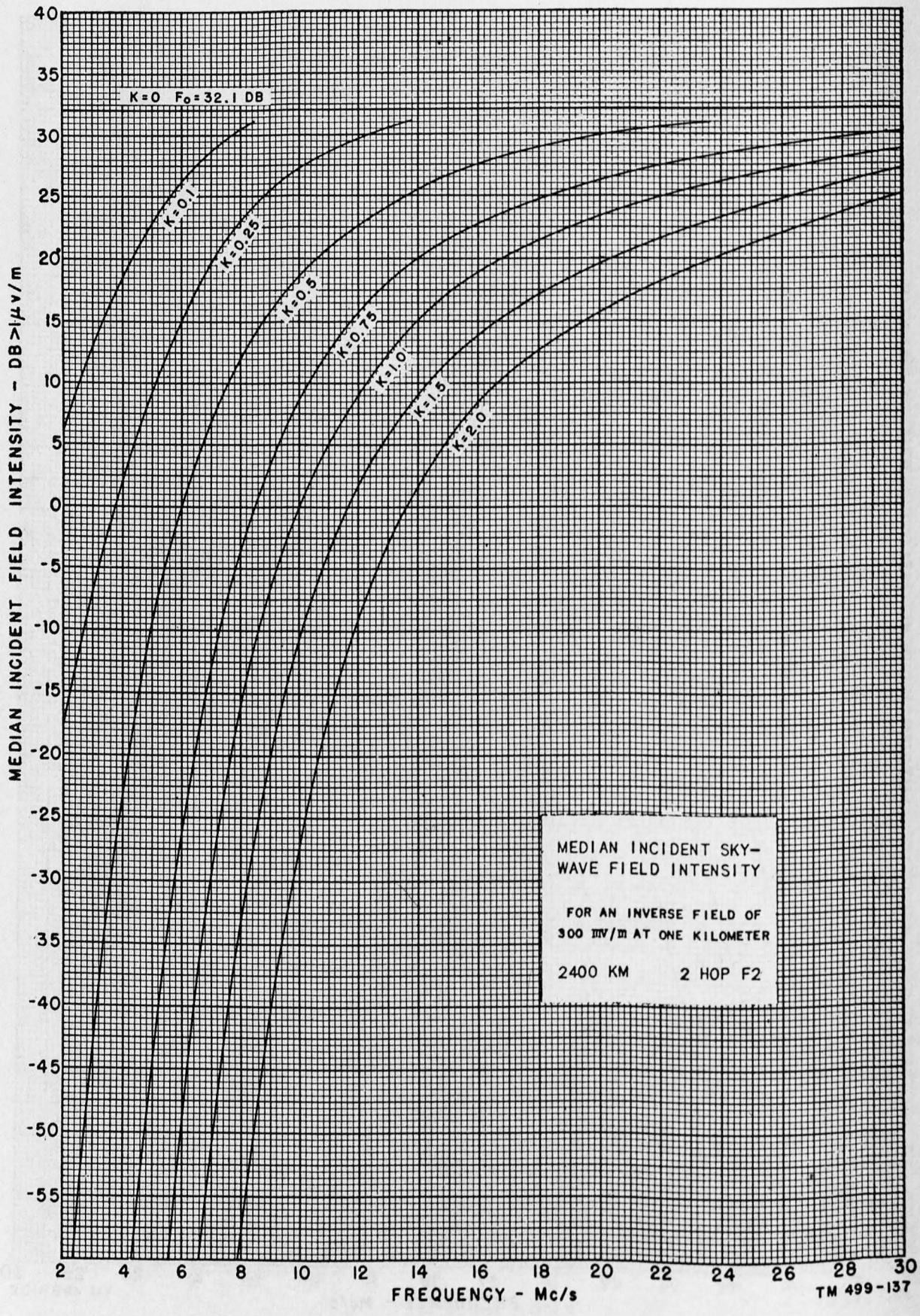


Figure 137. Median incident sky-wave field intensity, 2,400 km, 2 hop F2.

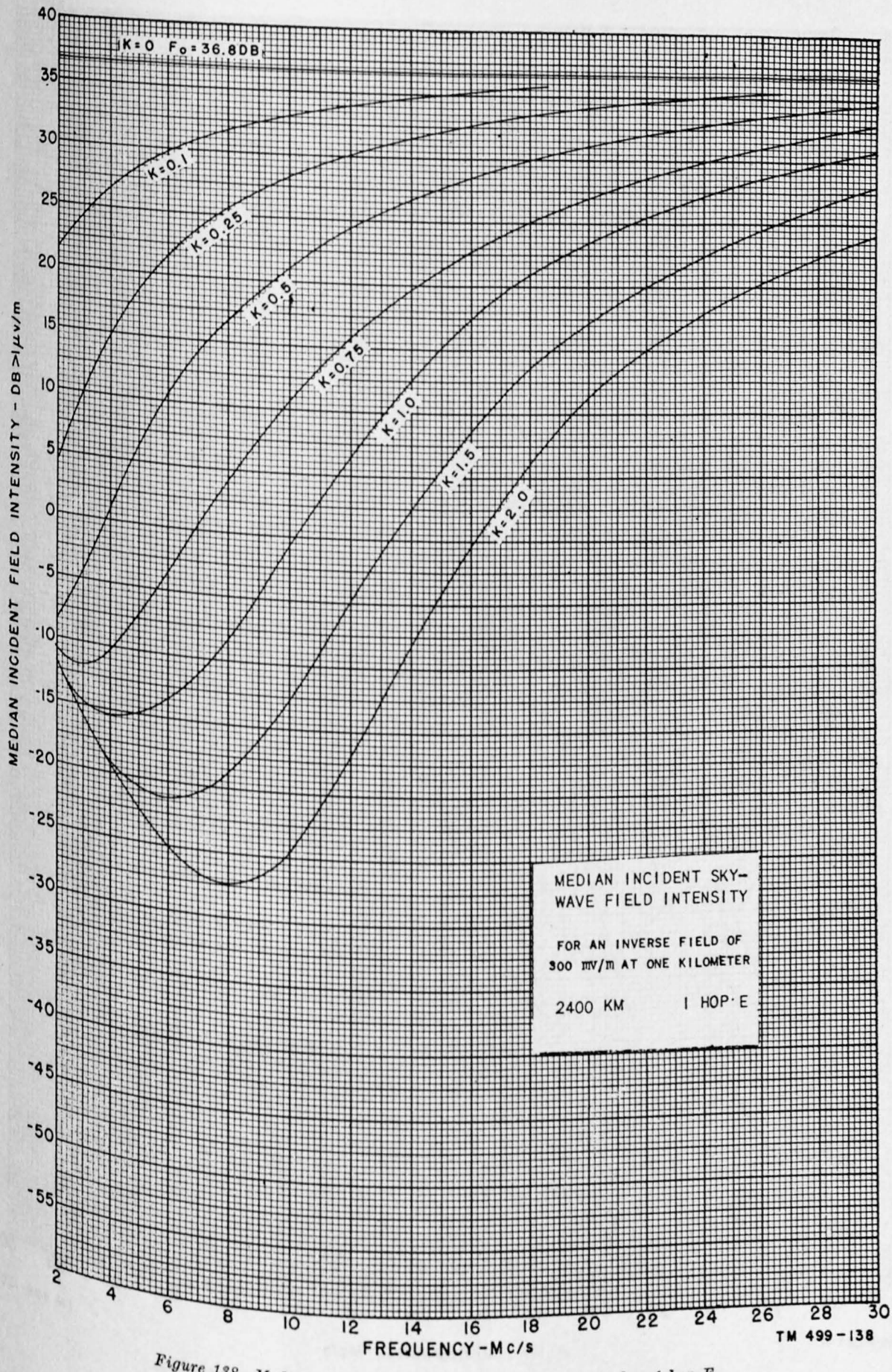


Figure 138. Median incident sky-wave field intensity, 2,400 km, 1 hop E.

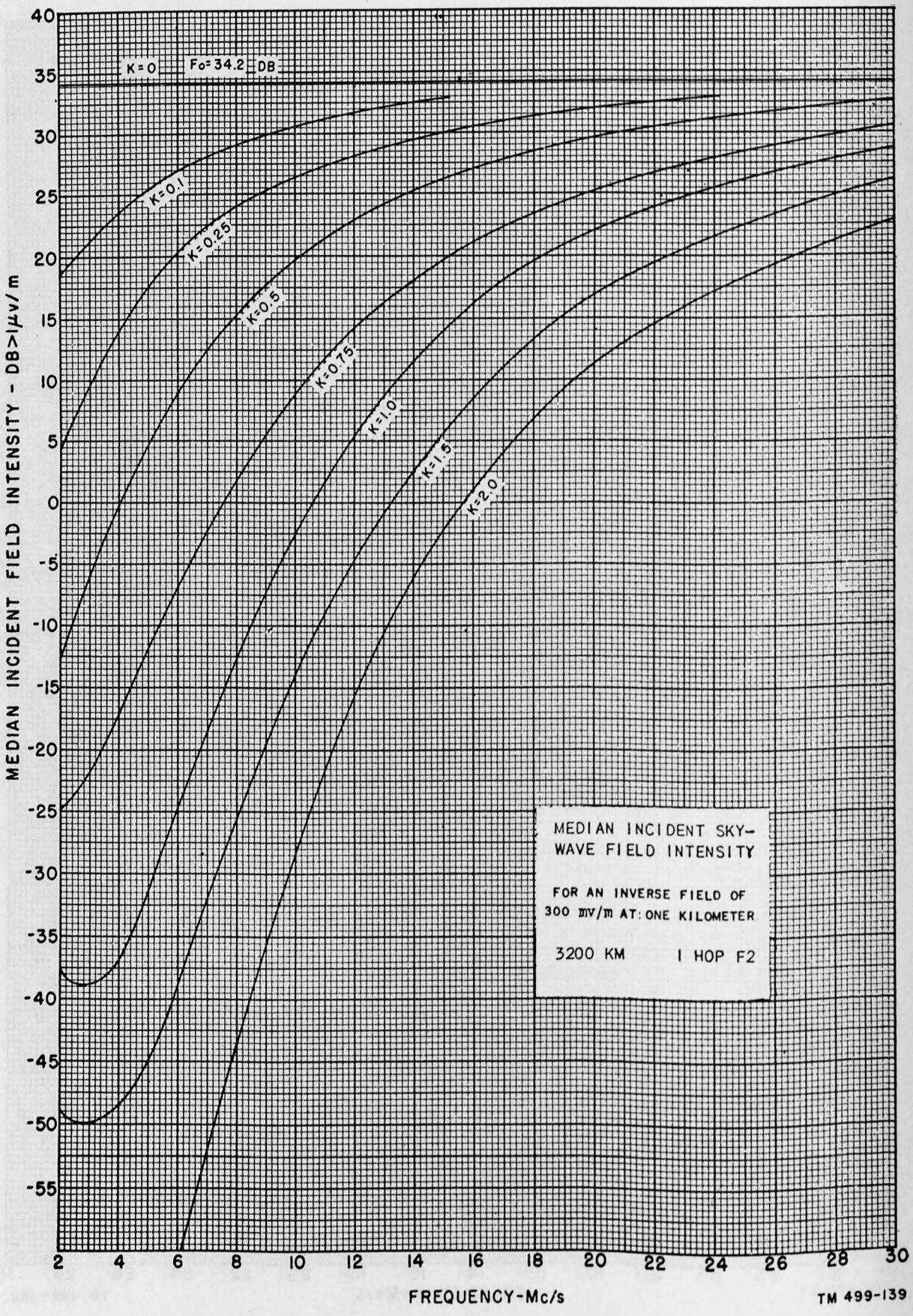


Figure 139. Median incident sky-wave field intensity, 3,200 km, 1 hop F2.

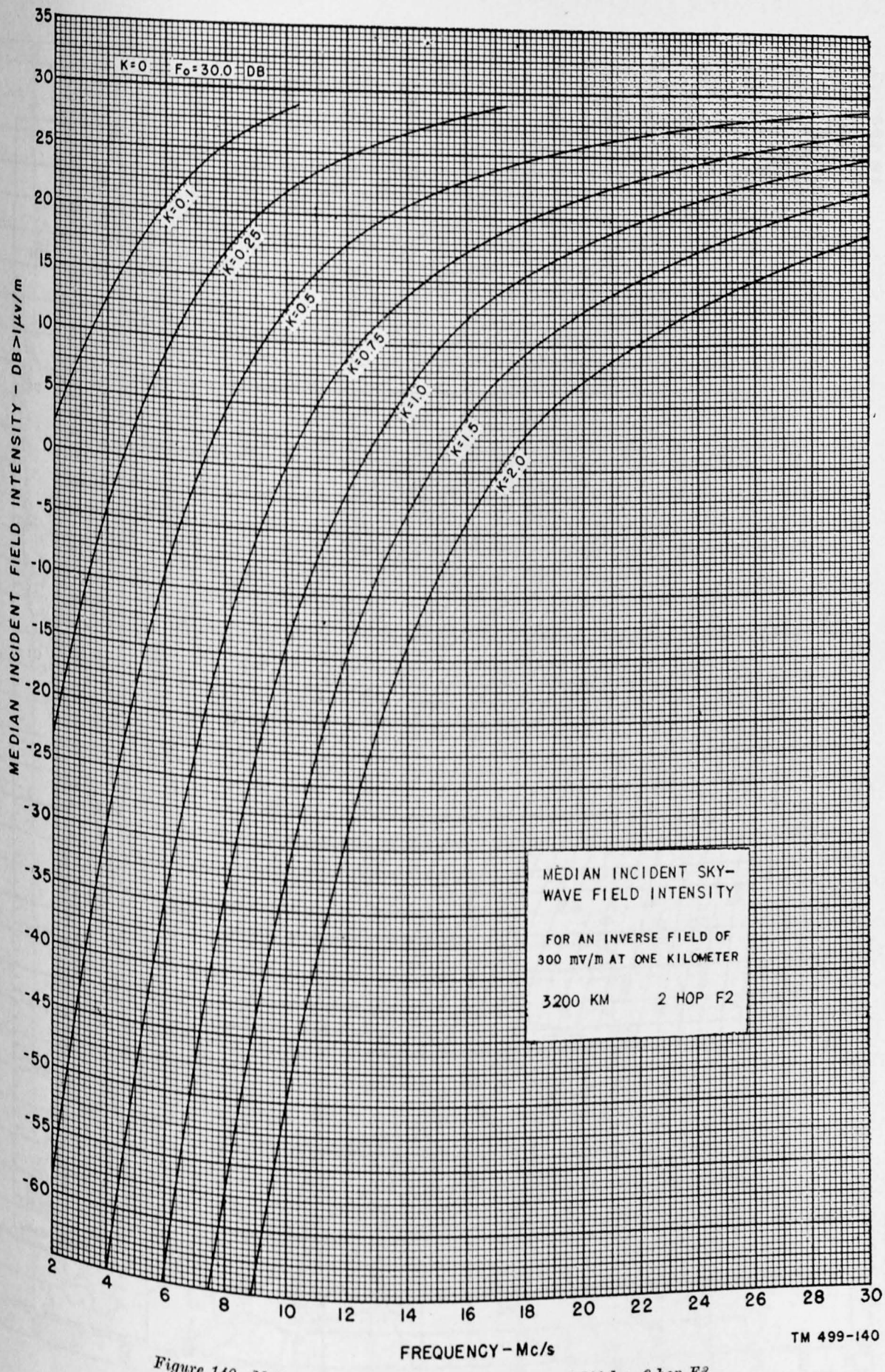
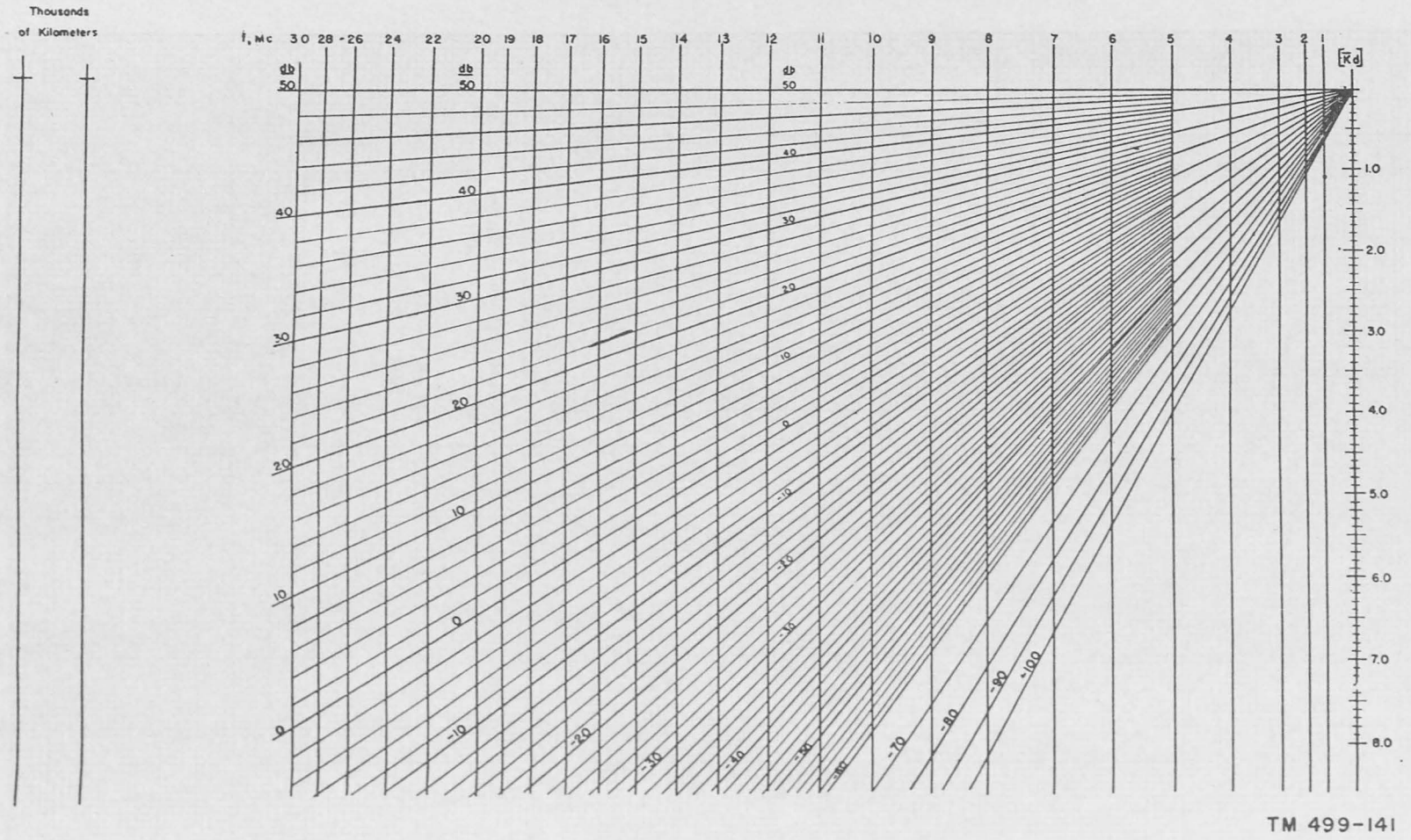


Figure 140. Median incident sky-wave field intensity, 3,200 km, 2 hop F2.



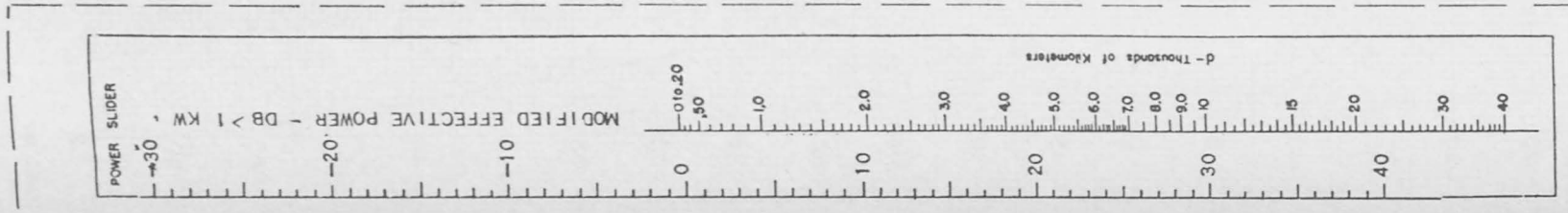


Figure 141. Field intensity nomogram, 3,000 km and greater.

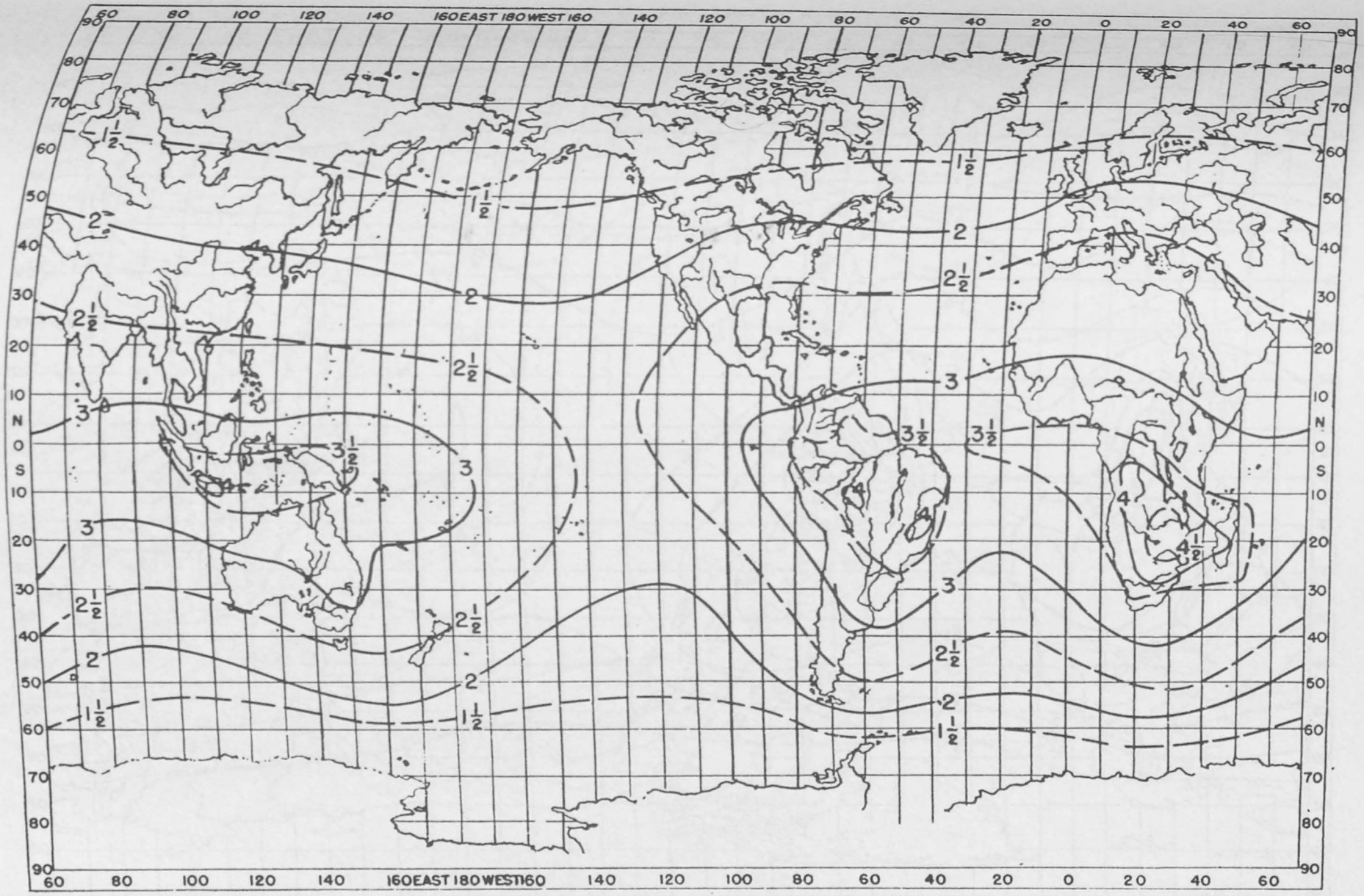


Figure 142. Noise distribution chart for December, January, and February.

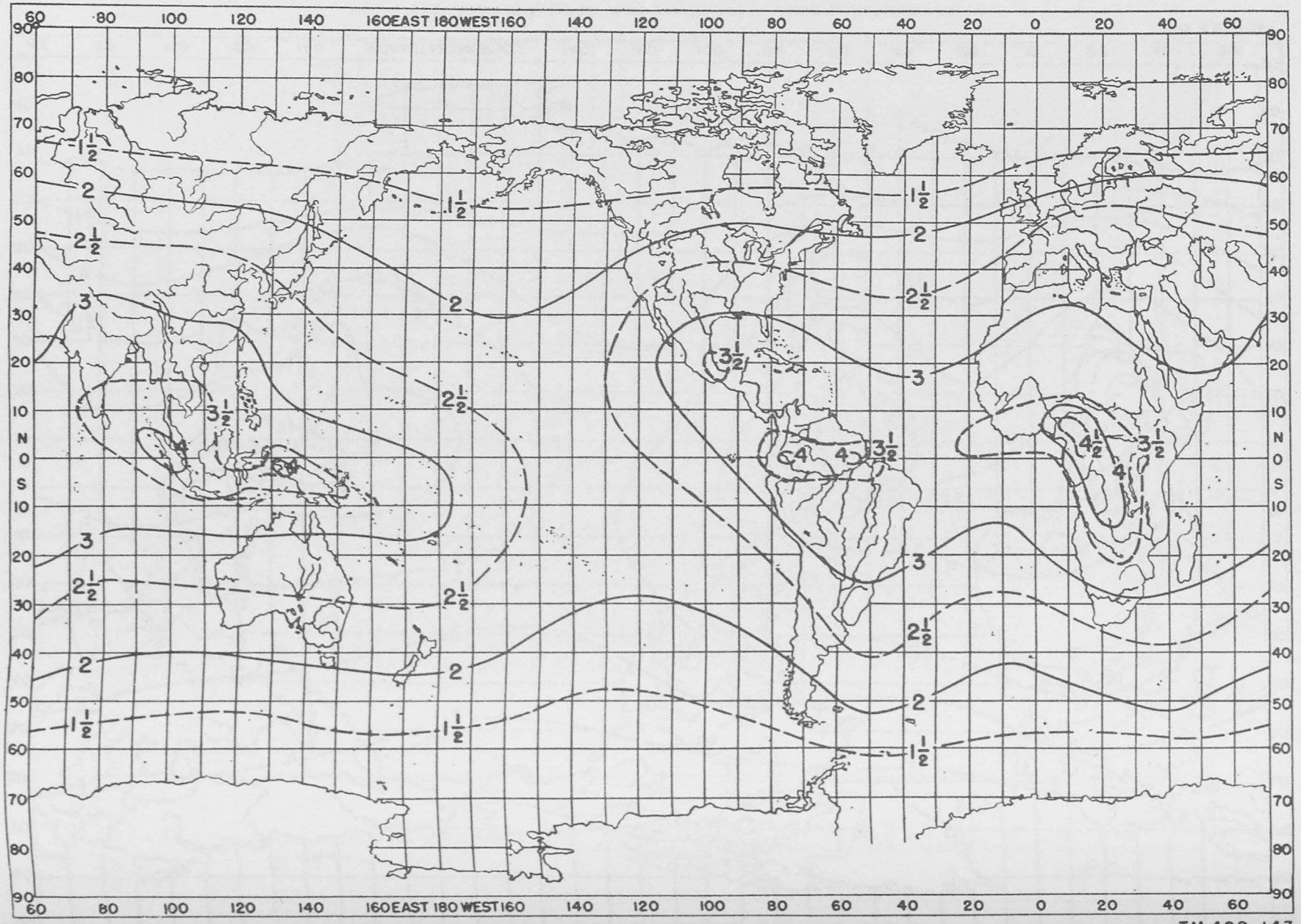


Figure 143. Noise distribution chart for March, April, and May.

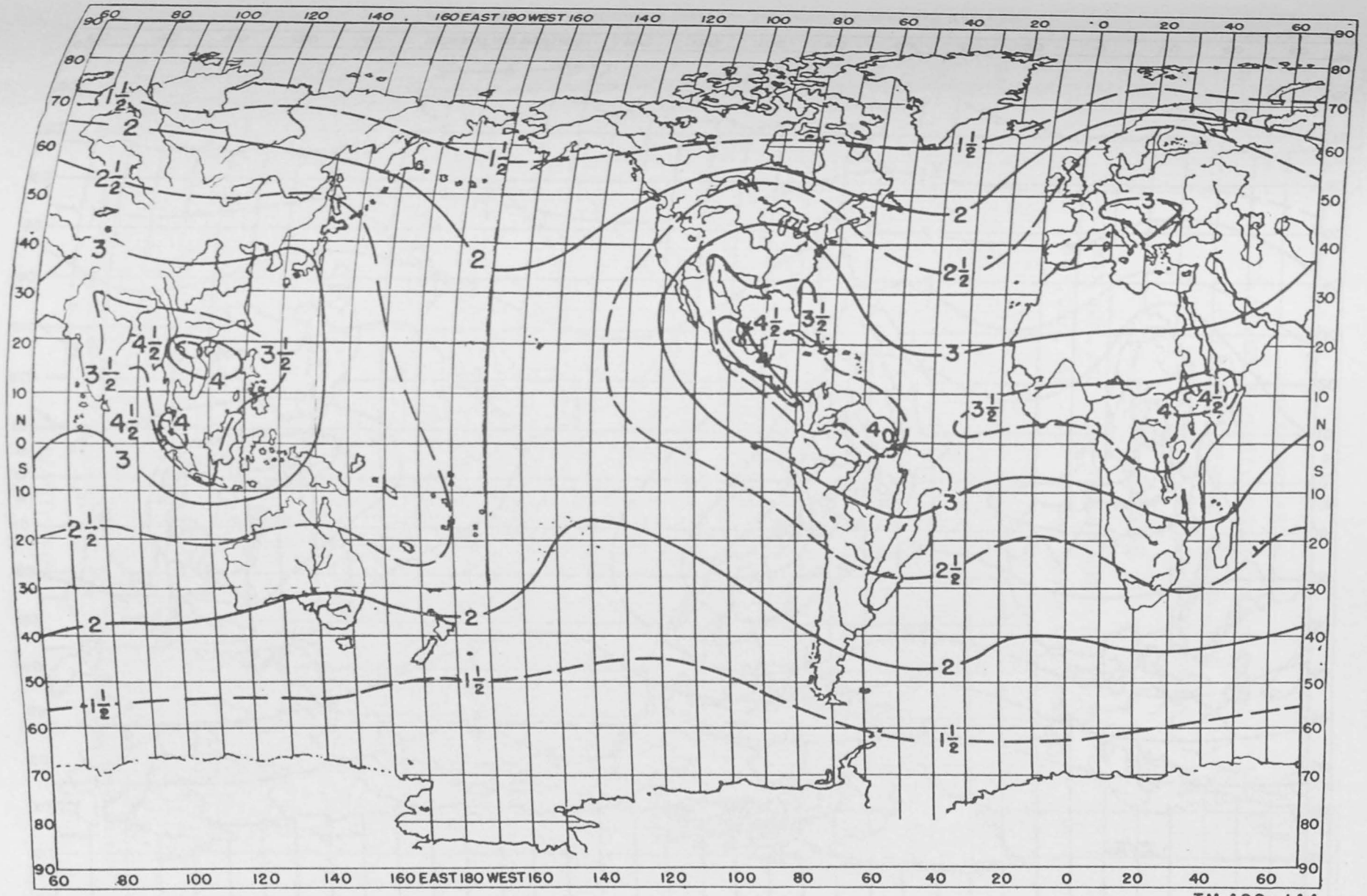


Figure 144. Noise distribution chart for June, July, and August.

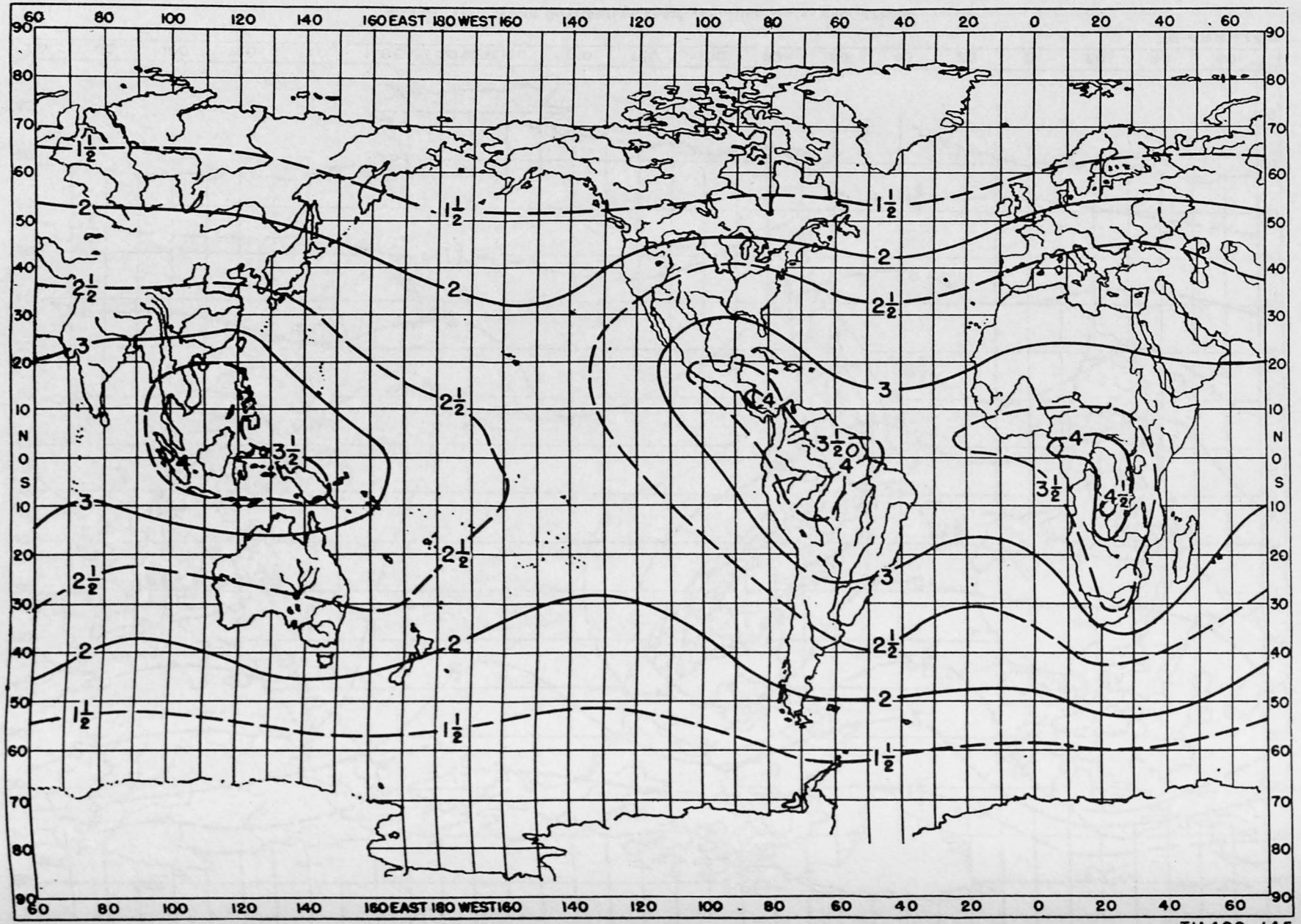


Figure 145. Noise distribution chart for September, October, and November.

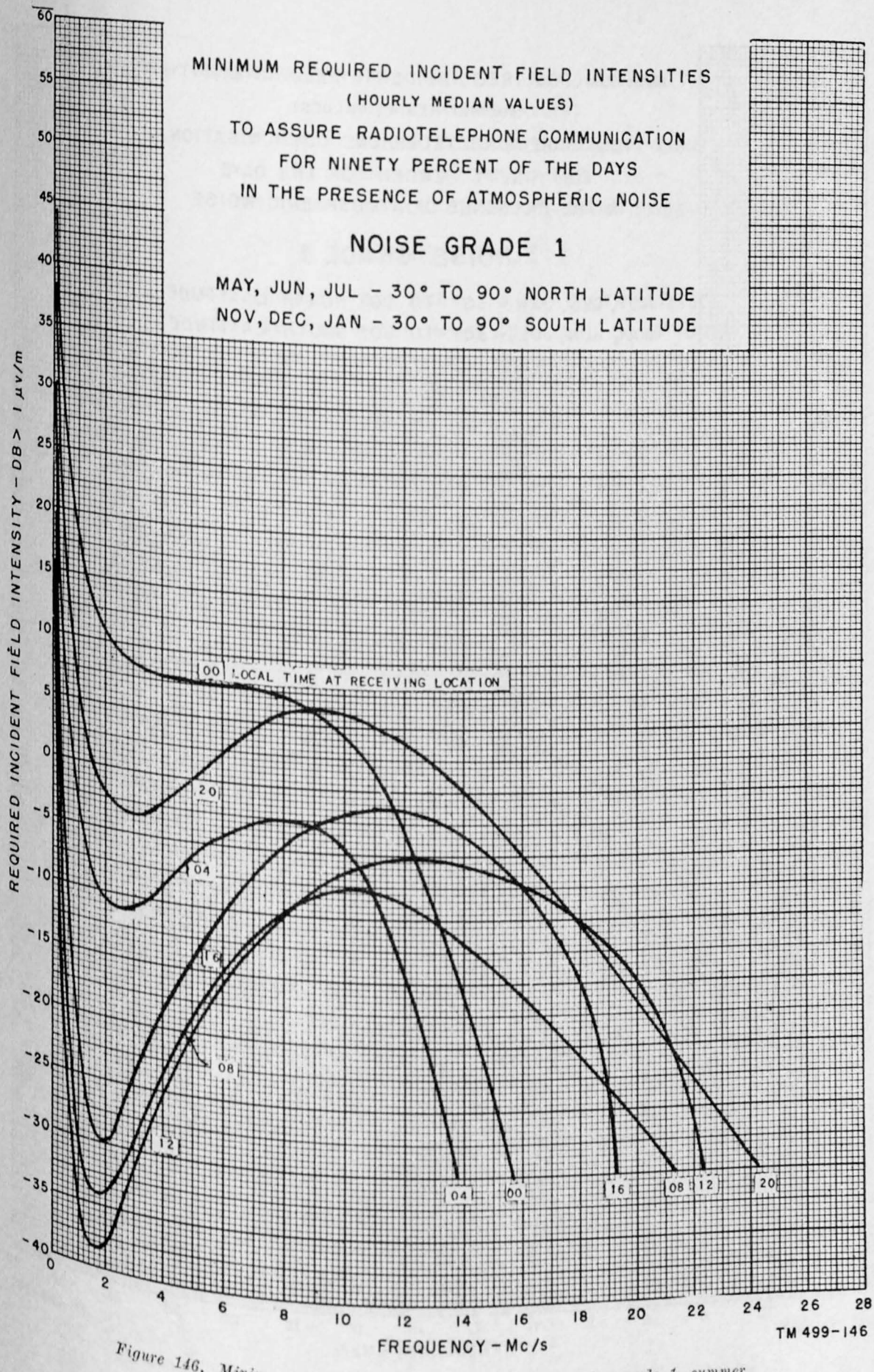


Figure 146. Minimum required incident field intensities, noise grade 1, summer

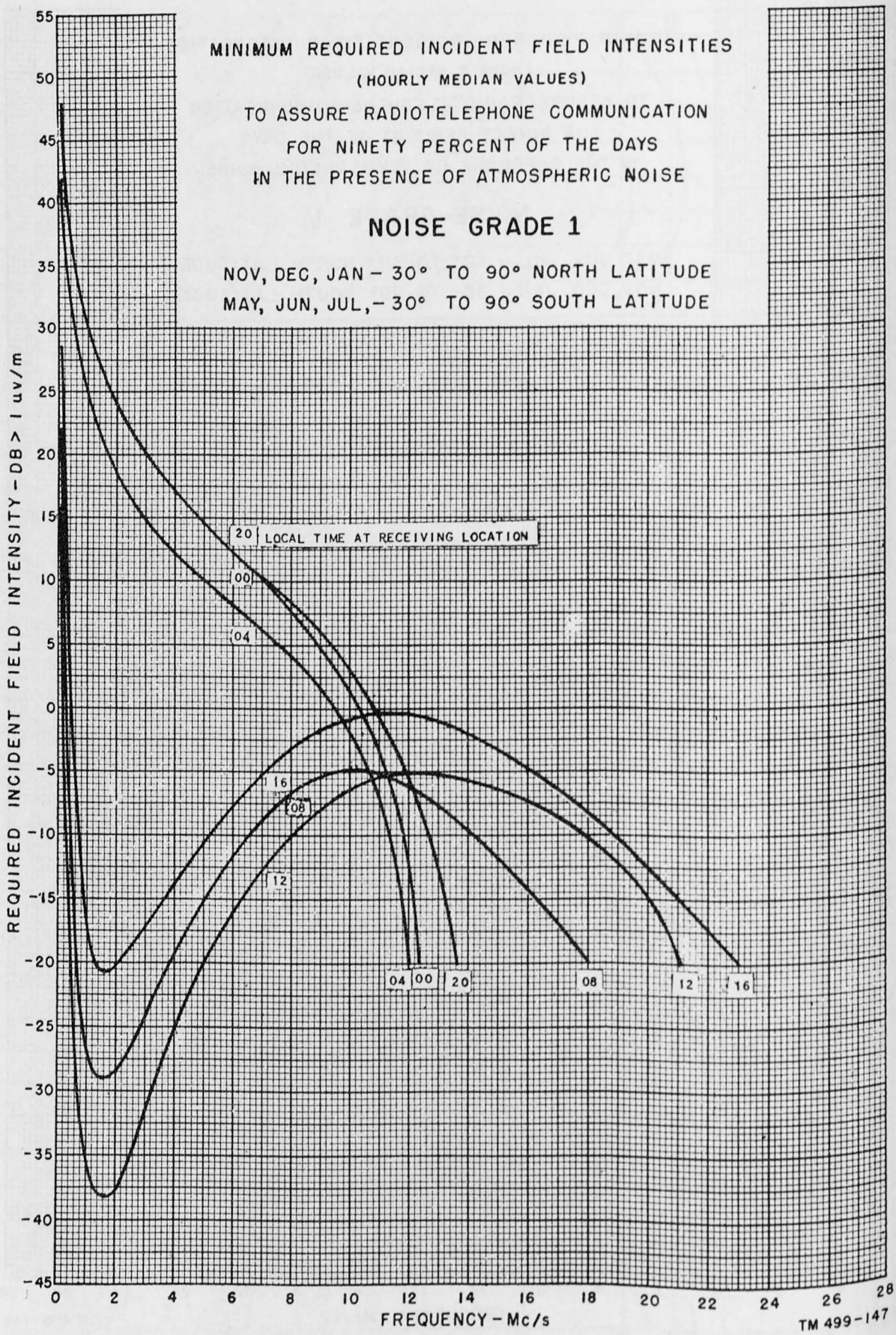


Figure 147. Minimum required incident field intensities, noise grade 1, winter.

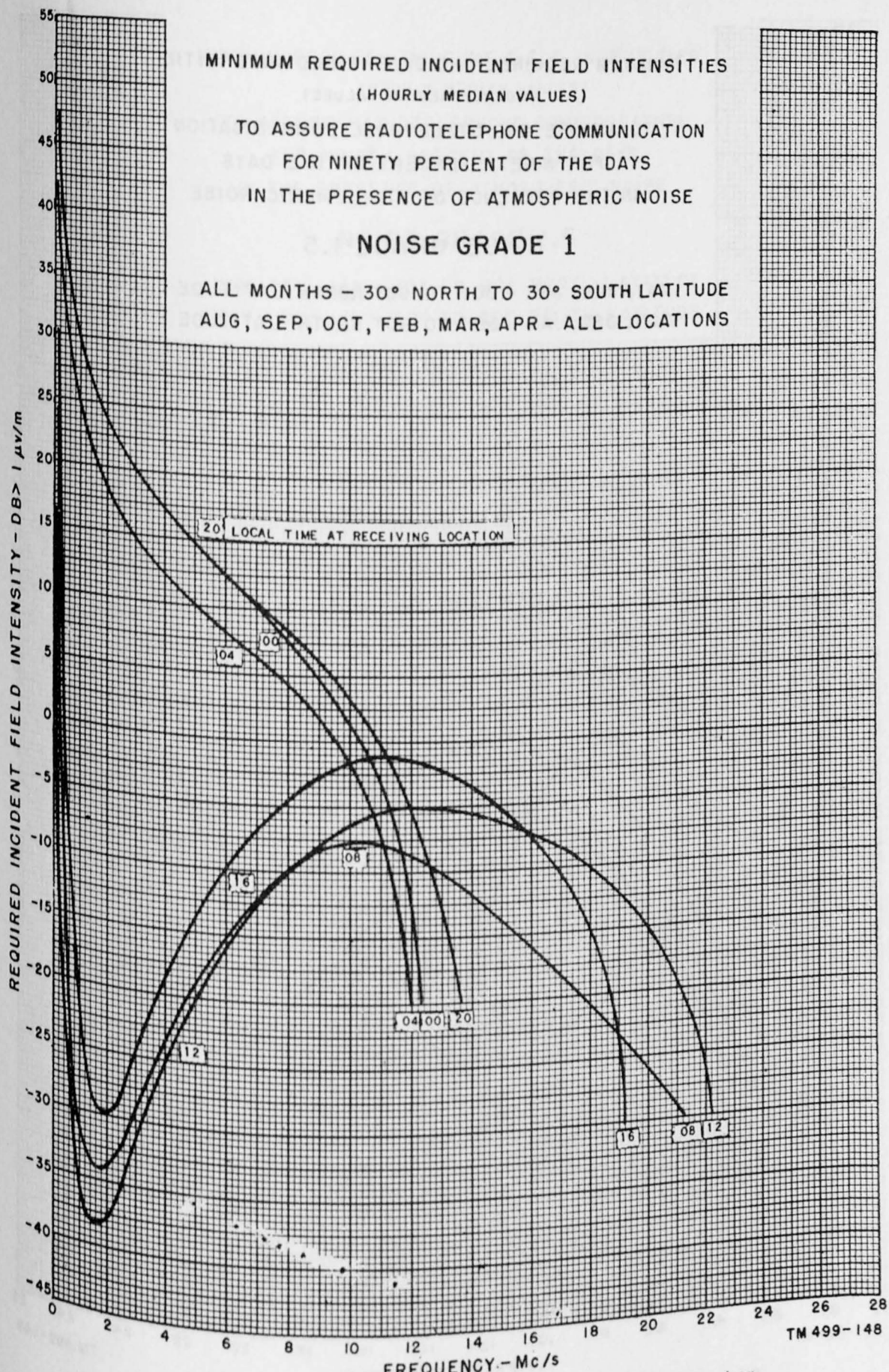


Figure 148. Minimum required incident field intensities, noise grade 1, equinox.

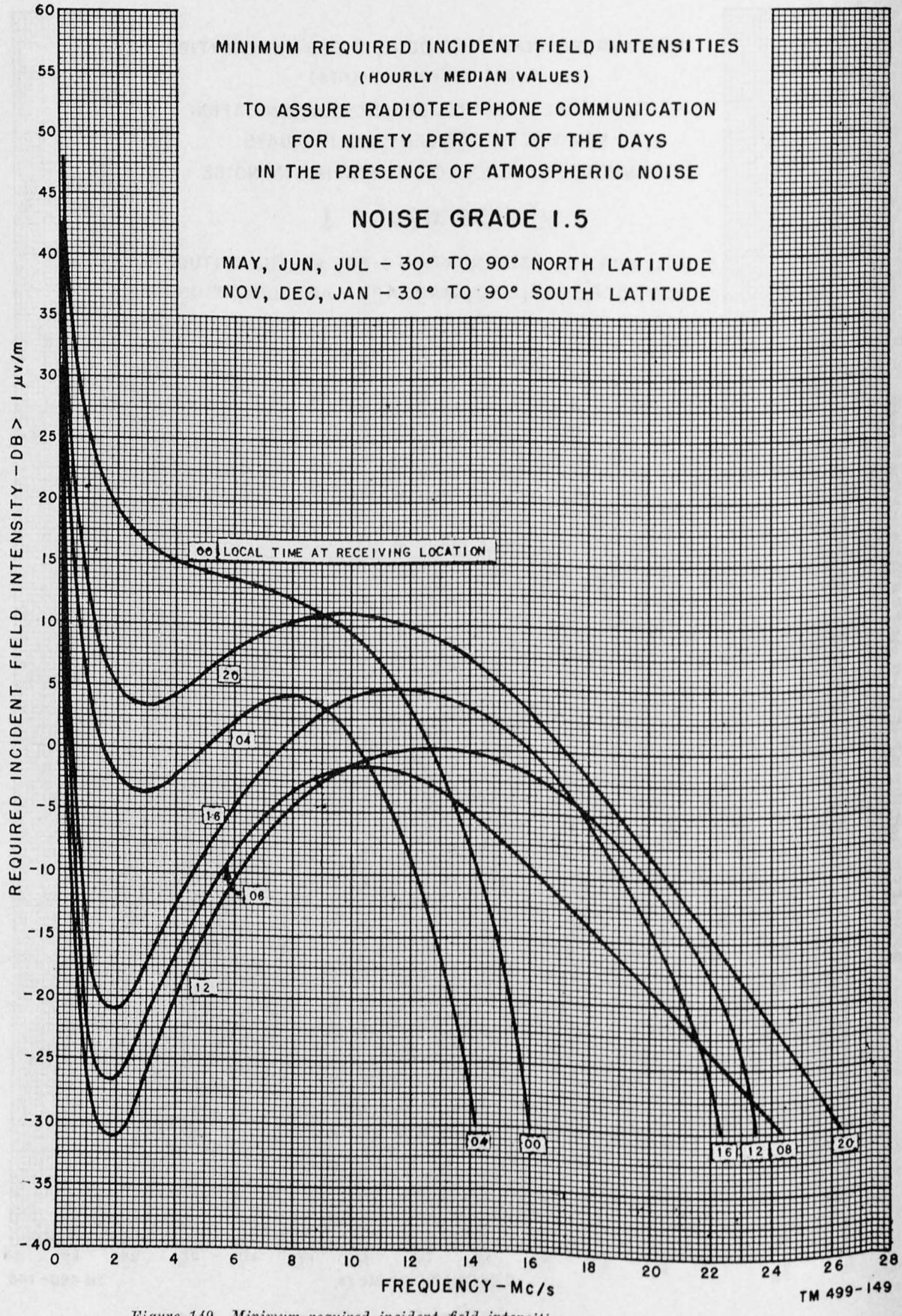


Figure 149. Minimum required incident field intensities, noise grade 1.5, summer.

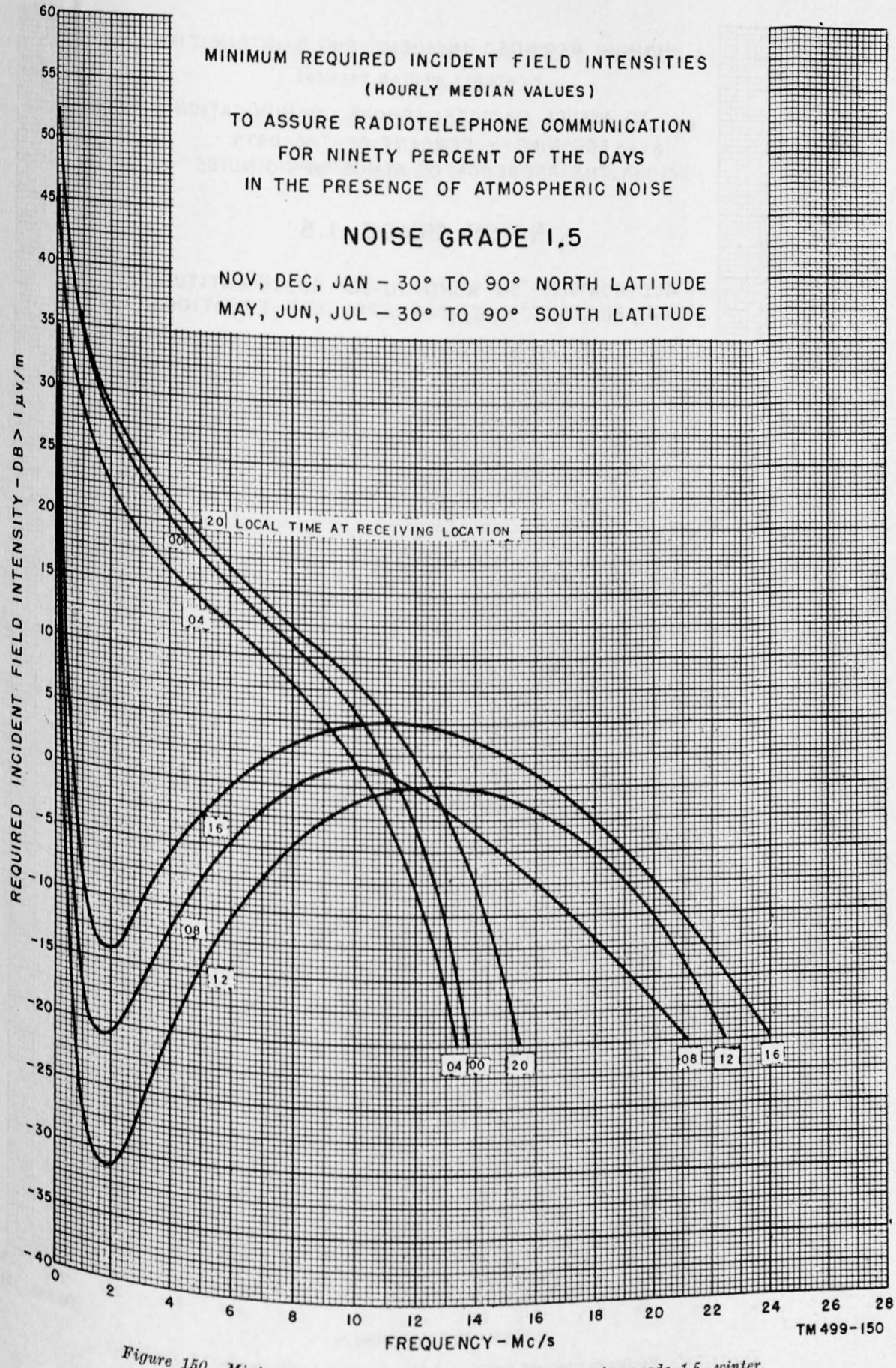


Figure 150. Minimum required incident field intensities, noise grade 1.5, winter.

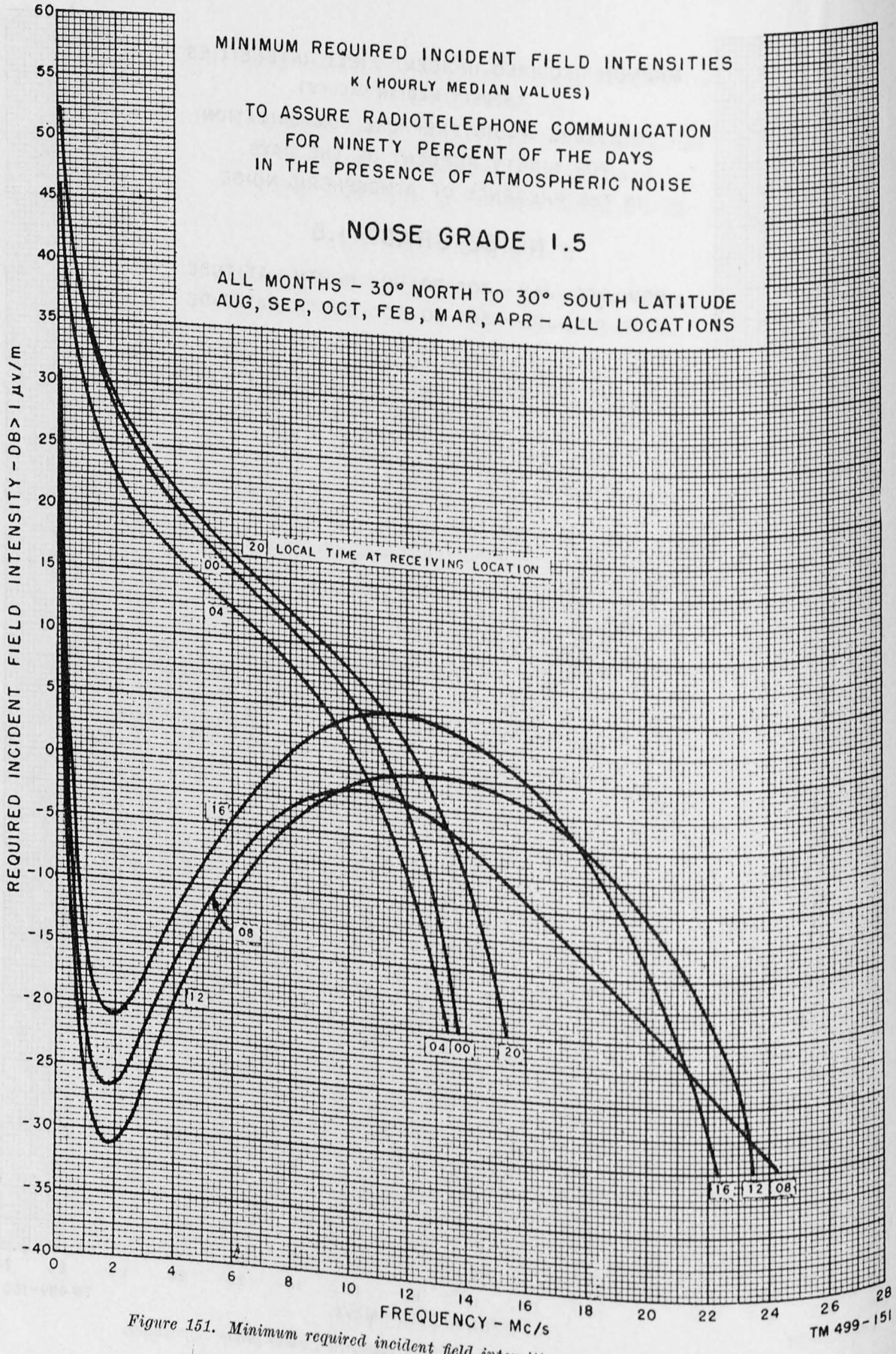


Figure 151. Minimum required incident field intensities, noise grade 1.5, equinox.

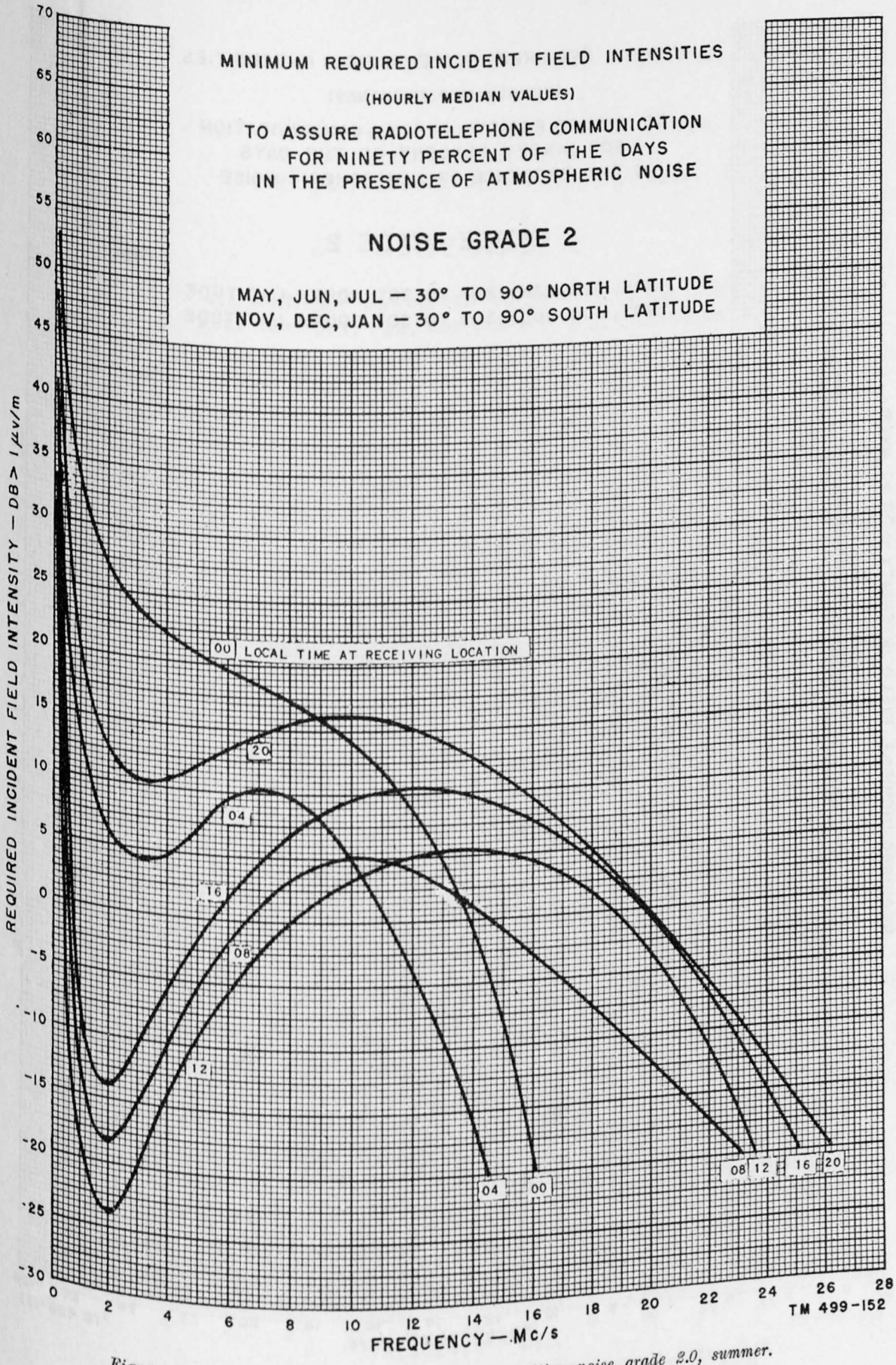


Figure 152. Minimum required incident field intensities, noise grade 2.0, summer.

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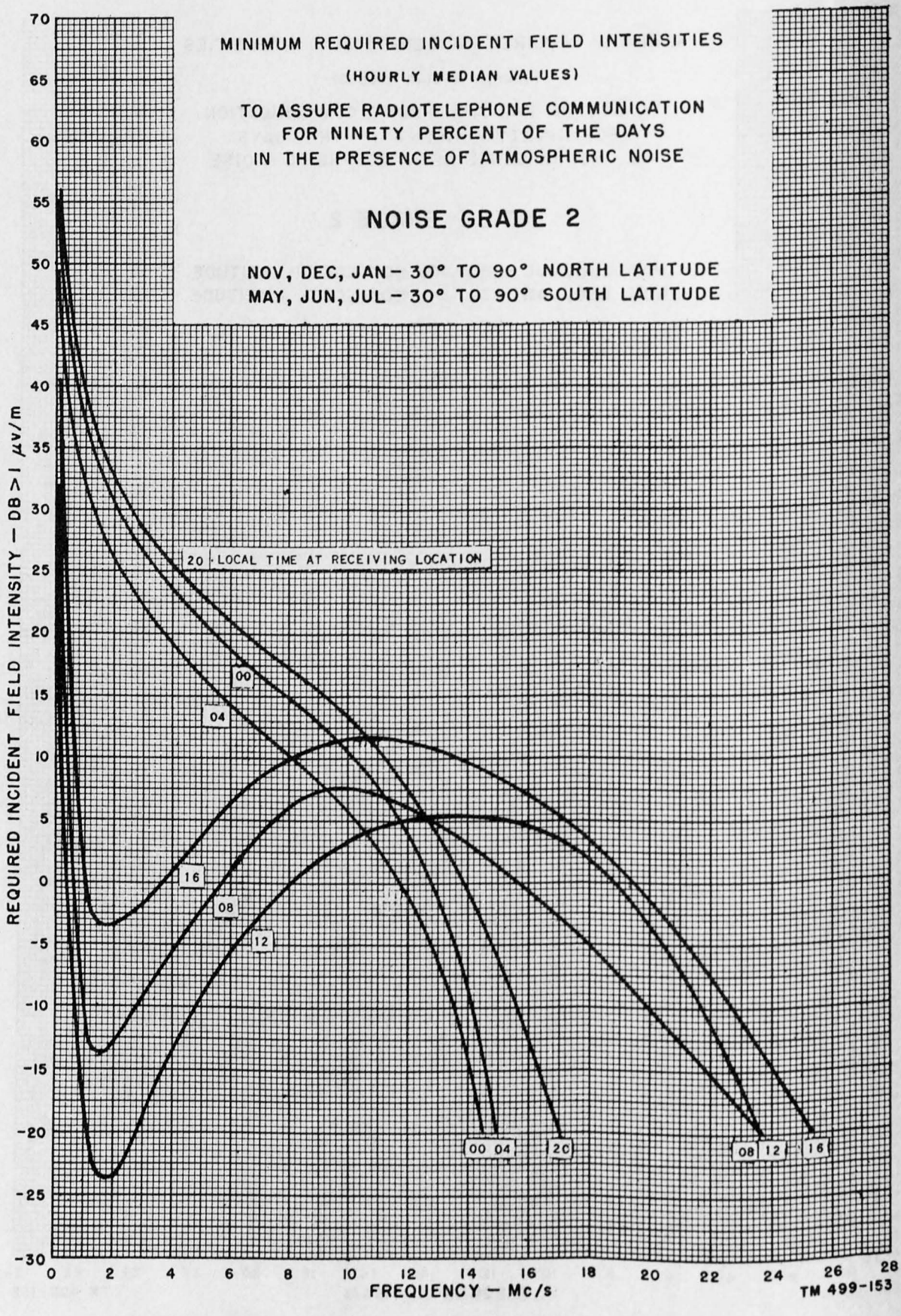


Figure 153. Minimum required incident field intensities, noise grade 2.0, winter.

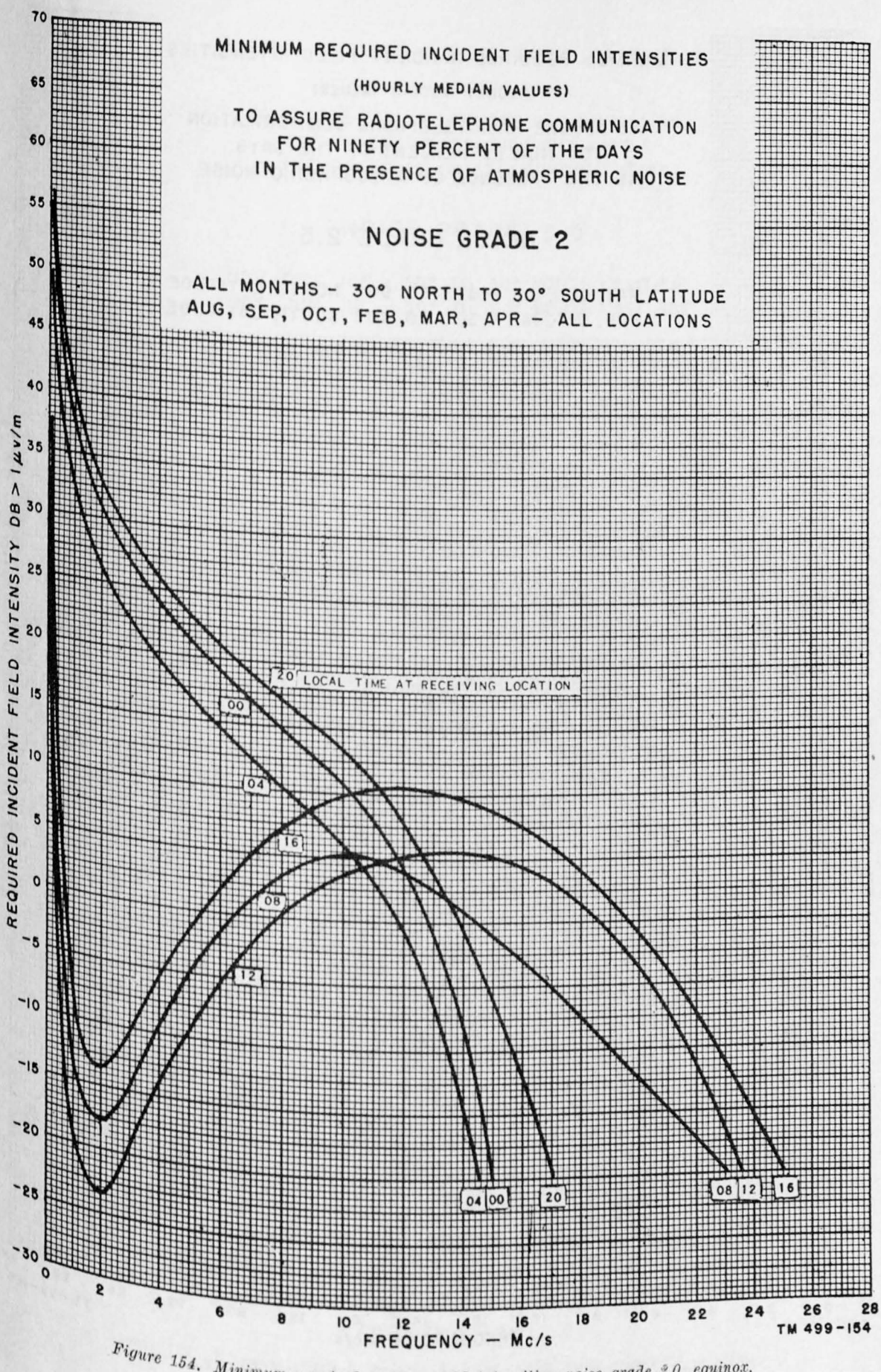


Figure 154. Minimum required incident field intensities, noise grade 2.0, equinox.

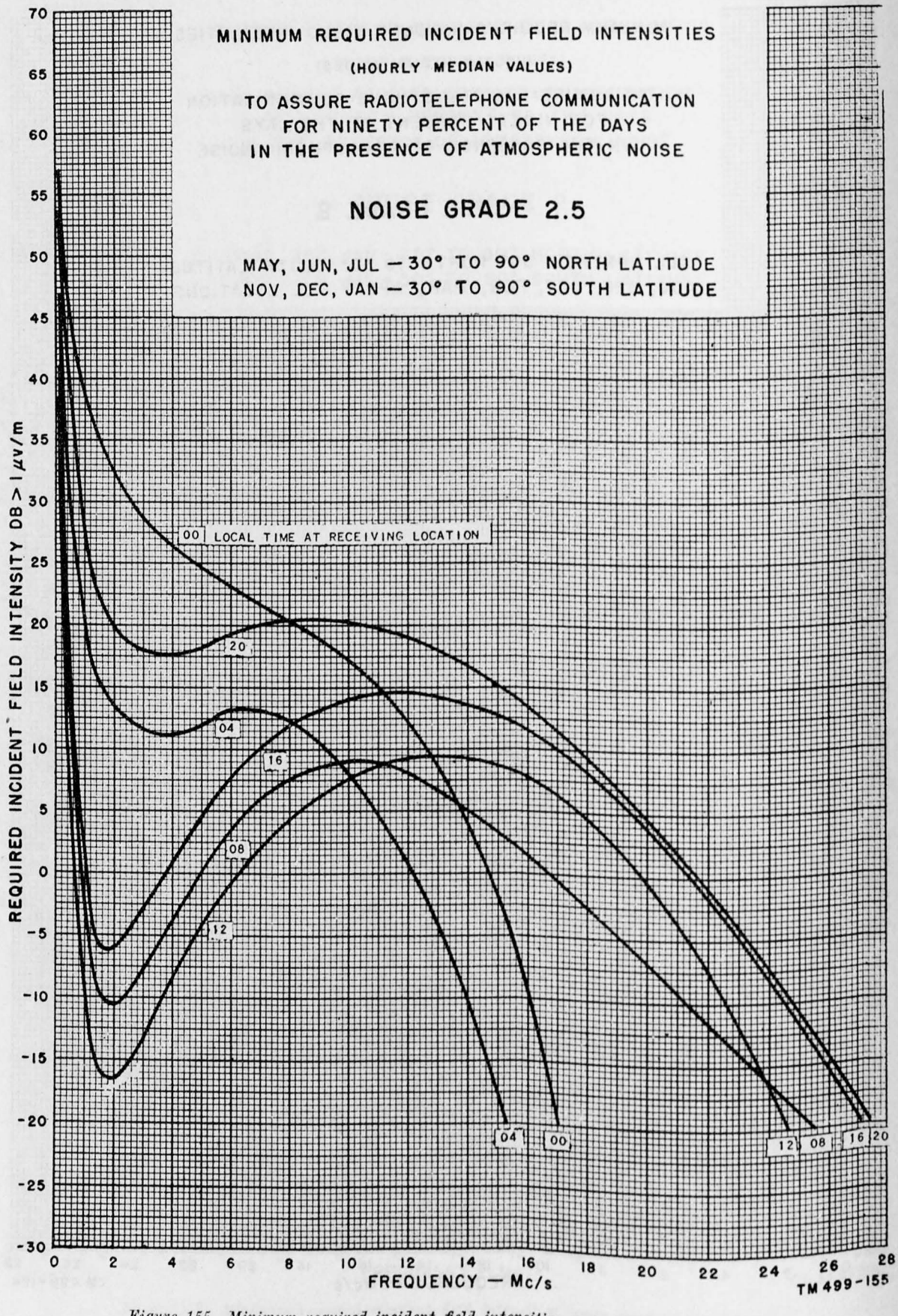


Figure 155. Minimum required incident field intensities, noise grade 2.5, summer.

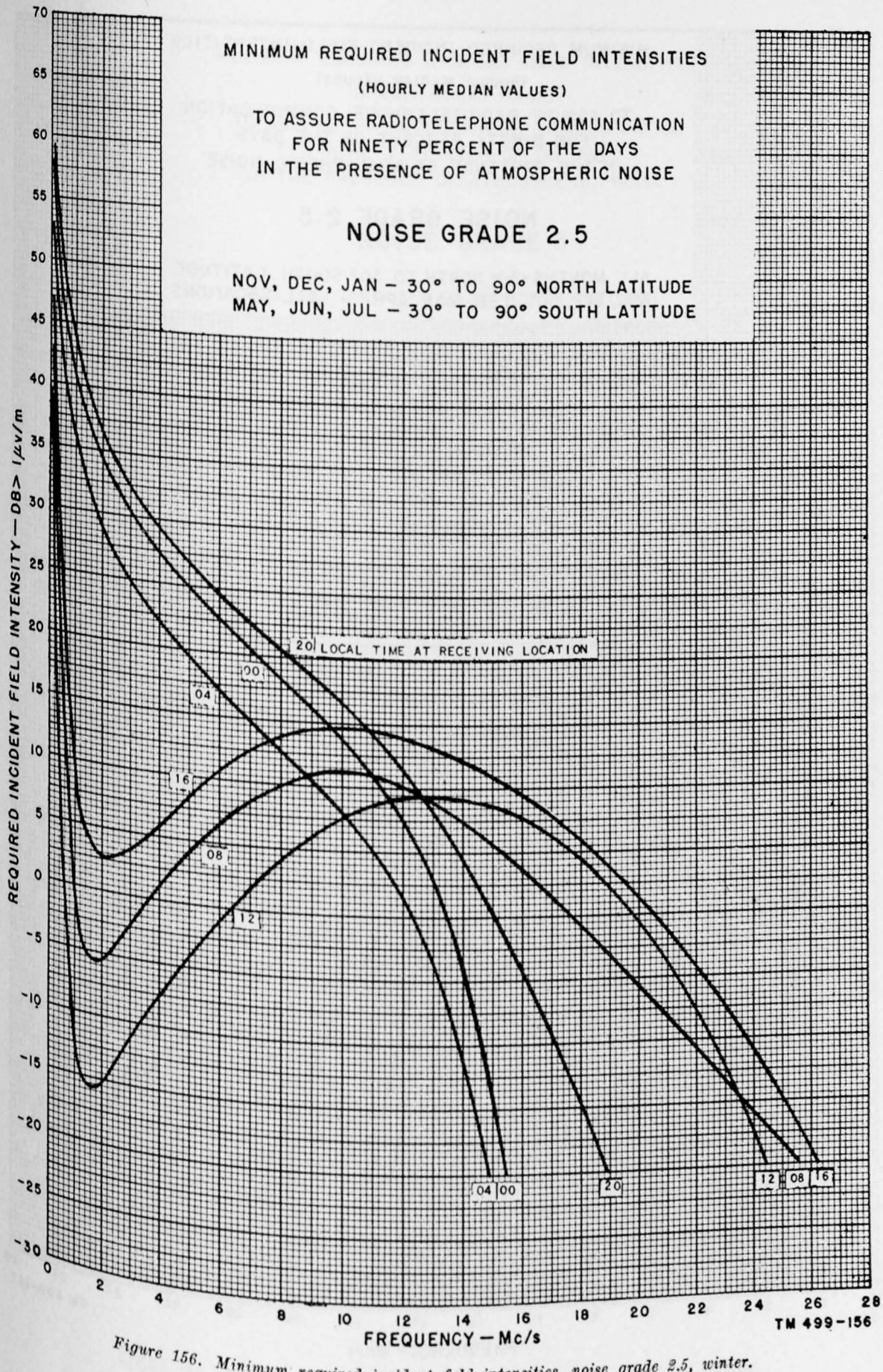


Figure 156. Minimum required incident field intensities, noise grade 2.5, winter.

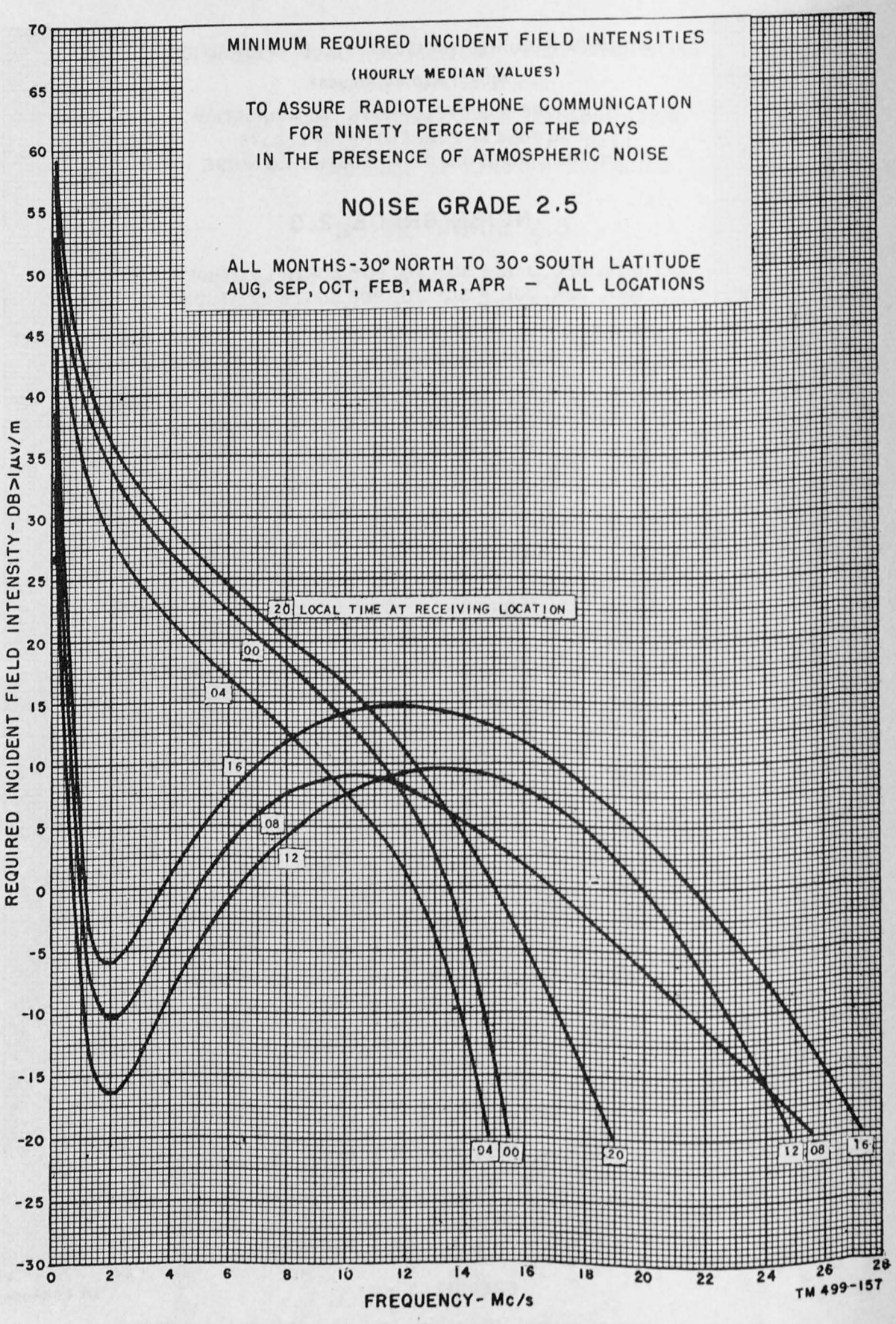


Figure 157. Minimum required incident field intensities, noise grade 2.5, equinox.

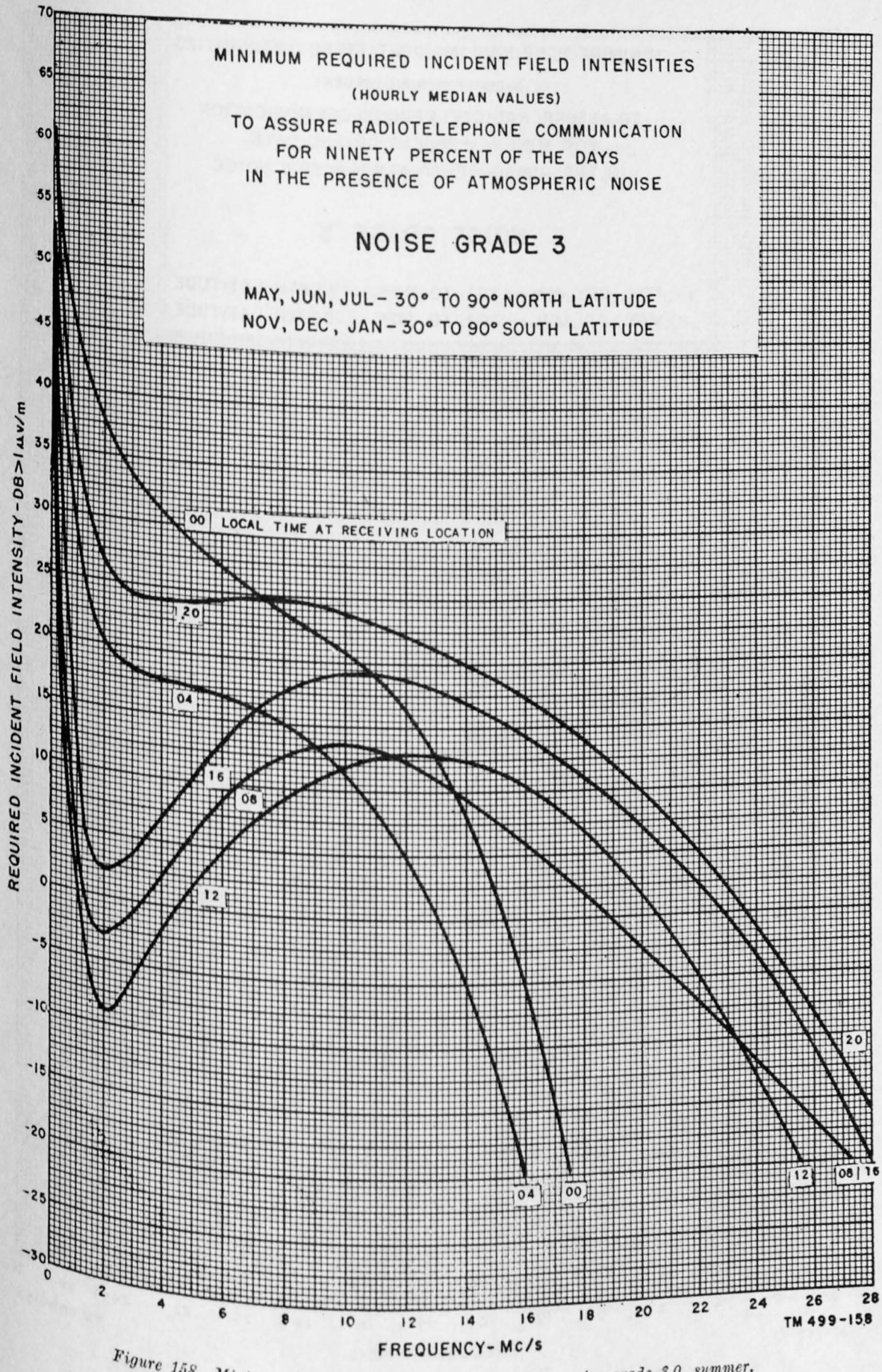


Figure 158. Minimum required incident field intensities, noise grade 3.0, summer.

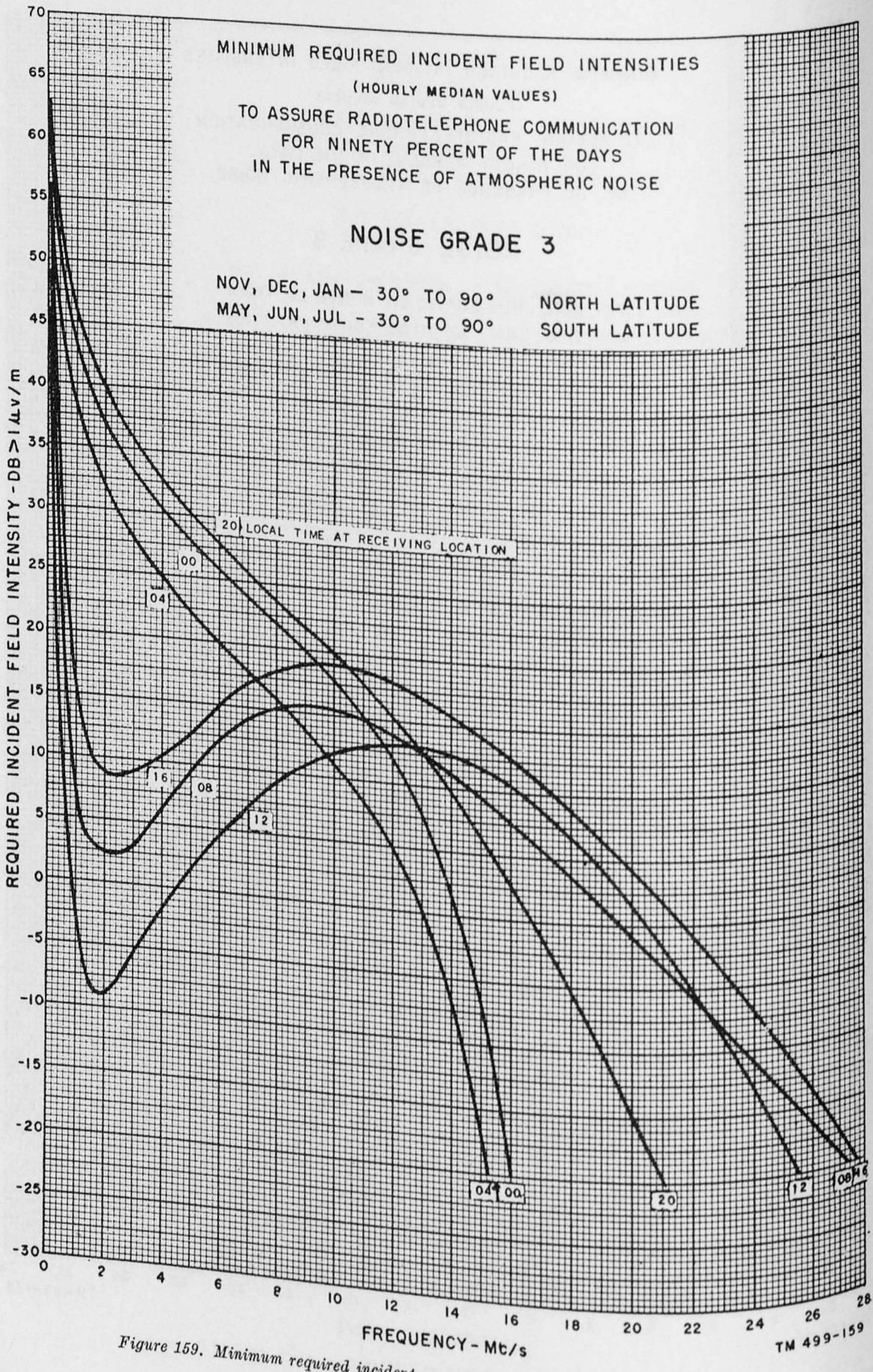


Figure 159. Minimum required incident required intensities, noise grade 3.0, winter.

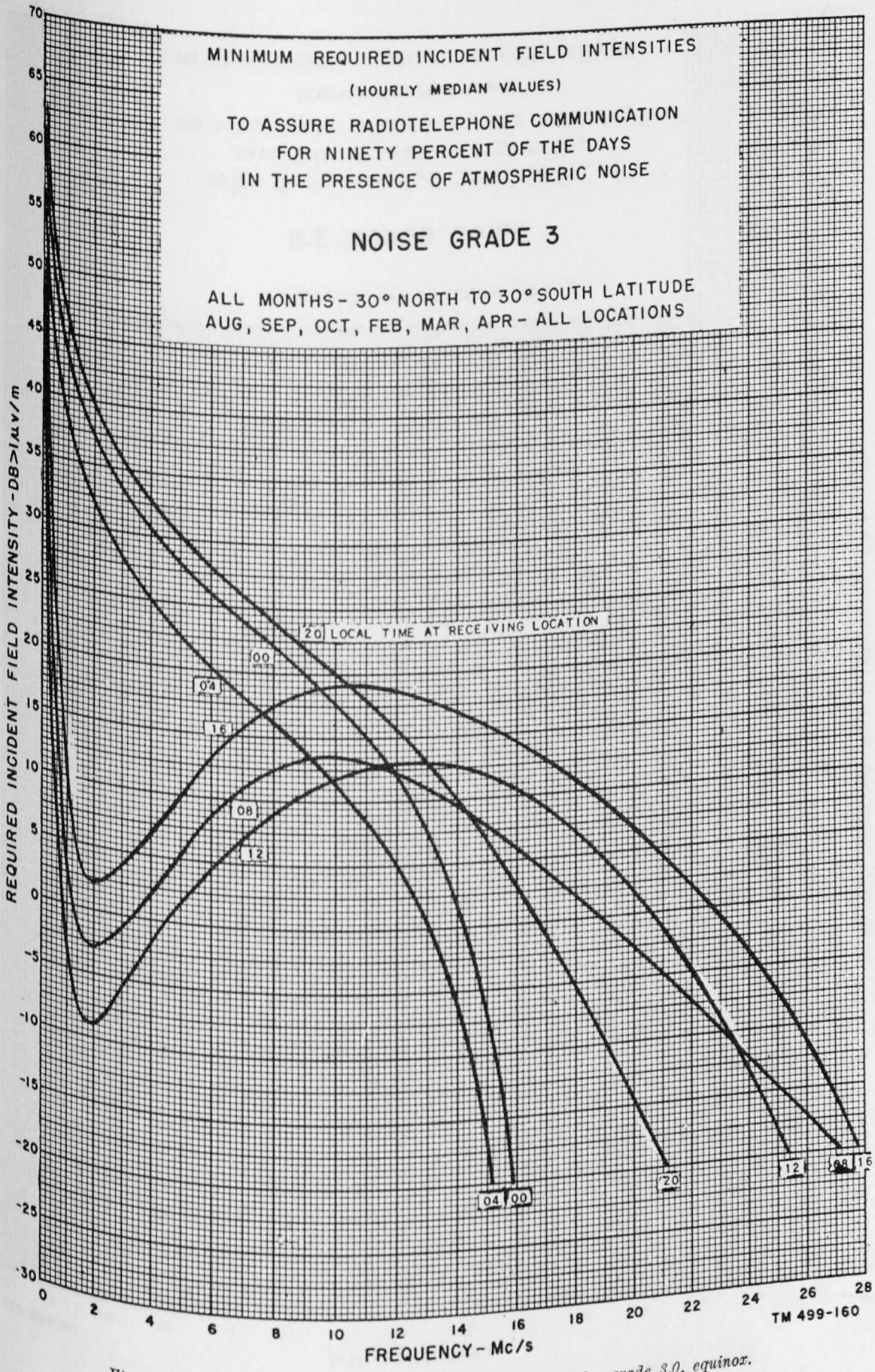


Figure 160. Minimum required incident field intensities, noise grade 3.0, equinox.

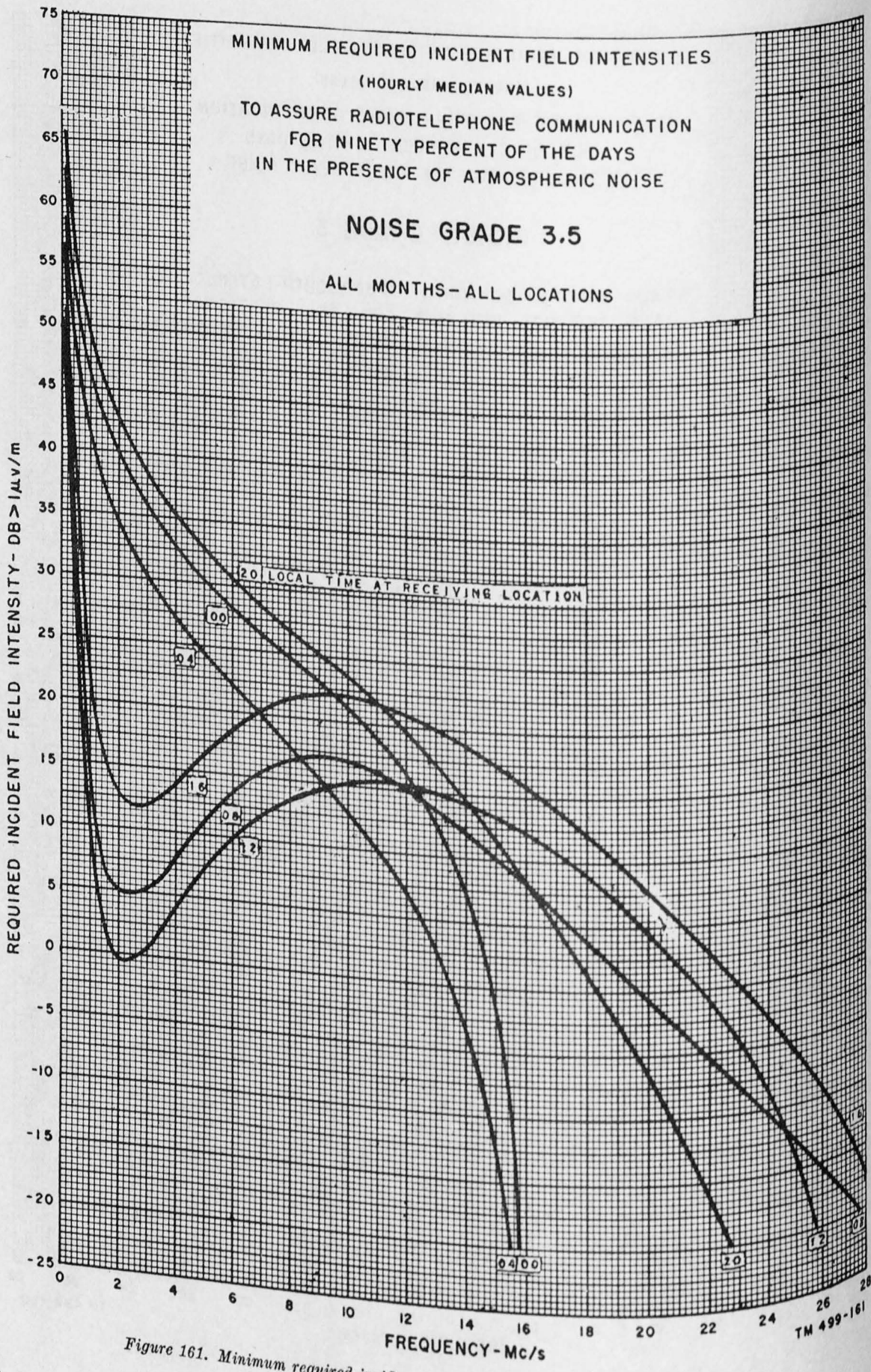


Figure 161. Minimum required incident field intensities, noise grade 3.5, all months.

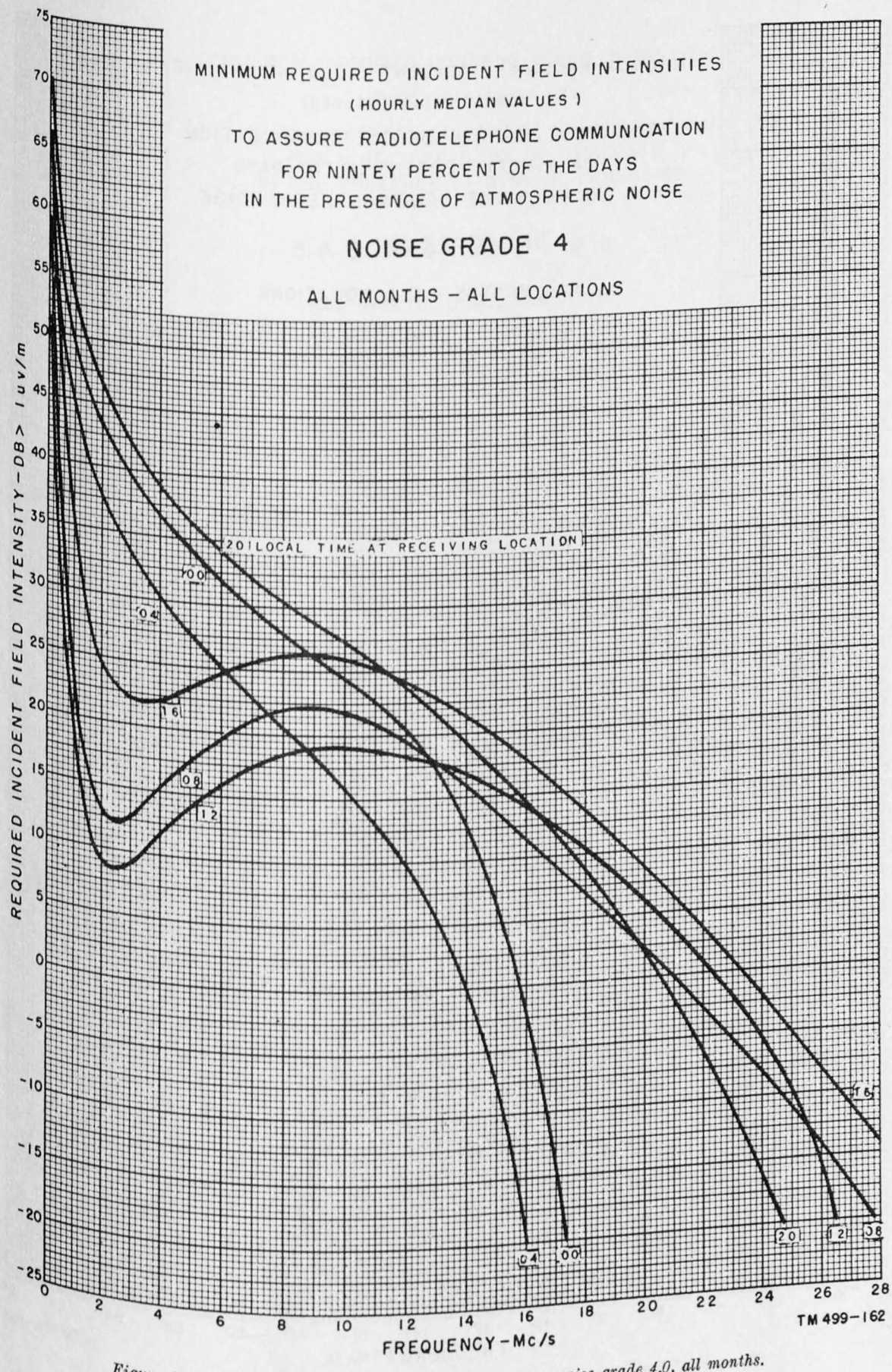


Figure 162. Minimum required incident field intensitics, noise grade 4.0, all months.

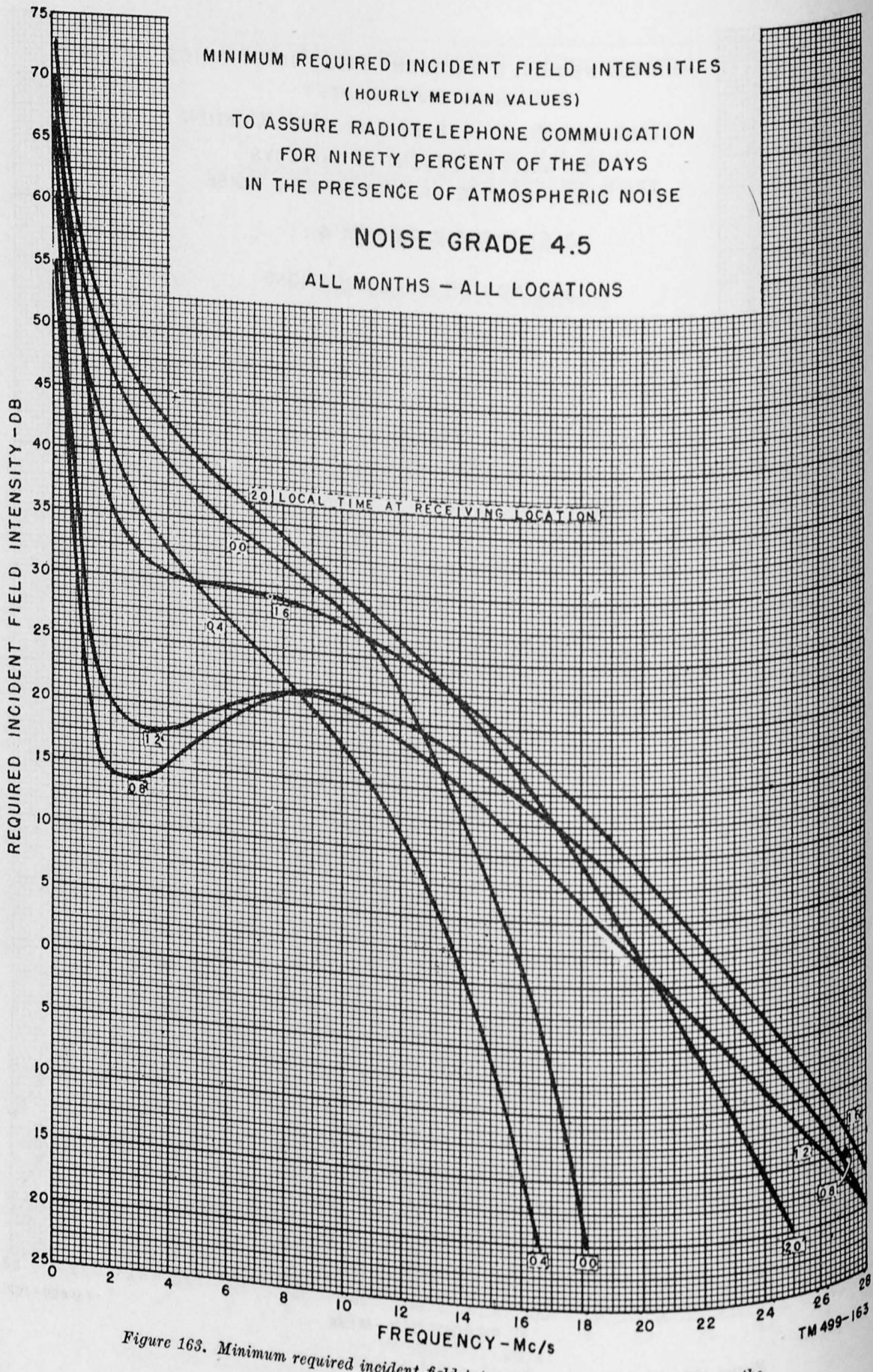


Figure 163. Minimum required incident field intensities, noise grade 4.5, all months.

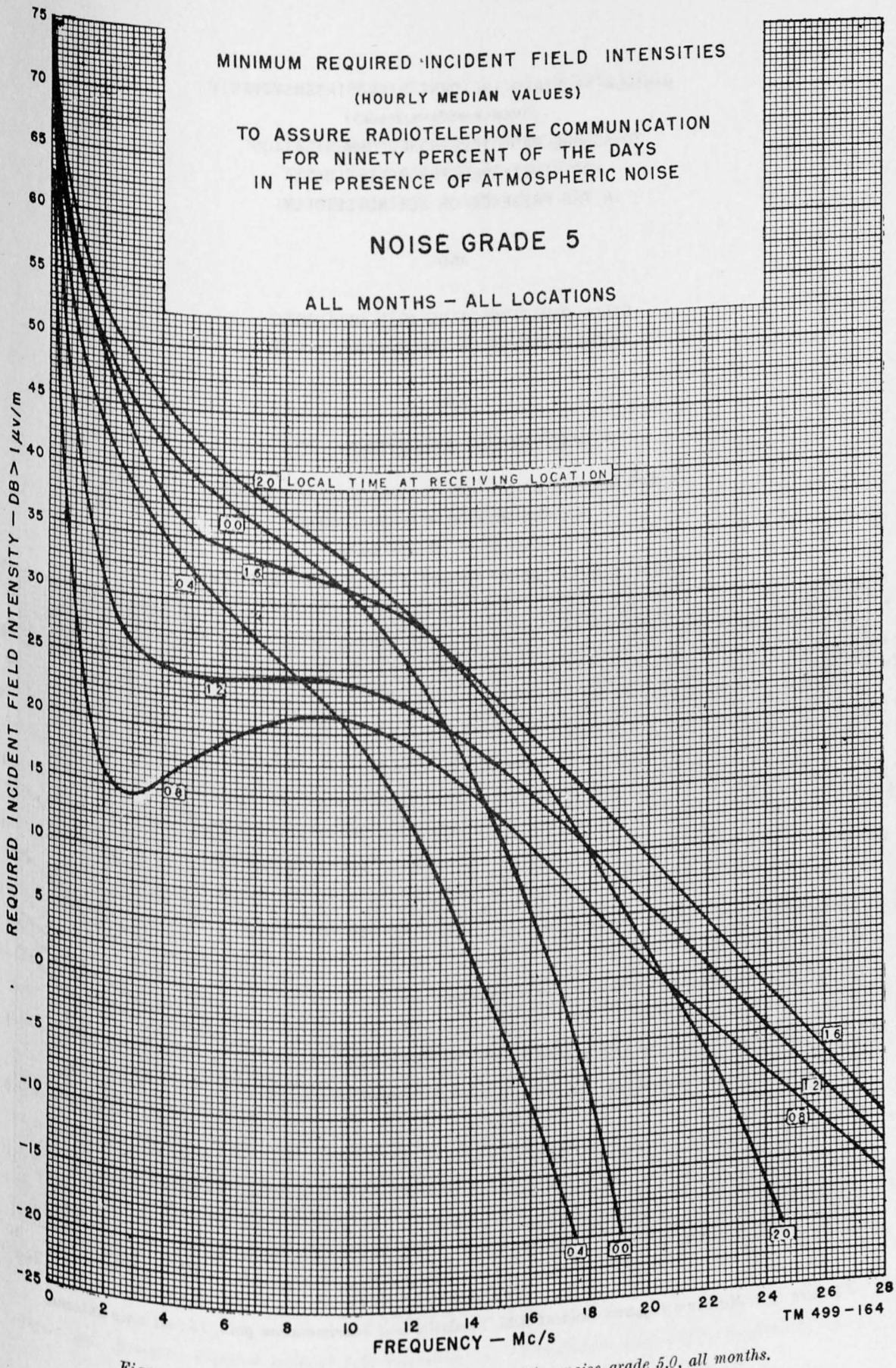


Figure 164. Minimum required incident field intensities, noise grade 5.0, all months.

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

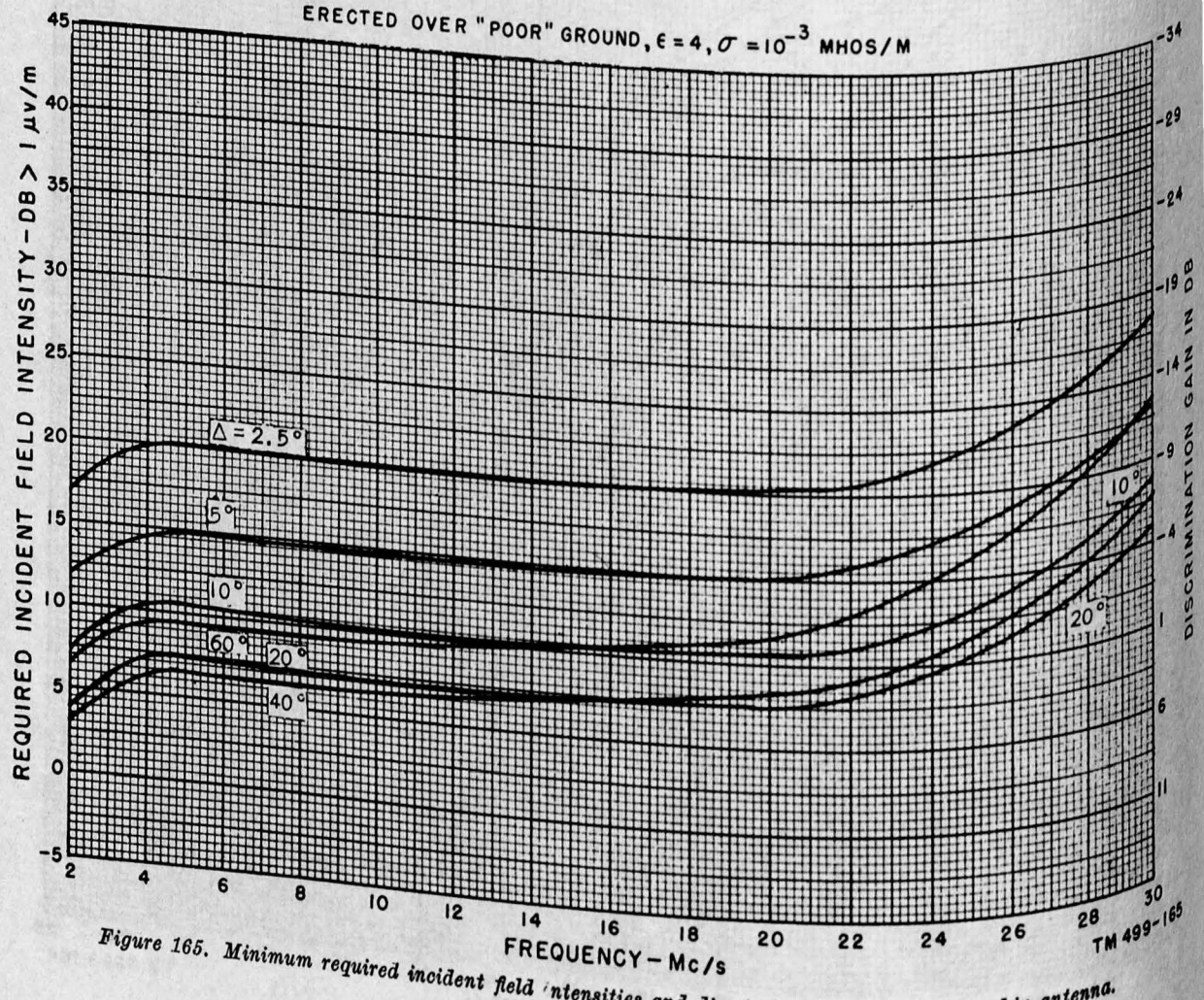


Figure 165. Minimum required incident field intensities and discrimination gain, 15-foot whip antenna.

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

50' INVERTED "L" ANTENNA

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL

MEASURED FROM THE HORIZONTAL PLANE

BROADSIDE TO THE ANTENNA

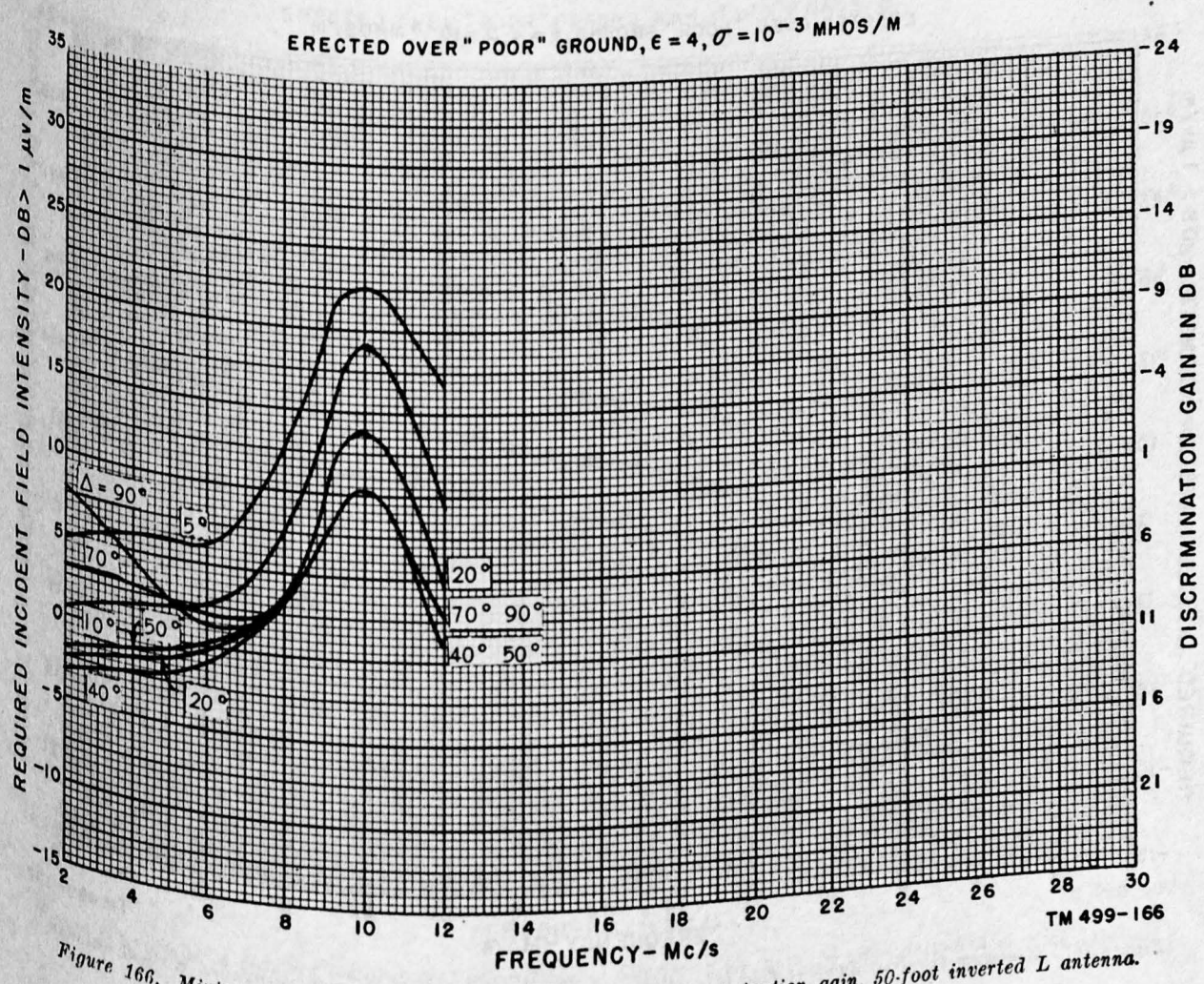


Figure 166. Minimum required incident field intensities and discrimination gain, 50-foot inverted L antenna.

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

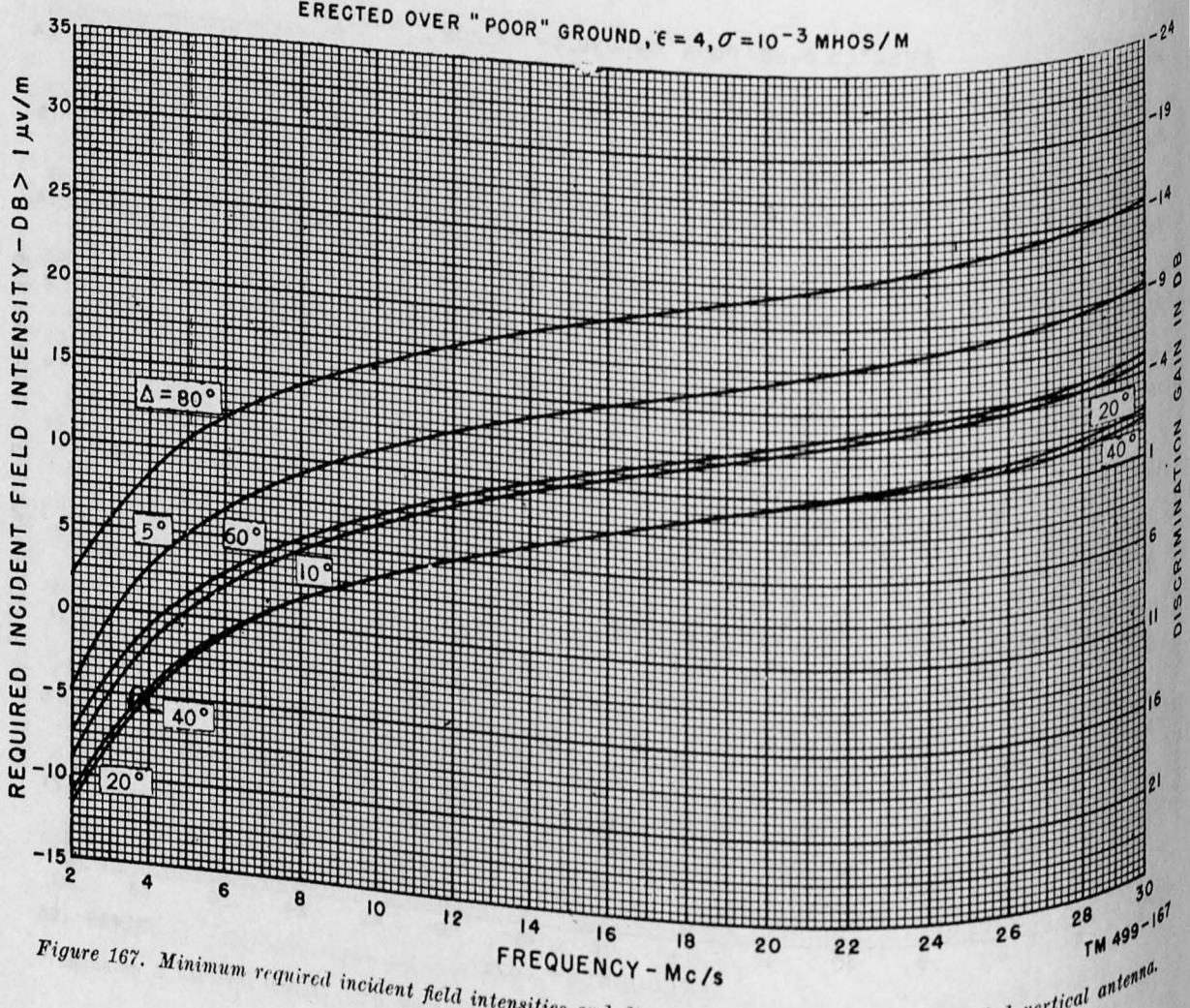


Figure 167. Minimum required incident field intensities and discrimination gain, ¼-wave grounded vertical antenna.

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 CENTER OF ANTENNA (OR

END FED WITH IMPEDANCE MATCHING TRANSFORMER)

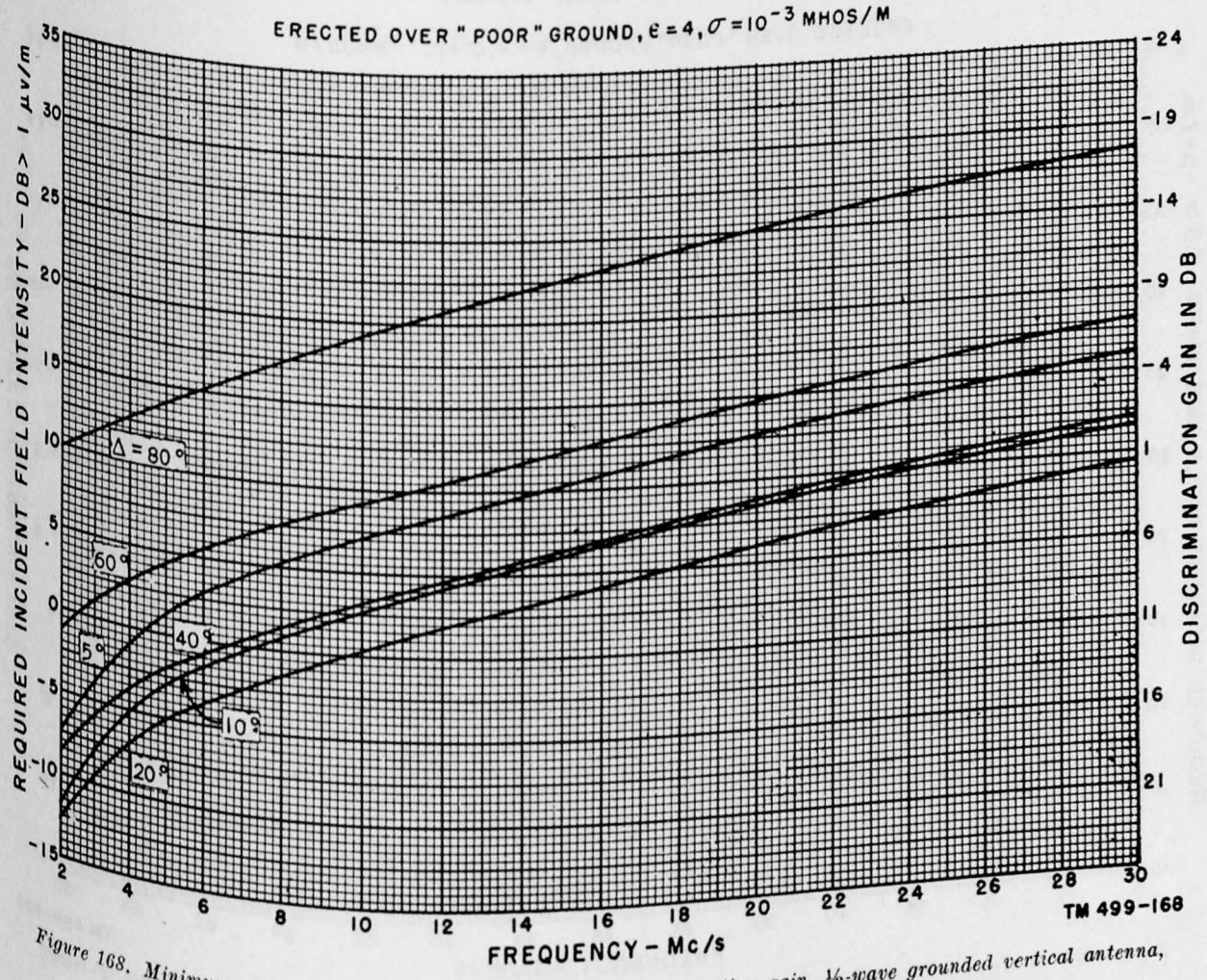


Figure 168. Minimum required incident field intensities and discrimination gain, ½-wave grounded vertical antenna, transmission line fed from center of antenna.

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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

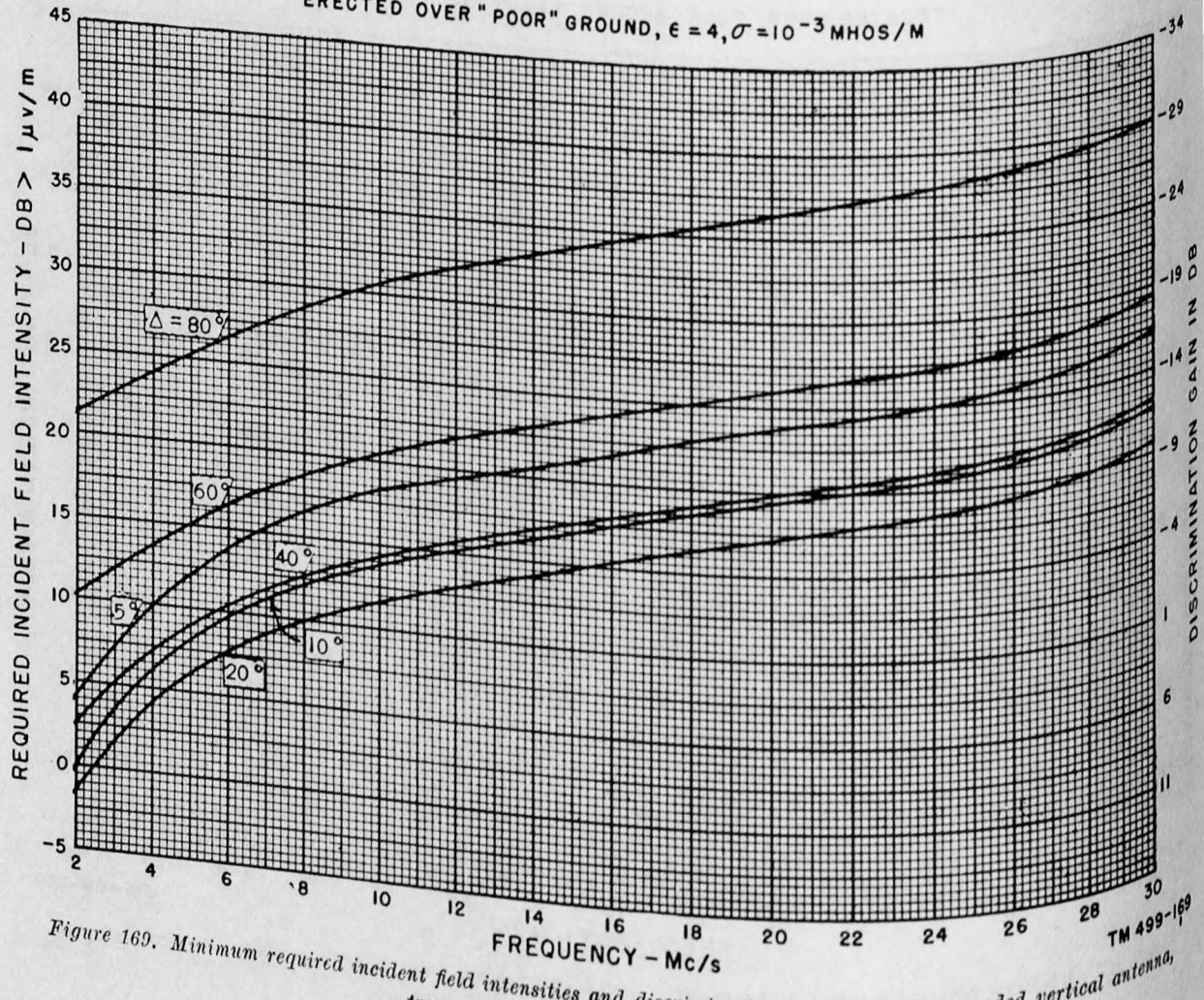


Figure 169. Minimum required incident field intensities and discrimination gain, ½-wave grounded vertical antenna, transmission line fed from base of antenna.

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 HORIZONTAL ANTENNA λ/4 HIGH

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL

MEASURED FROM THE HORIZONTAL PLANE

BROADSIDE TO THE ANTENNA

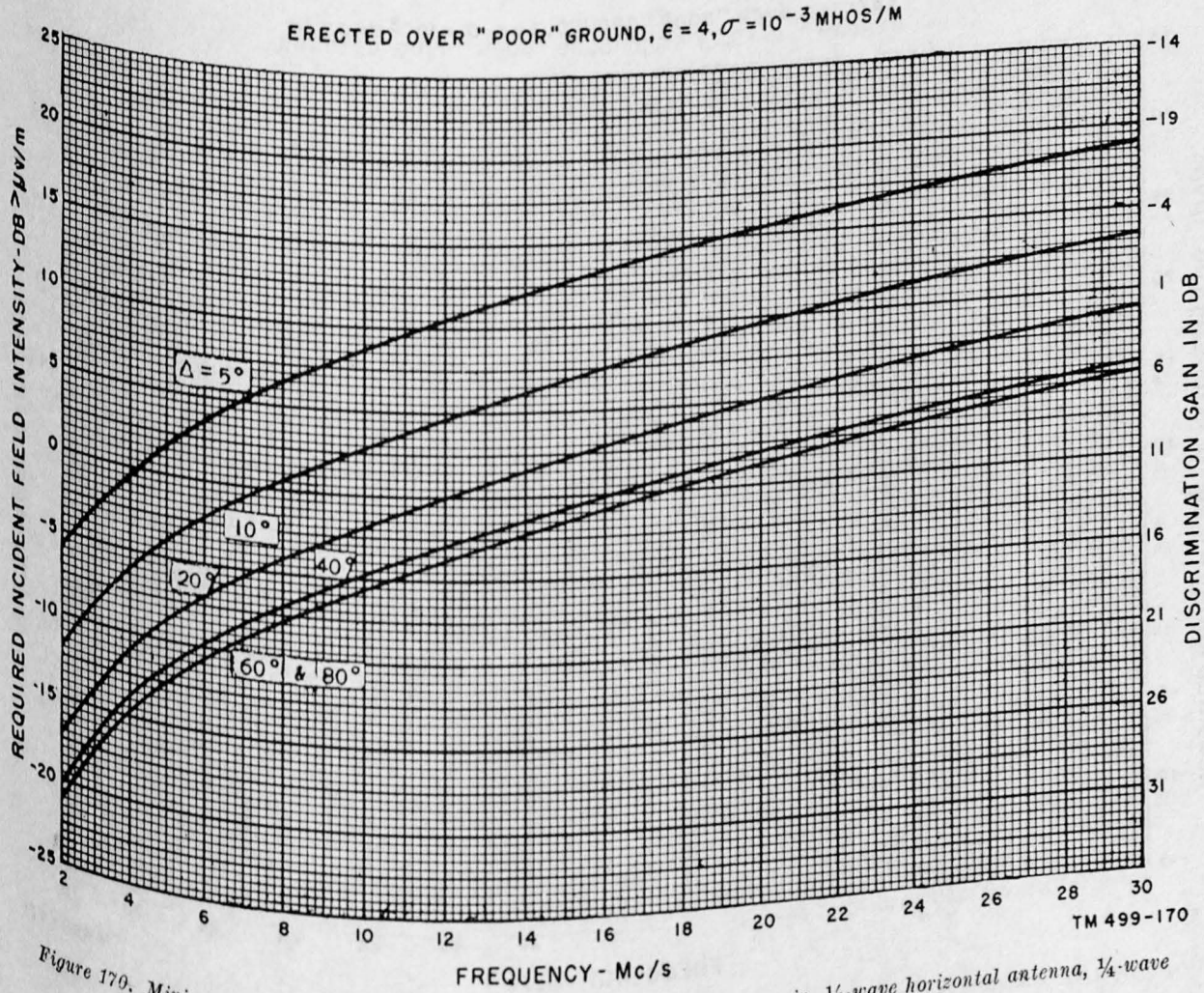


Figure 179. Minimum required incident field intensities and discrimination gain, ½-wave horizontal antenna, ¼-wave high.

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 HORIZONTAL ANTENNA 10' HIGH

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

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

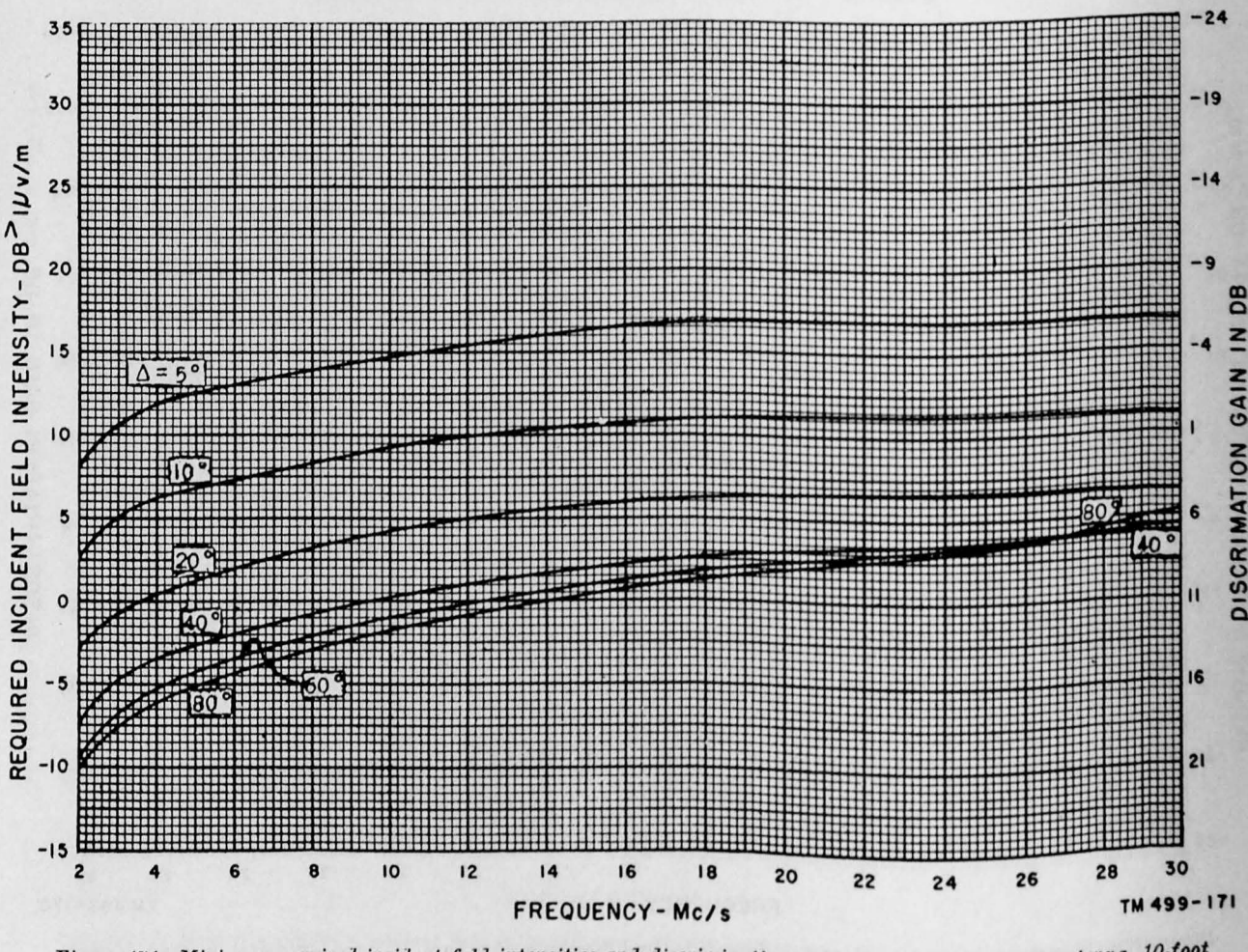


Figure 171. Minimum required incident field intensities and discrimination gain, ½-wave horizontal antenna, 10-foot high.

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 HORIZONTAL ANTENNA 30' HIGH

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL

MEASURED FROM THE HORIZONTAL PLANE

BROADSIDE TO THE ANTENNA

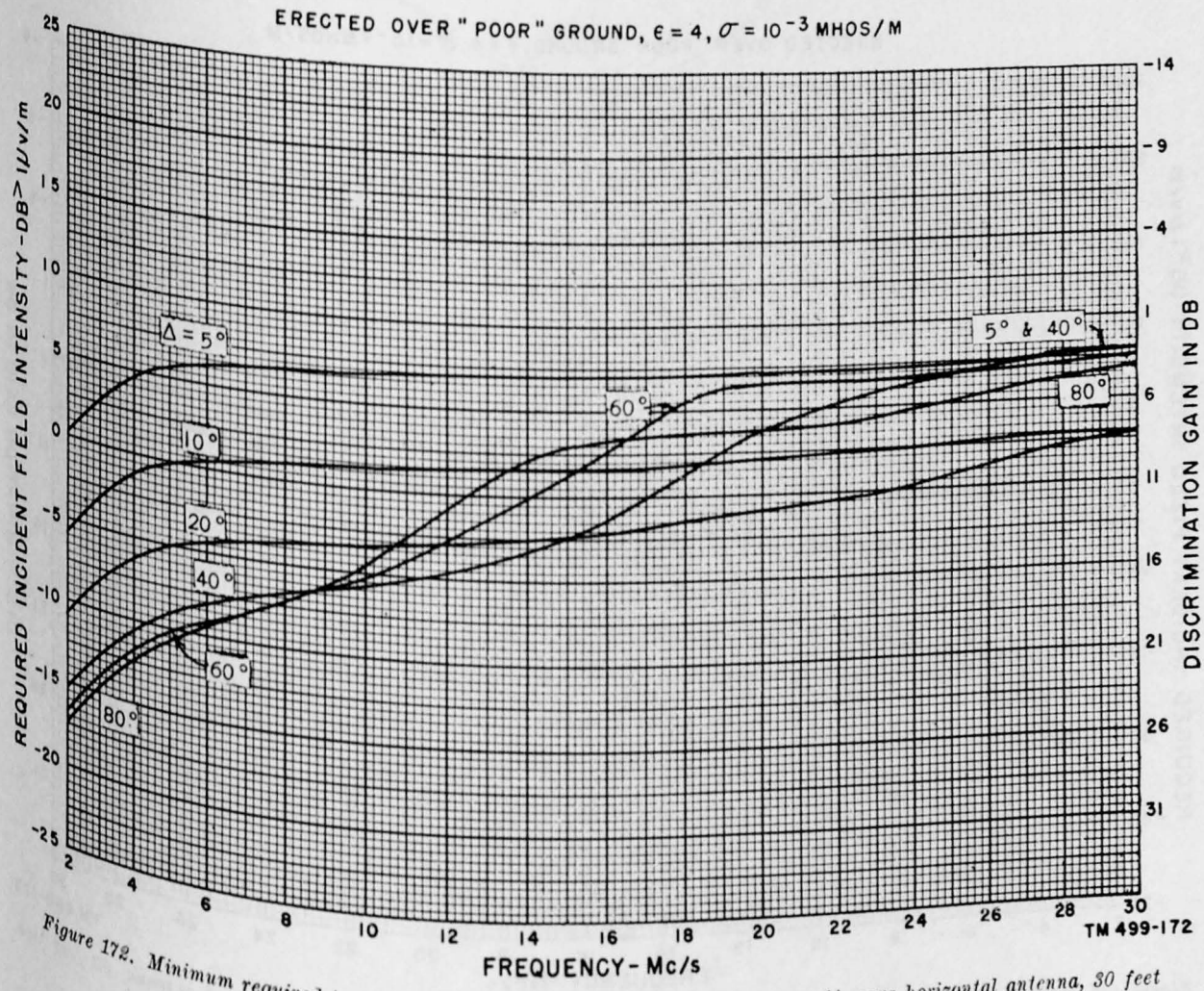


Figure 172. Minimum required incident field intensities and discrimination gain, ½-wave horizontal antenna, 30 feet high.

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 HORIZONTAL ANTENNA 60' HIGH

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL

MEASURED FROM THE HORIZONTAL PLANE

BROADSIDE TO THE ANTENNA

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

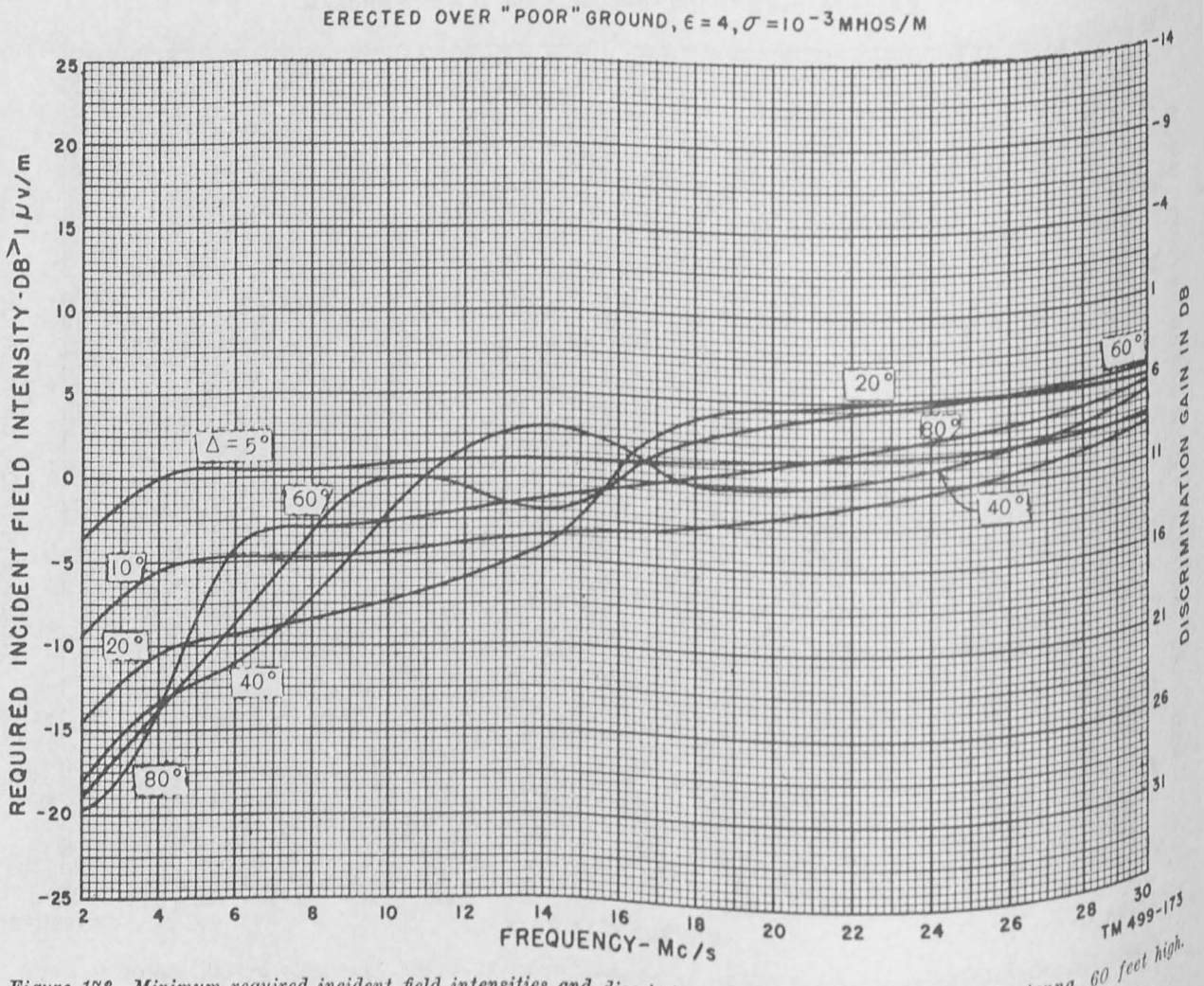
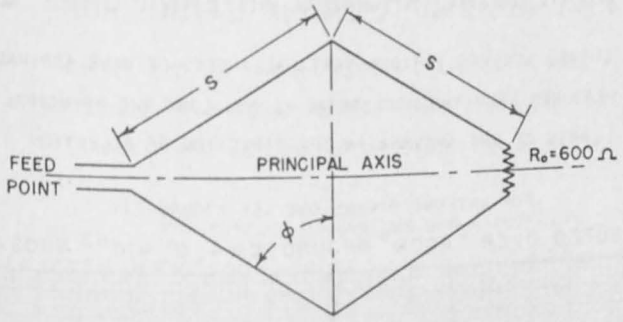


Figure 173. Minimum required incident field intensities and discrimination gain, ½-wave horizontal antenna, 60 feet high.



ANTENNA TYPE	SIDE S FEET	ANGLE ϕ DEGREES	ANTENNA HEIGHT FEET
A	375	70	65
B	350	70	60
C	315	70	57
D	290	67.5	55
E	270	65	53
F	245	62.5	51
G	225	60	50

TM 499-174

Figure 174. Dimensions of Signal Corps rhombic antennas.

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

HORIZONTAL RHOMBIC ANTENNA TYPE "A"

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL MEASURED FROM THE HORIZONTAL PLANE ALONG THE PRINCIPAL AXIS OF THE ANTENNA IN THE DIRECTION OF RECEPTION

FOR ANTENNA DIMENSIONS SEE FIGURE 174

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

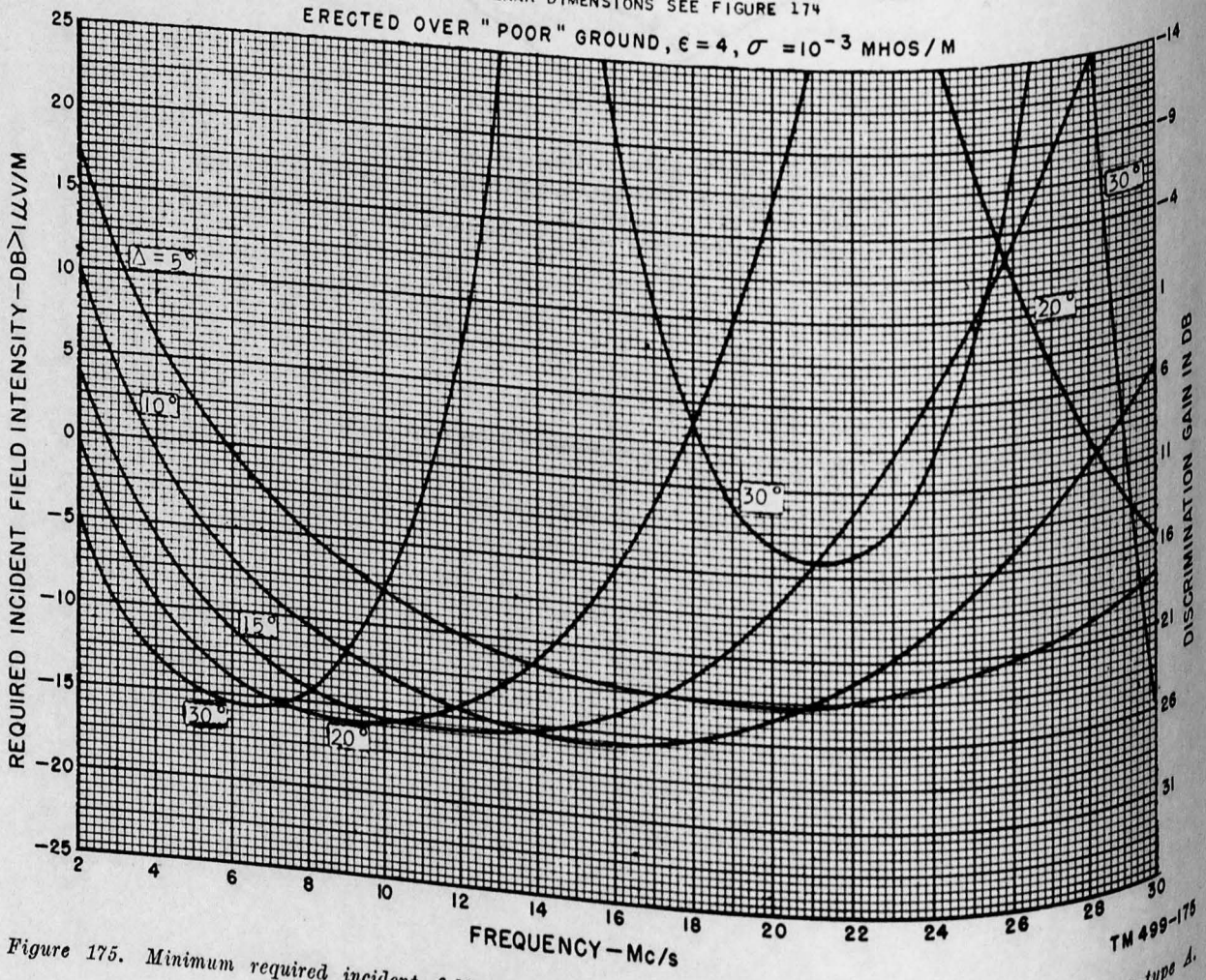


Figure 175. Minimum required incident field intensities and discrimination gain, horizontal rhombic antenna type A.

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

HORIZONTAL RHOMBIC ANTENNA TYPE "B"

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL
MEASURED FROM THE HORIZONTAL PLANE ALONG THE PRINCIPAL
AXIS OF THE ANTENNA IN THE DIRECTION OF RECEPTION

FOR ANTENNA DIMENSIONS SEE FIGURE 174

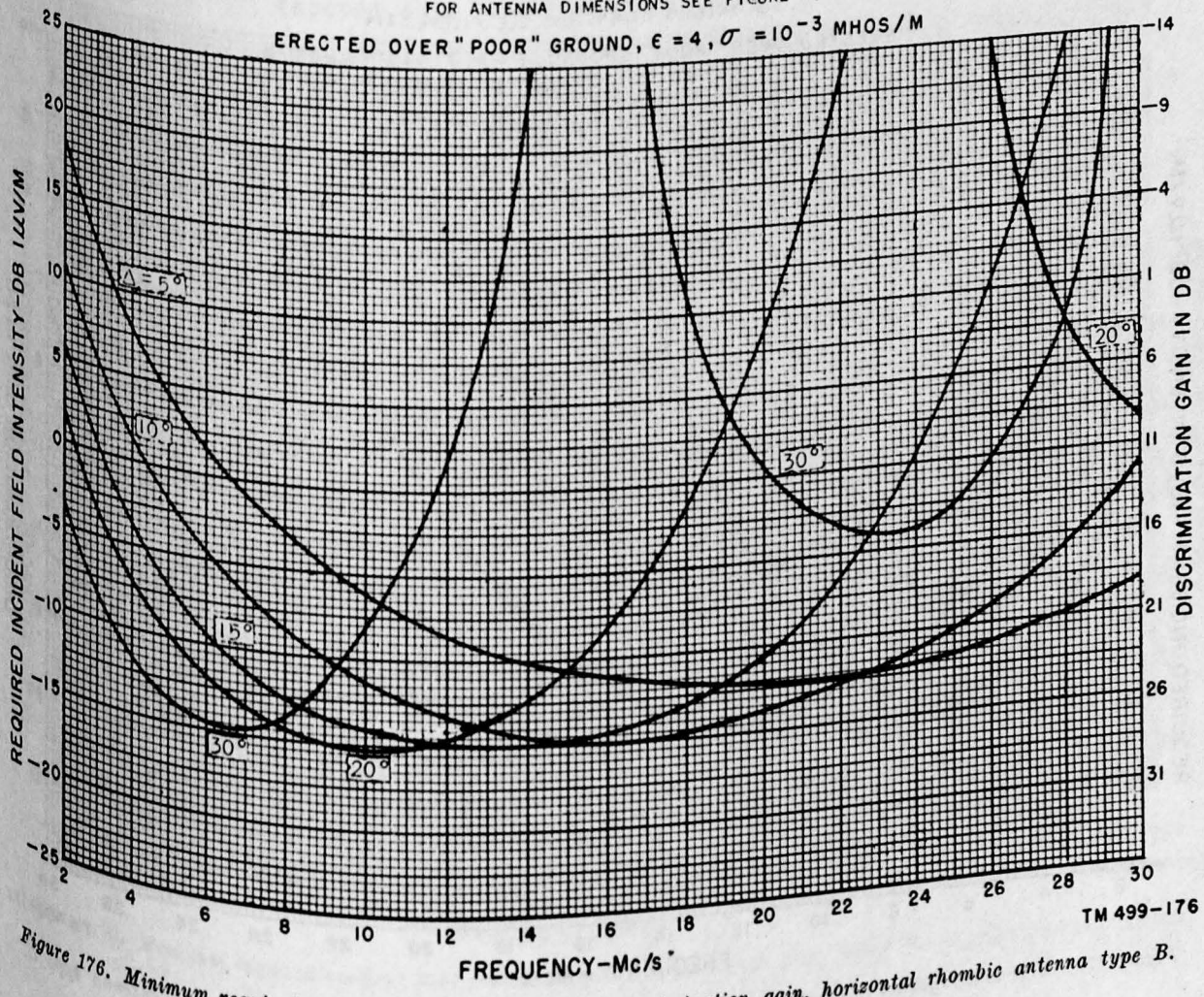


Figure 176. Minimum required incident field intensities and discrimination gain, horizontal rhombic antenna type B.

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

HORIZONTAL RHOMBIC ANTENNA TYPE "C"

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL

MEASURED FROM THE HORIZONTAL PLANE ALONG THE PRINCIPAL

AXIS OF THE ANTENNA IN THE DIRECTION OF RECEPTION

FOR ANTENNA DIMENSIONS SEE FIGURE 174

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

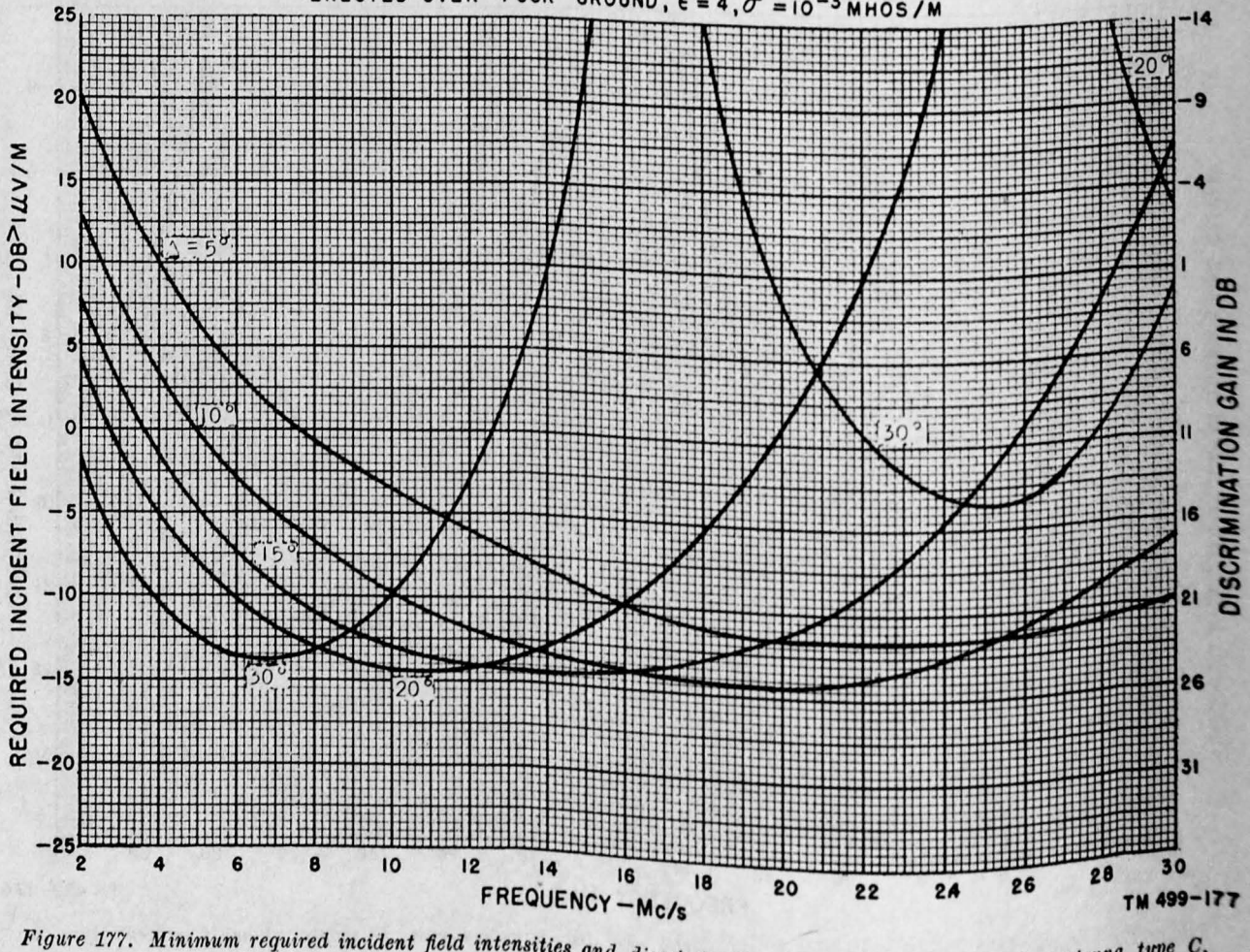


Figure 177. Minimum required incident field intensities and discrimination gain, horizontal rhombic antenna type C.

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

HORIZONTAL RHOMBIC ANTENNA TYPE "D"

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL

MEASURED FROM THE HORIZONTAL PLANE ALONG THE PRINCIPAL

AXIS OF THE ANTENNA IN THE DIRECTION OF RECEPTION

FOR ANTENNA DIMENSIONS SEE FIGURE 174

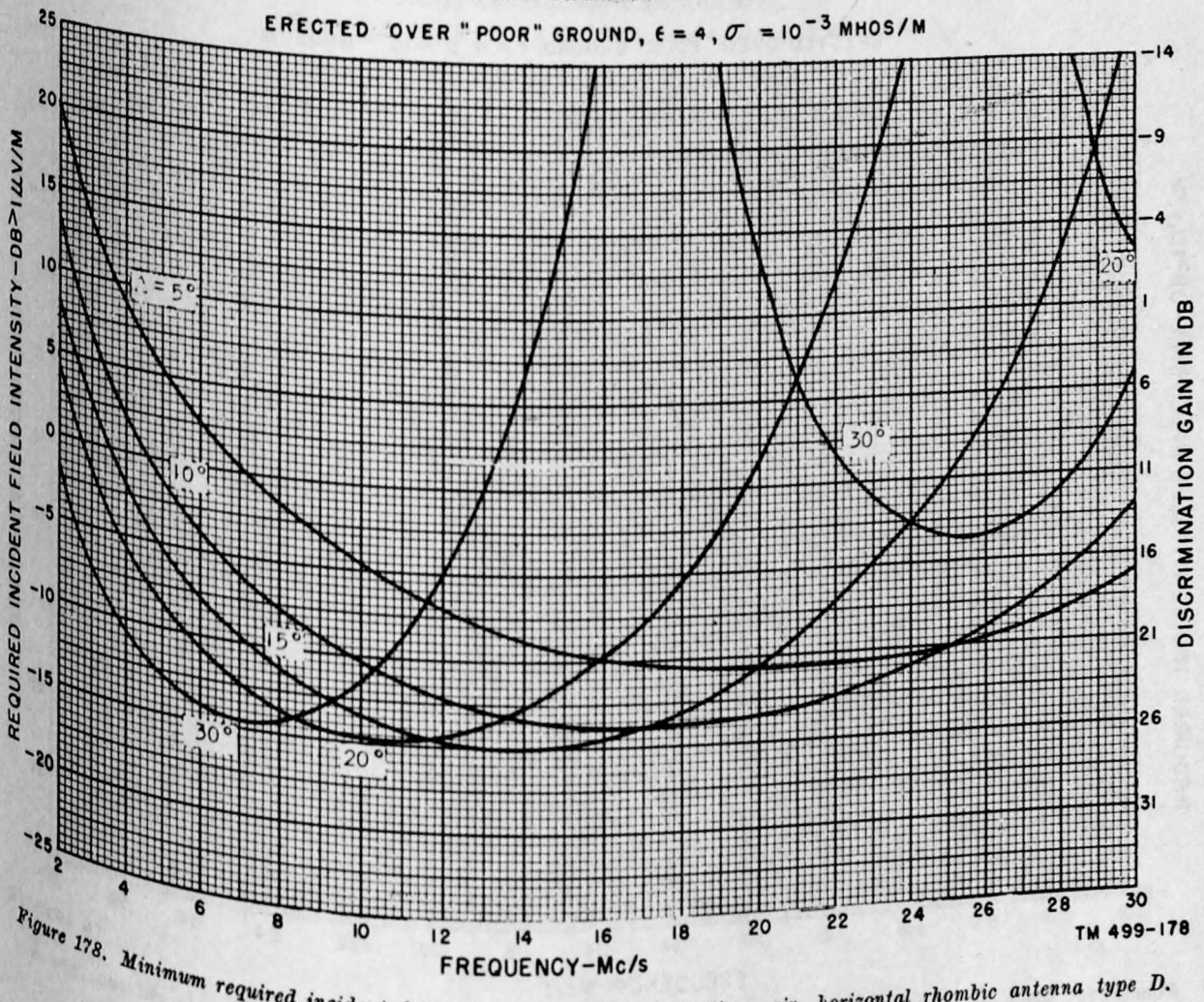


Figure 178. Minimum required incident field intensities and discrimination gain, horizontal rhombic antenna type D.

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

HORIZONTAL RHOMBIC ANTENNA TYPE "E"

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL
MEASURED FROM THE HORIZONTAL PLANE ALONG THE PRINCIPAL
AXIS OF THE ANTENNA IN THE DIRECTION OF RECEPTION

FOR ANTENNA DIMENSIONS SEE FIGURE 174

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

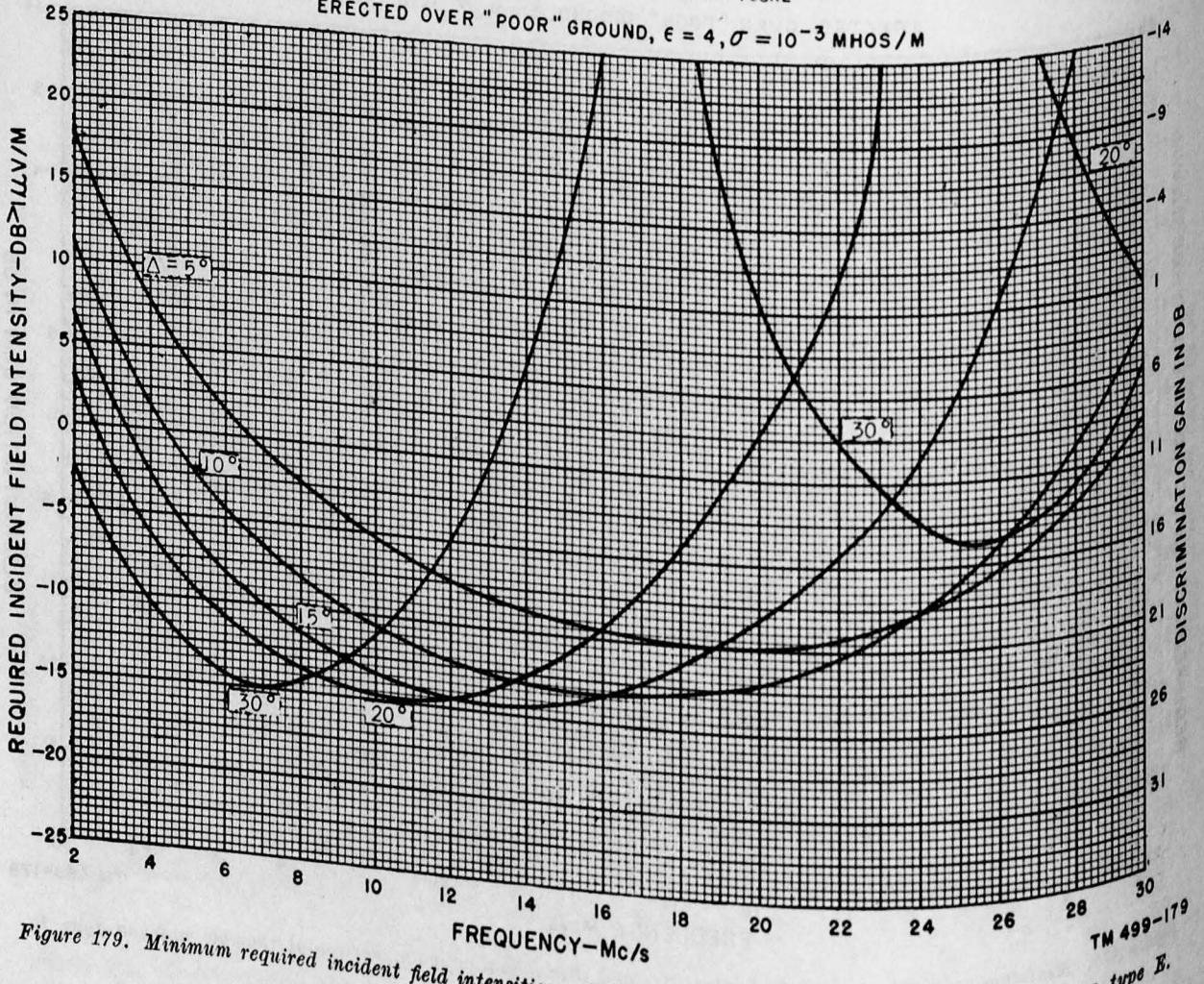


Figure 179. Minimum required incident field intensities and discrimination gain, horizontal rhombic antenna type E.

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

HORIZONTAL RHOMBIC ANTENNA TYPE "F"

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL

MEASURED FROM THE HORIZONTAL PLANE ALONG THE PRINCIPAL

AXIS OF THE ANTENNA IN THE DIRECTION OF RECEPTION

FOR ANTENNA DIMENSIONS SEE FIGURE 174

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

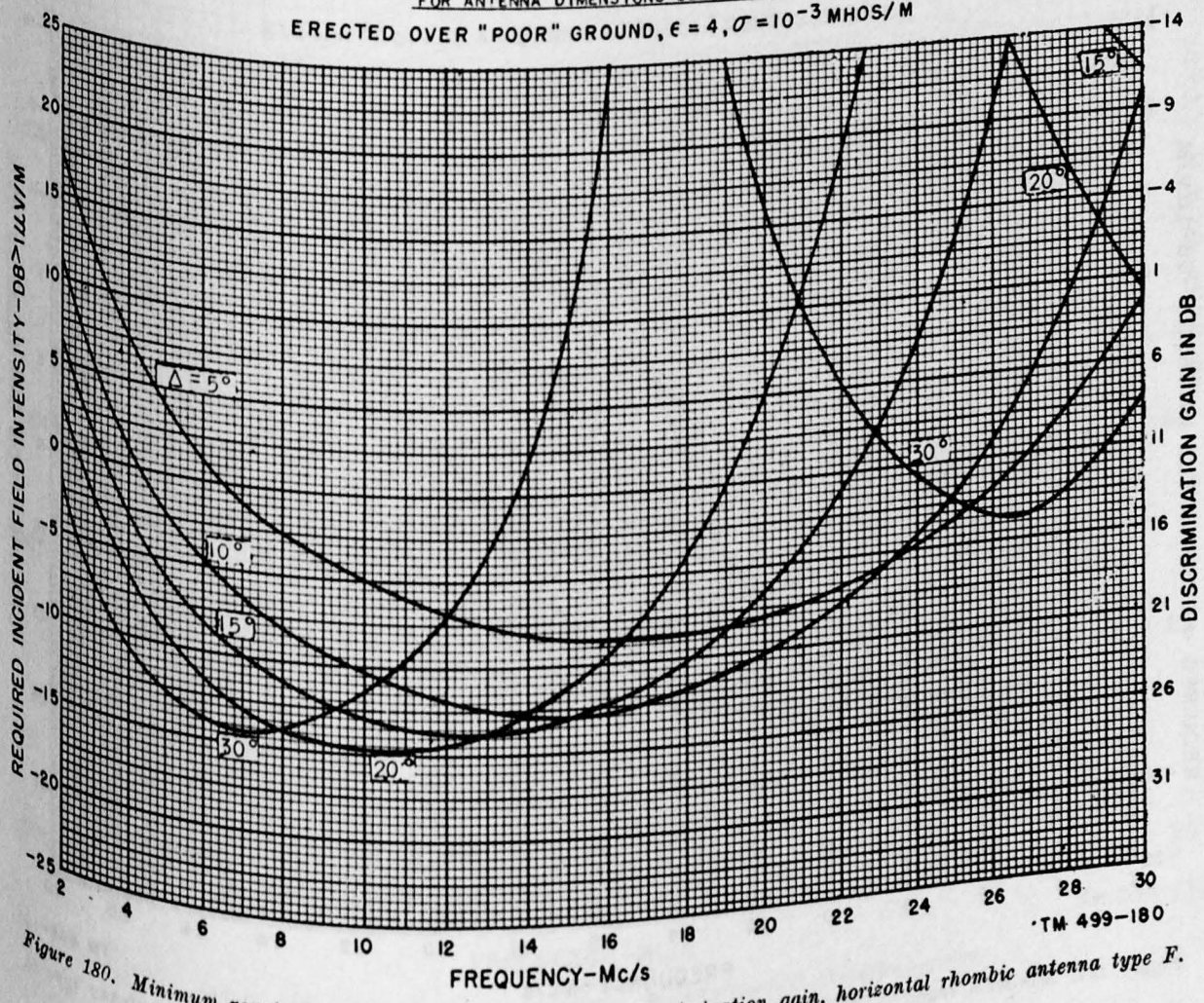


Figure 180. Minimum required incident field intensities and discrimination gain, horizontal rhombic antenna type F.

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

HORIZONTAL RHOMBIC ANTENNA TYPE "G"

CURVES ARE FOR VARIOUS VERTICAL ANGLES OF WAVE ARRIVAL

MEASURED FROM THE HORIZONTAL PLANE ALONG THE PRINCIPAL

AXIS OF THE ANTENNA IN THE DIRECTION OF RECEPTION

FOR ANTENNA DIMENSIONS SEE FIGURE 17

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

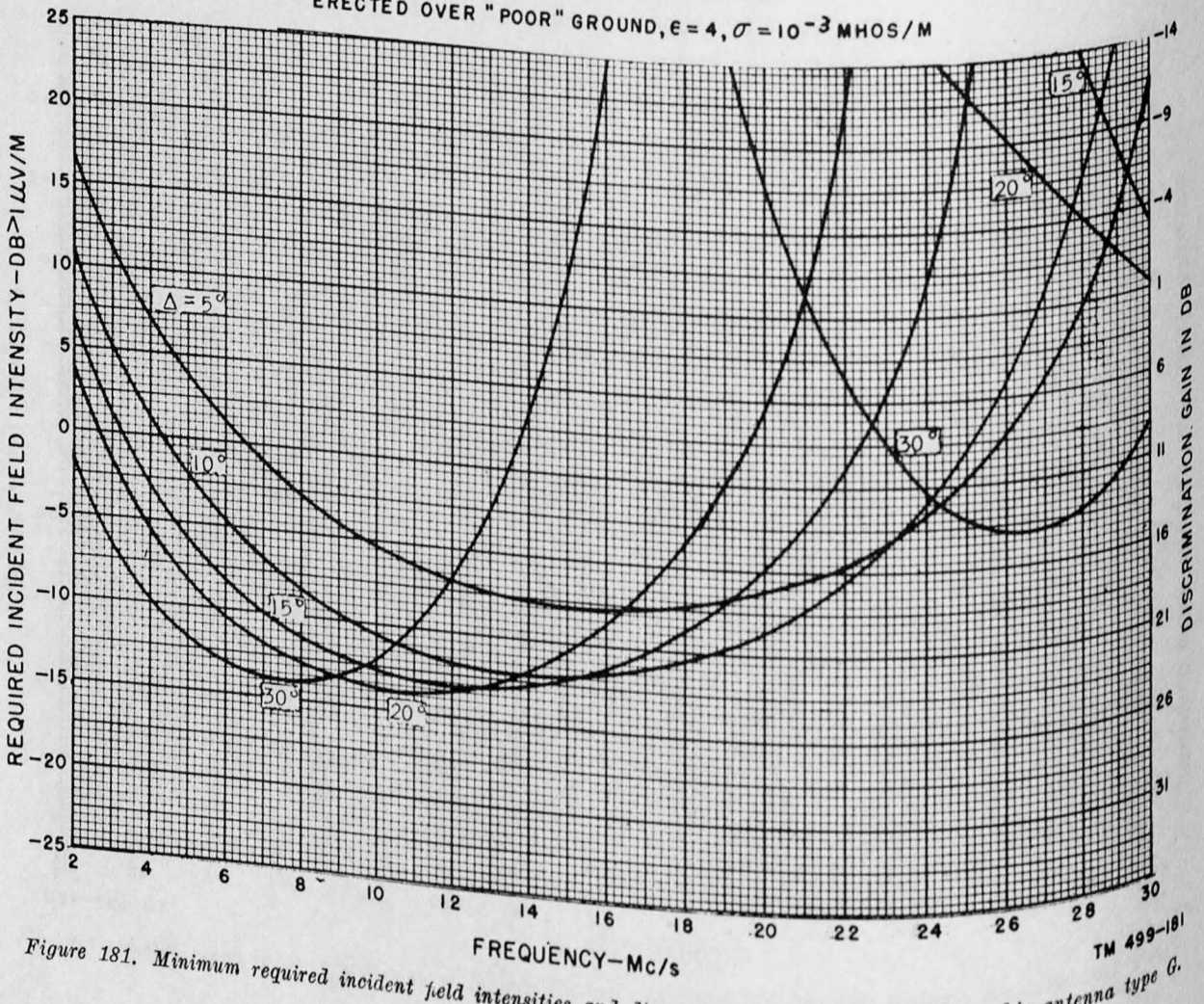


Figure 181. Minimum required incident field intensities and discrimination gain, horizontal rhombic antenna type G.

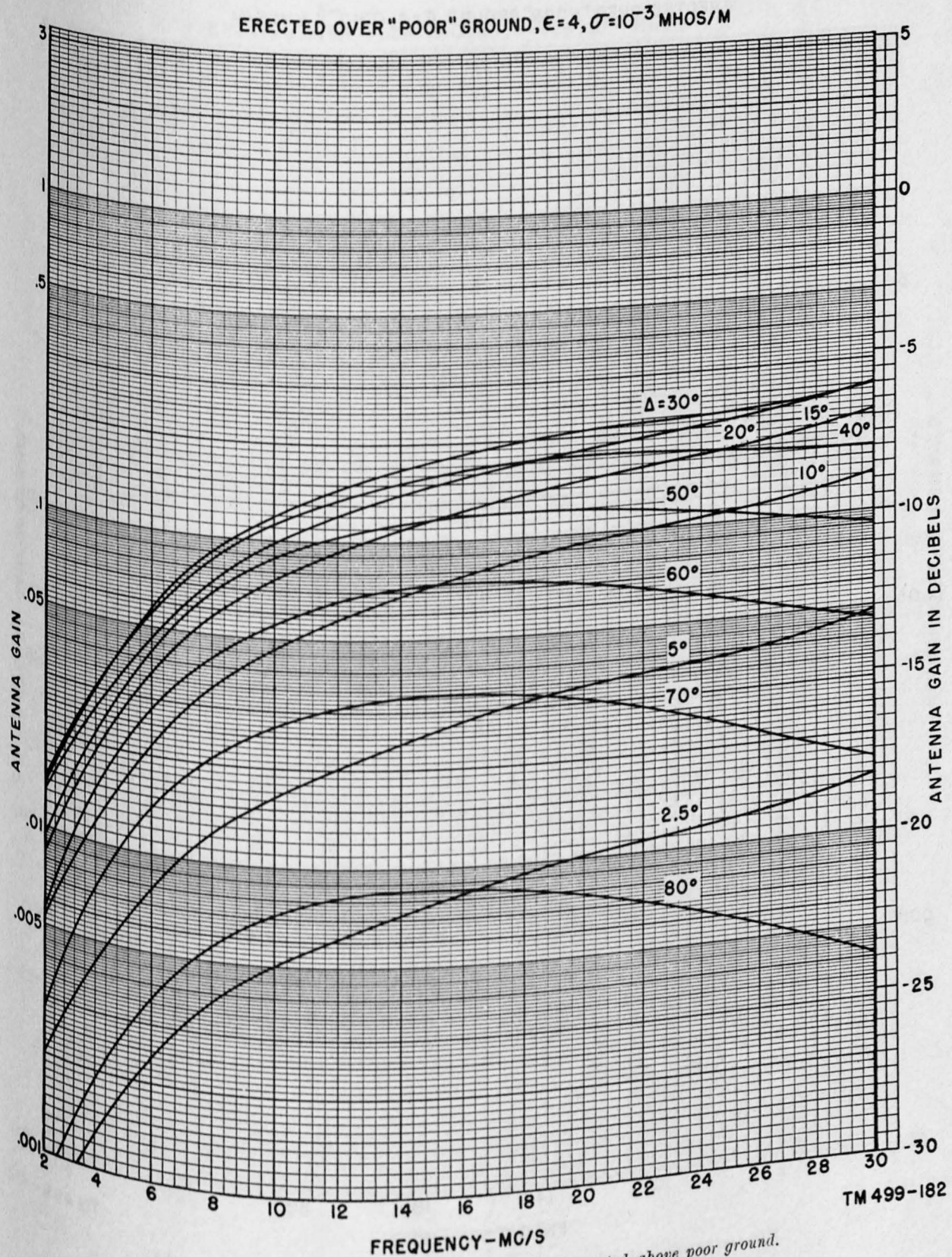


Figure 182. Gain curves, 15-foot whip antenna erected above poor ground.

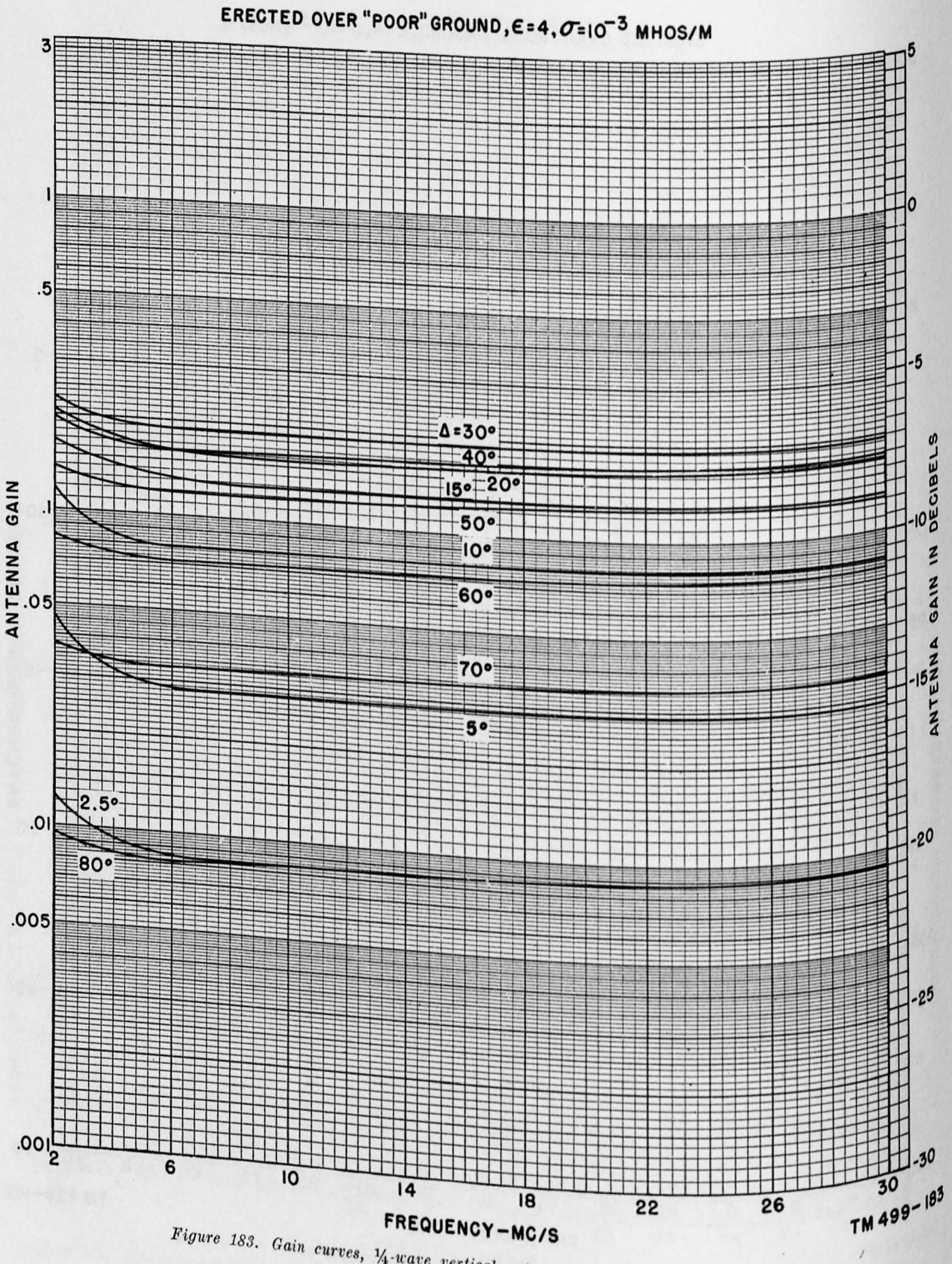


Figure 183. Gain curves, ¼-wave vertical antenna erected above poor ground.

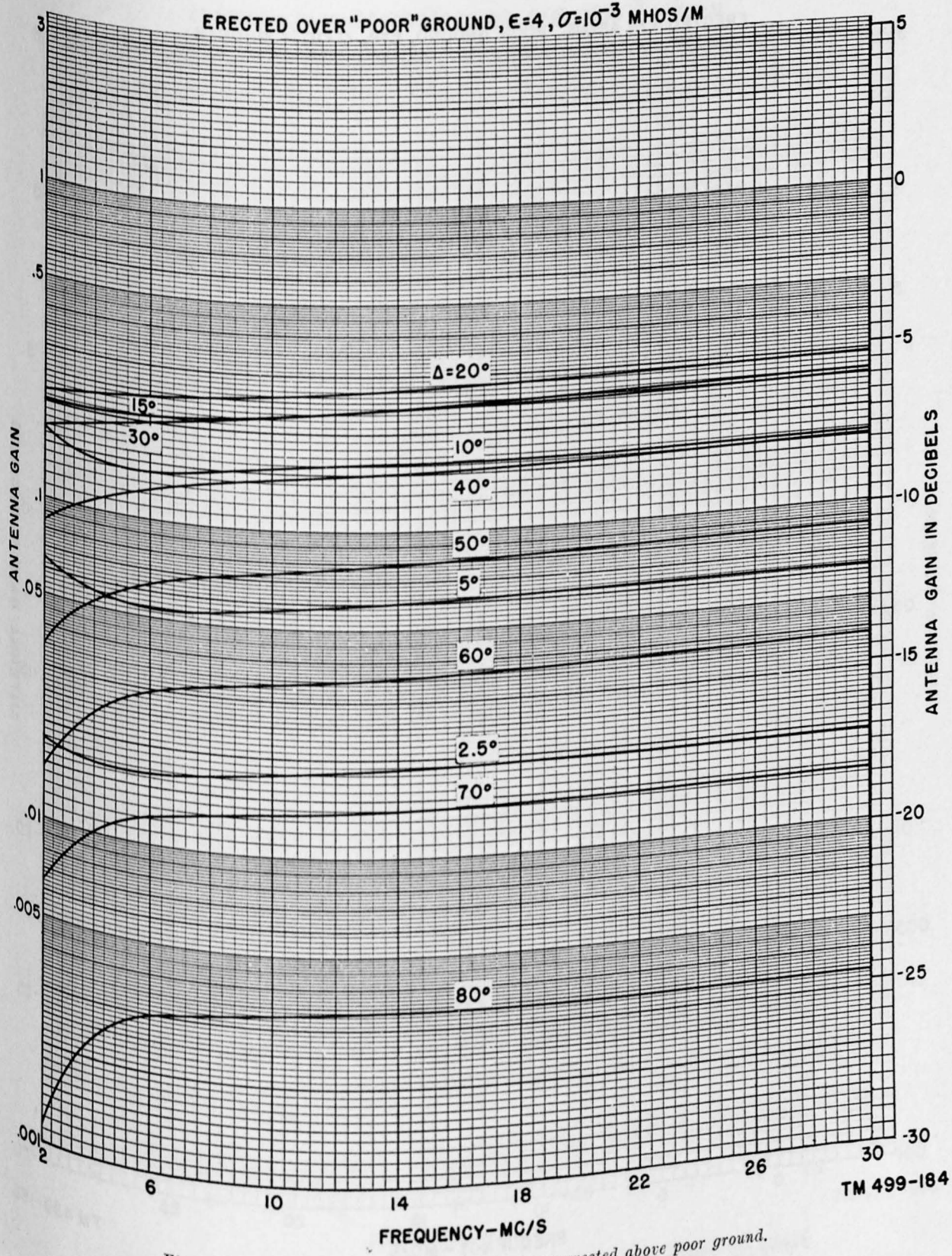


Figure 184. Gain curves, ½-wave vertical antenna erected above poor ground.

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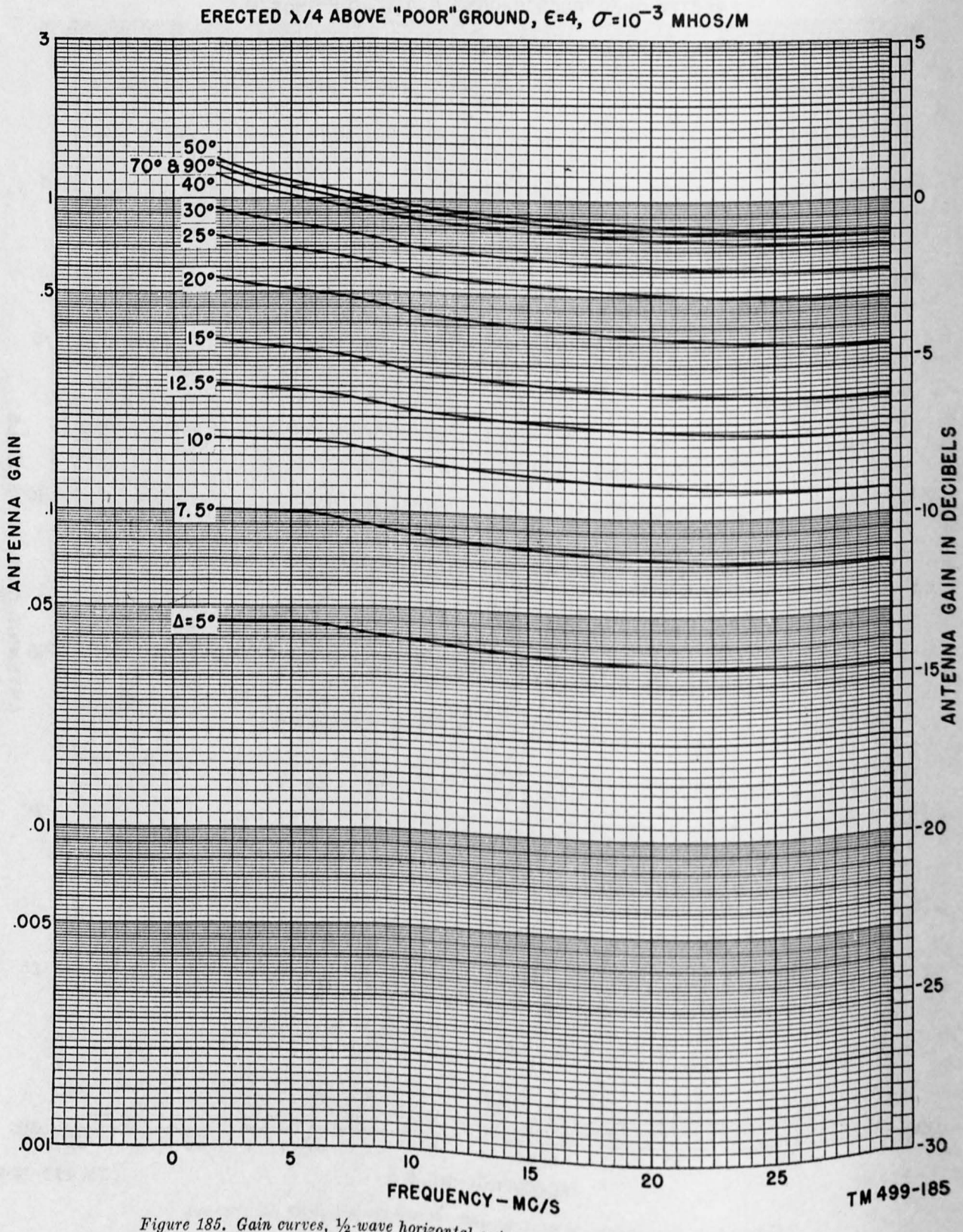


Figure 185. Gain curves, ½-wave horizontal antenna erected ¼-wave above poor ground.

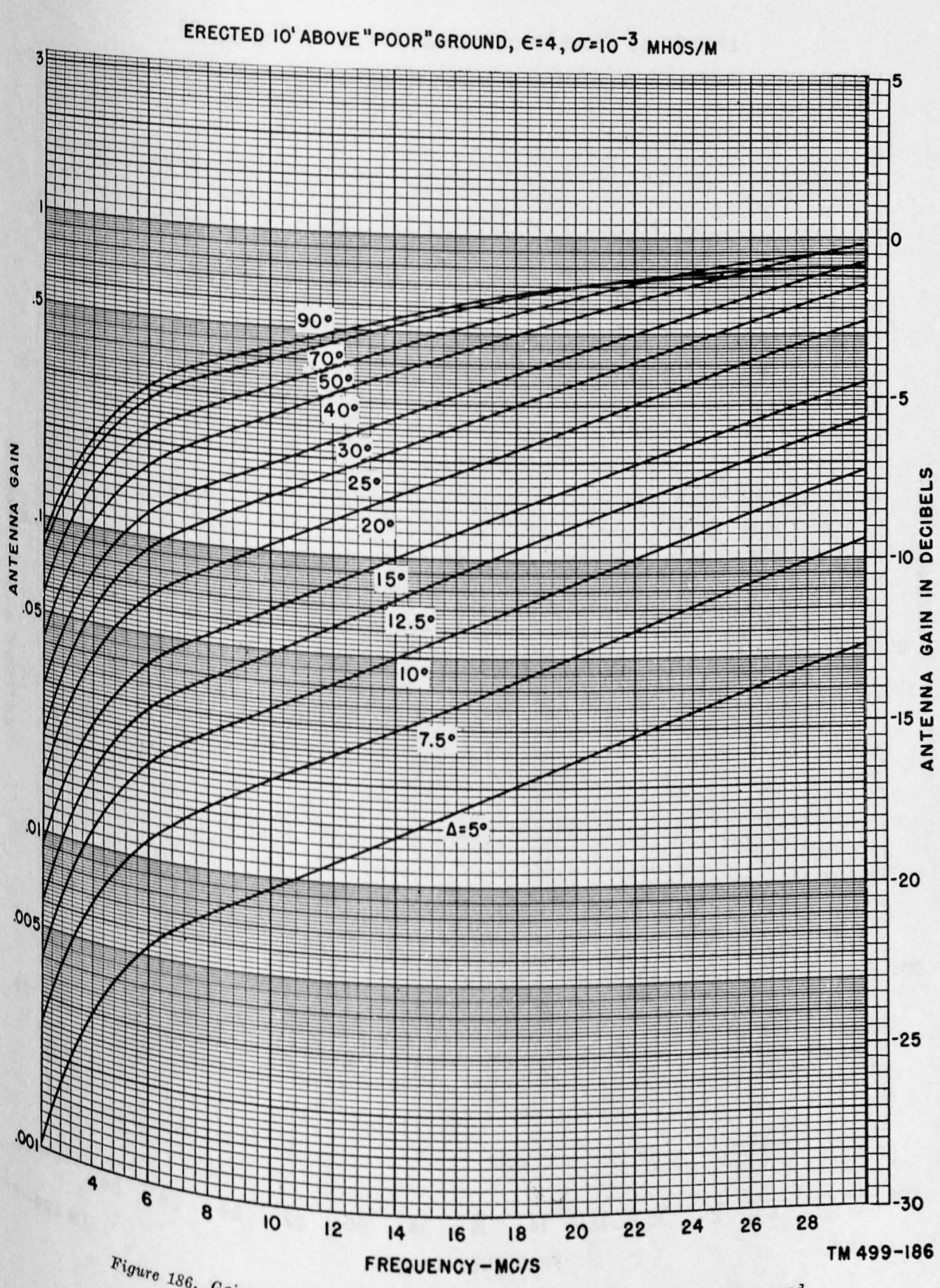


Figure 186. Gain curves, ½-wave horizontal antenna erected 10-feet above poor ground.

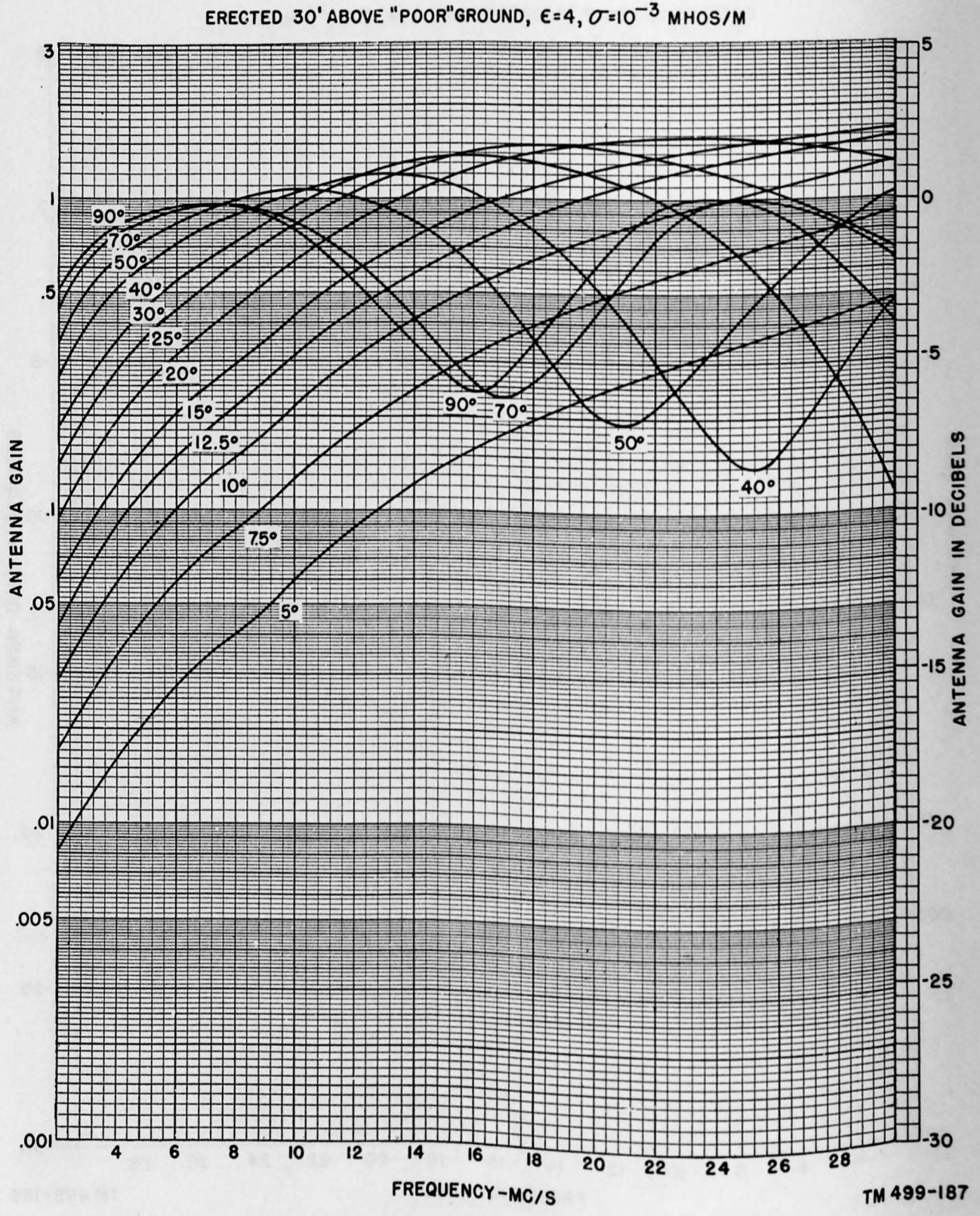


Figure 187. Gain curves, ½-wave horizontal antenna erected 30-feet above poor ground.

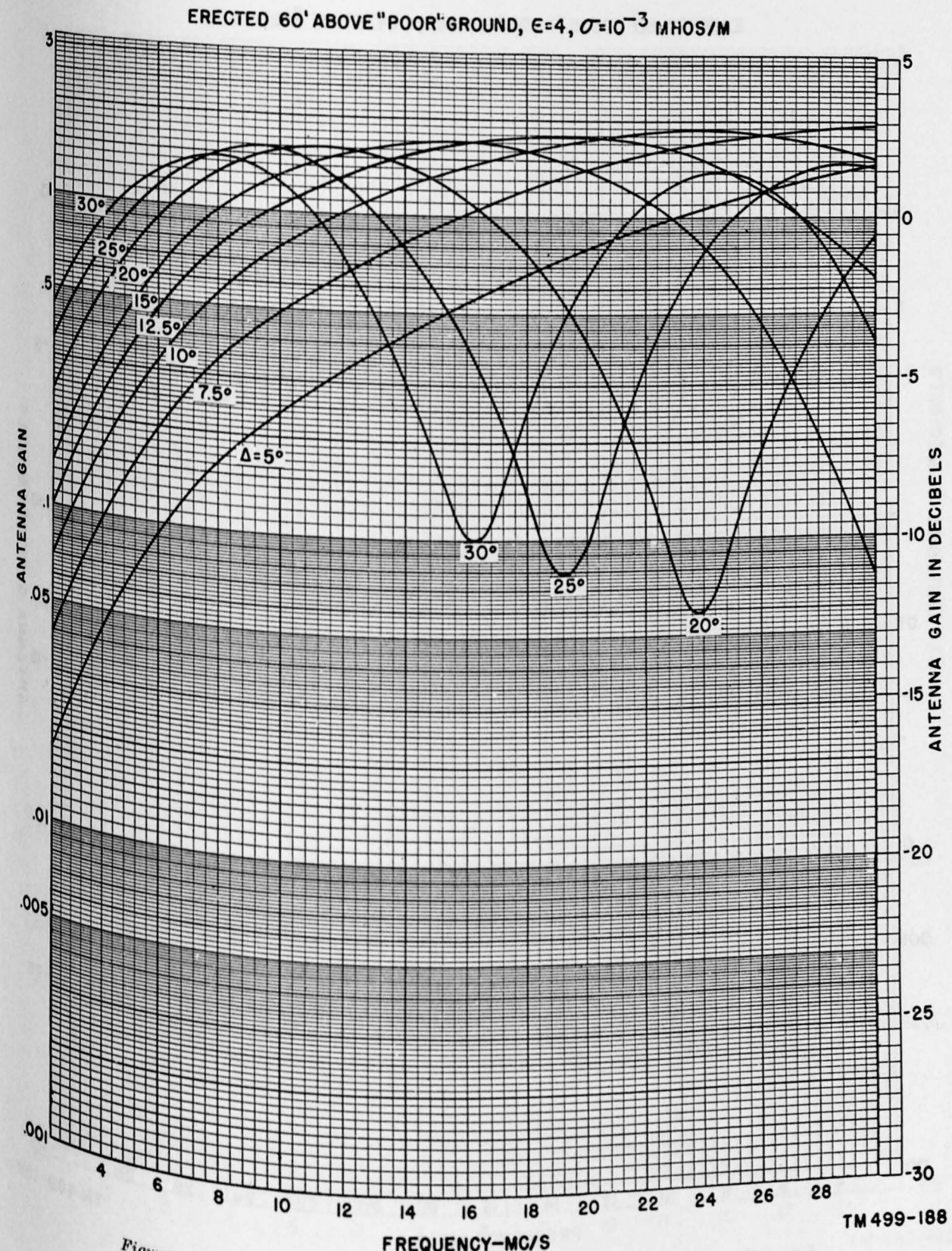


Figure 188. Gain curves, ½-wave horizontal antenna erected 60-feet above poor ground.

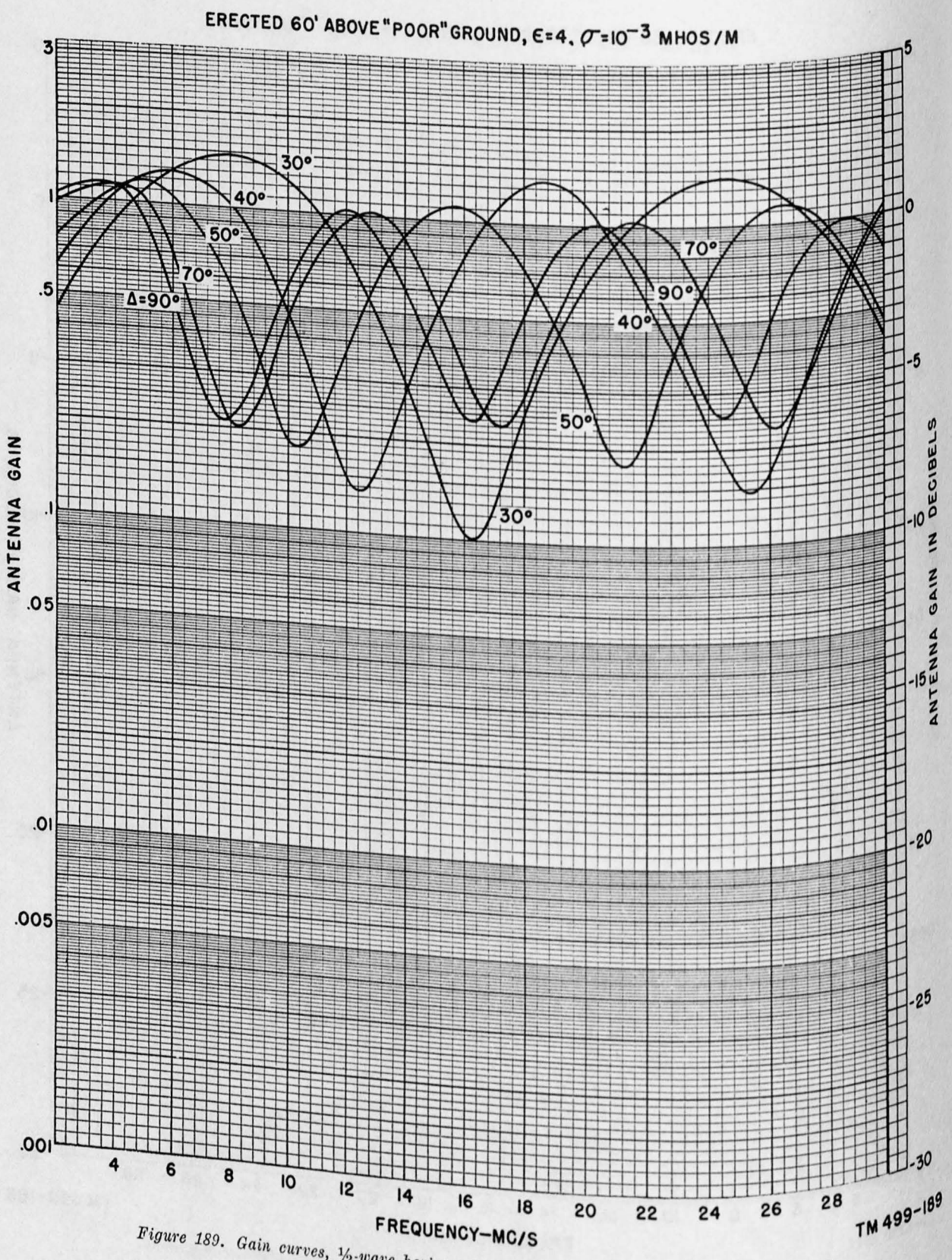


Figure 189. Gain curves, ½-wave horizontal antenna erected 60-feet above poor ground.

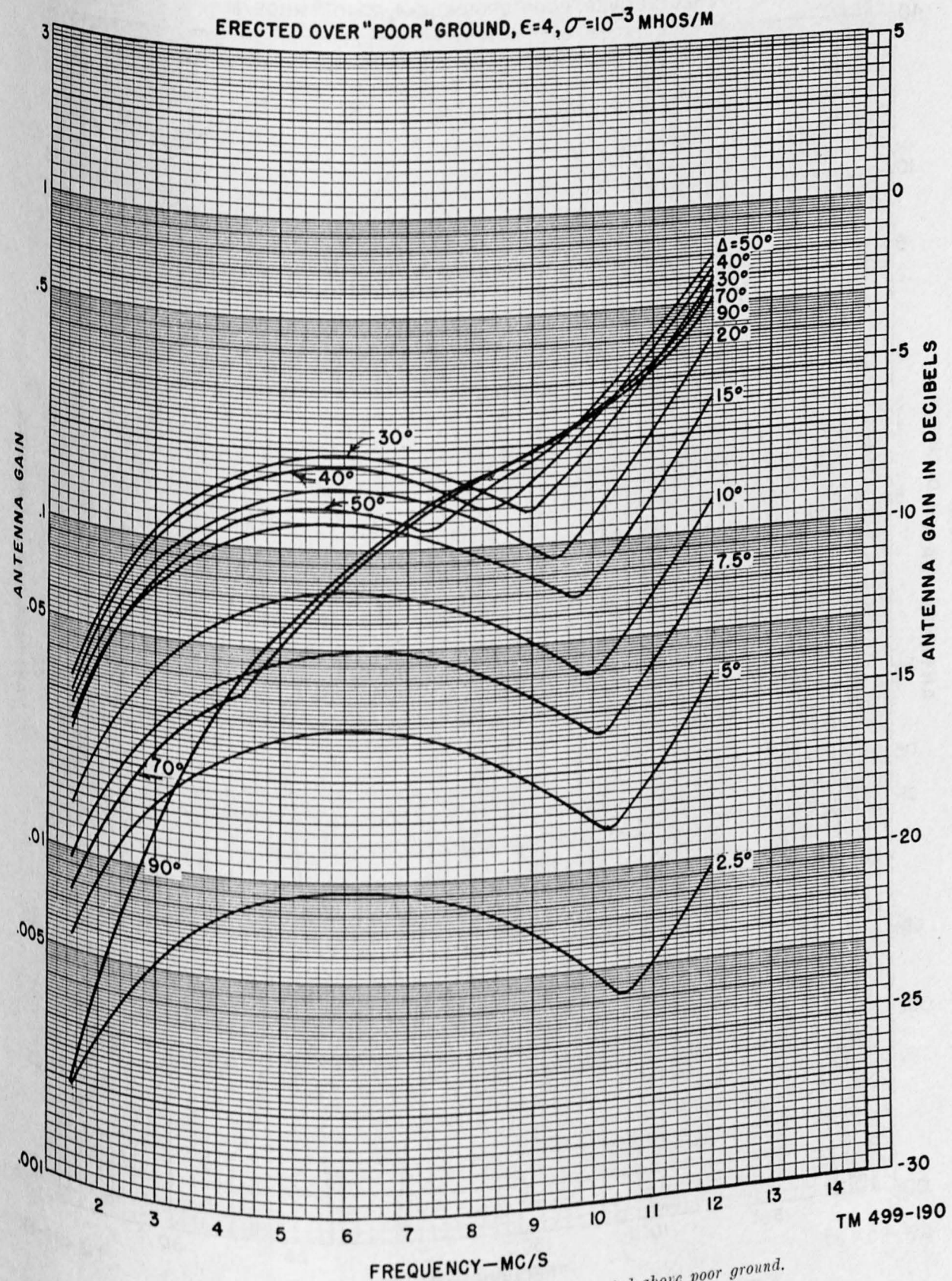


Figure 190. Gain curves, 50-foot inverted L antenna erected above poor ground.

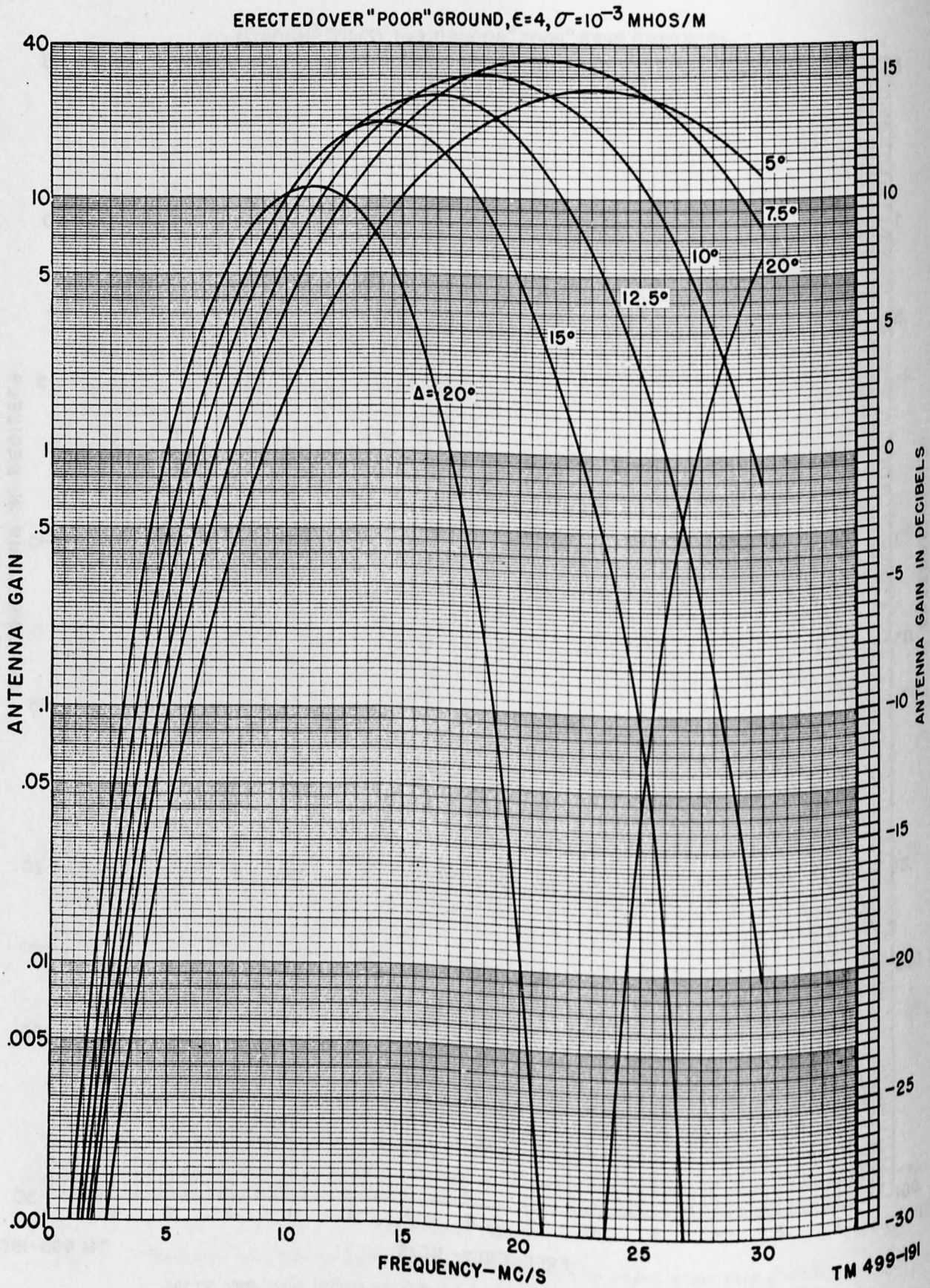


Figure 191. Gain curves, type A rhombic antenna erected above poor ground.

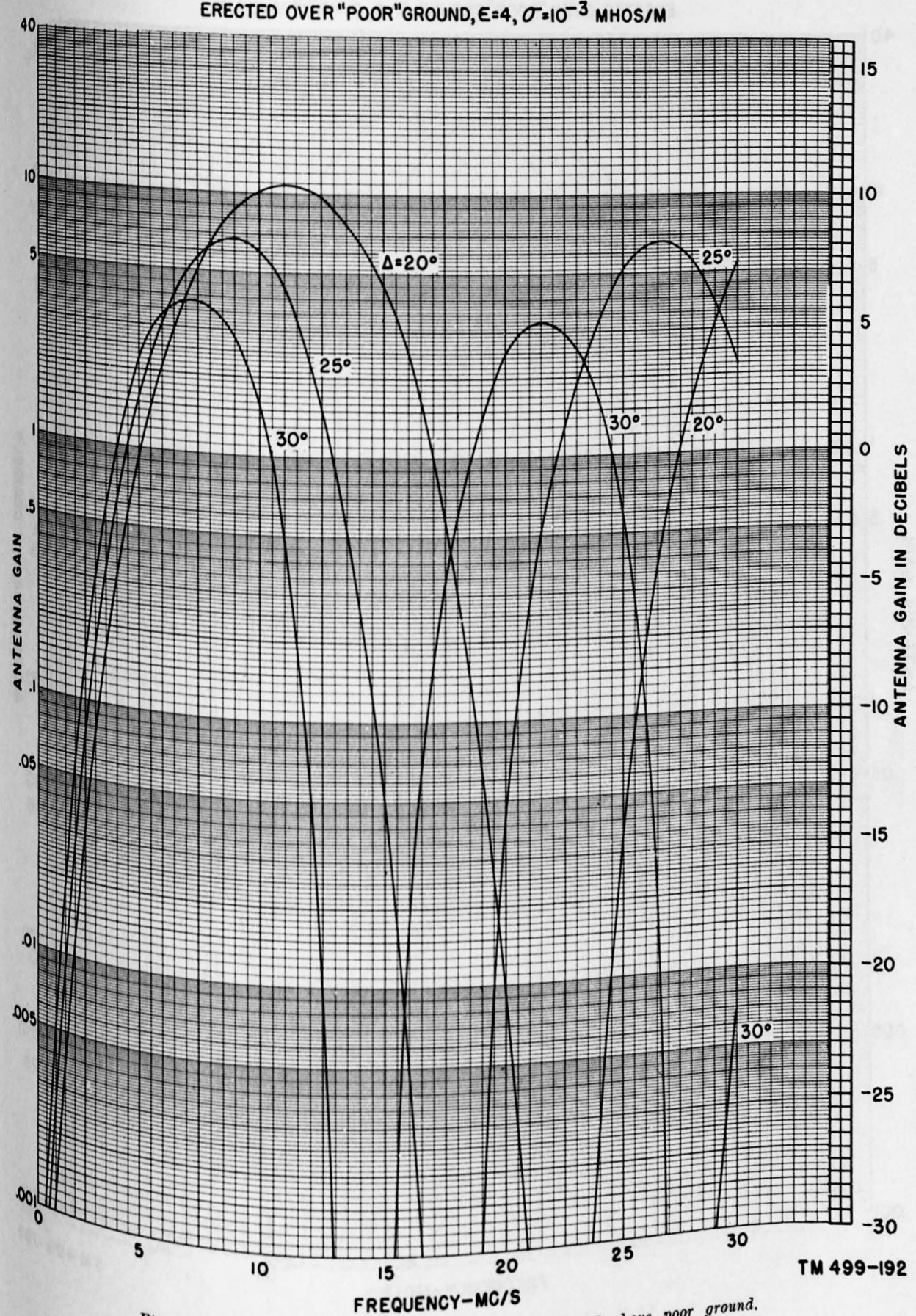


Figure 192. Gain curves, type A rhombic antenna erected above poor ground.

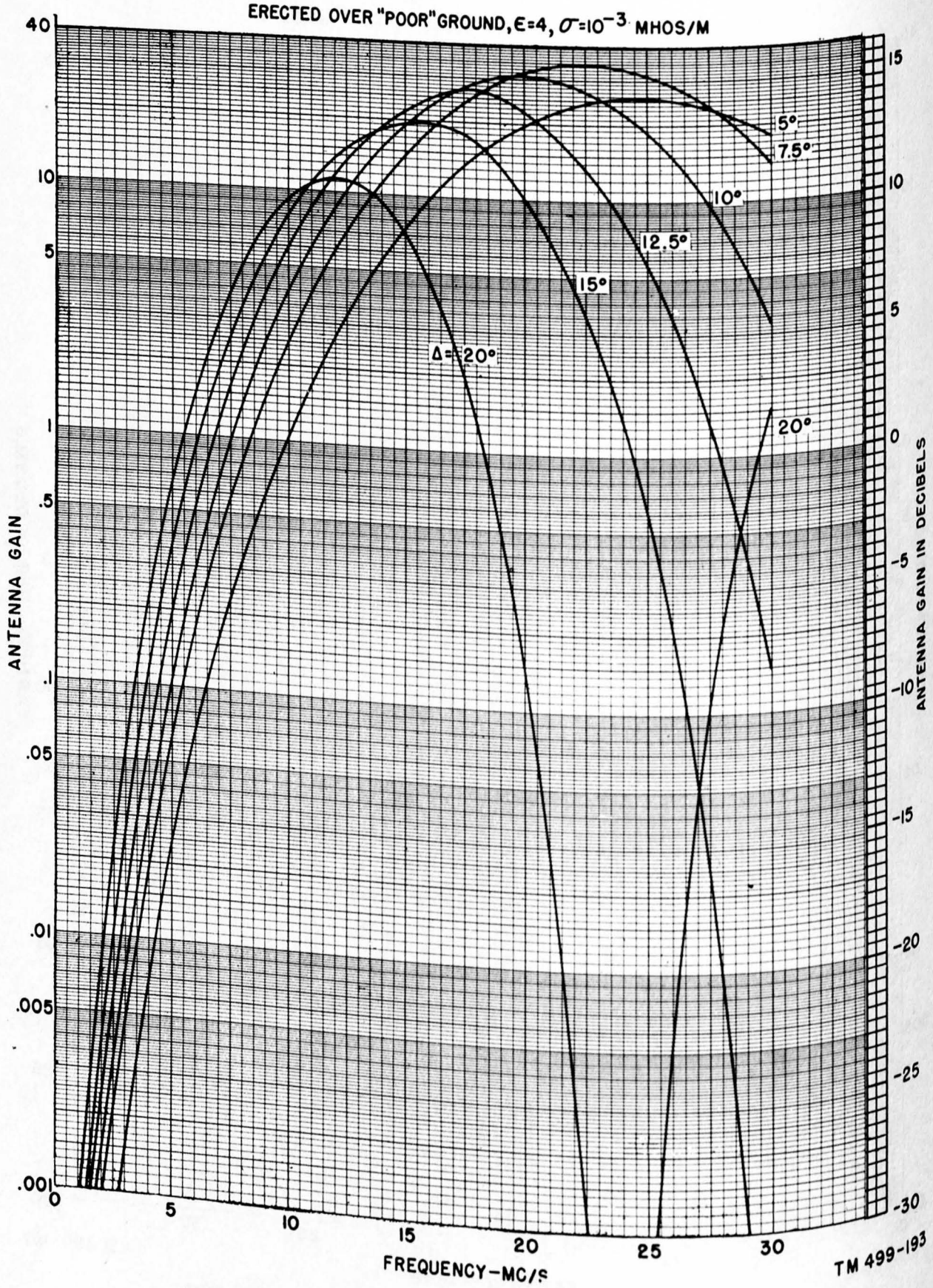


Figure 193. Gain curves, type B rhombic antenna erected above poor ground.

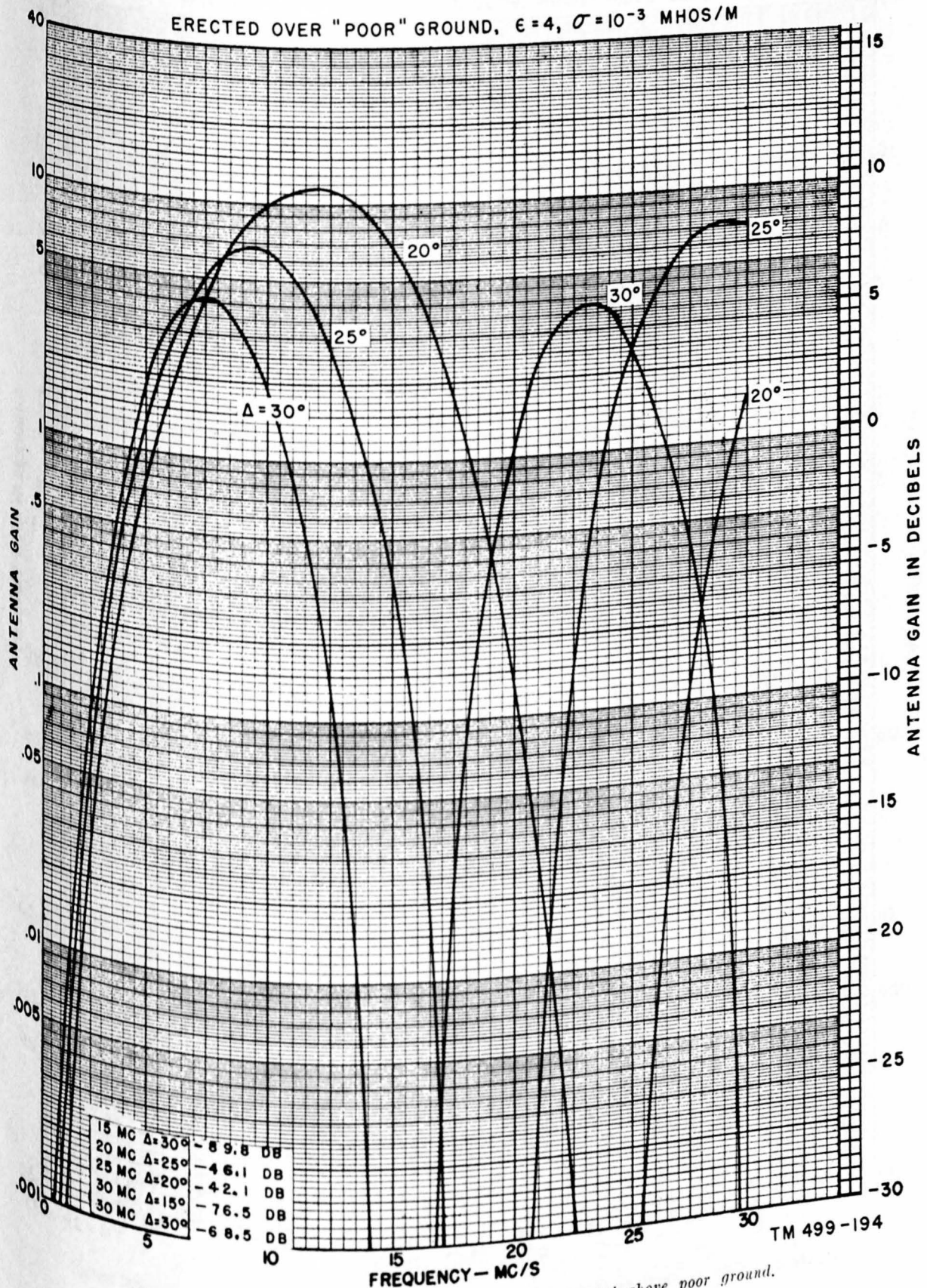


Figure 194. Gain curves, type B rhombic antenna erected above poor ground.

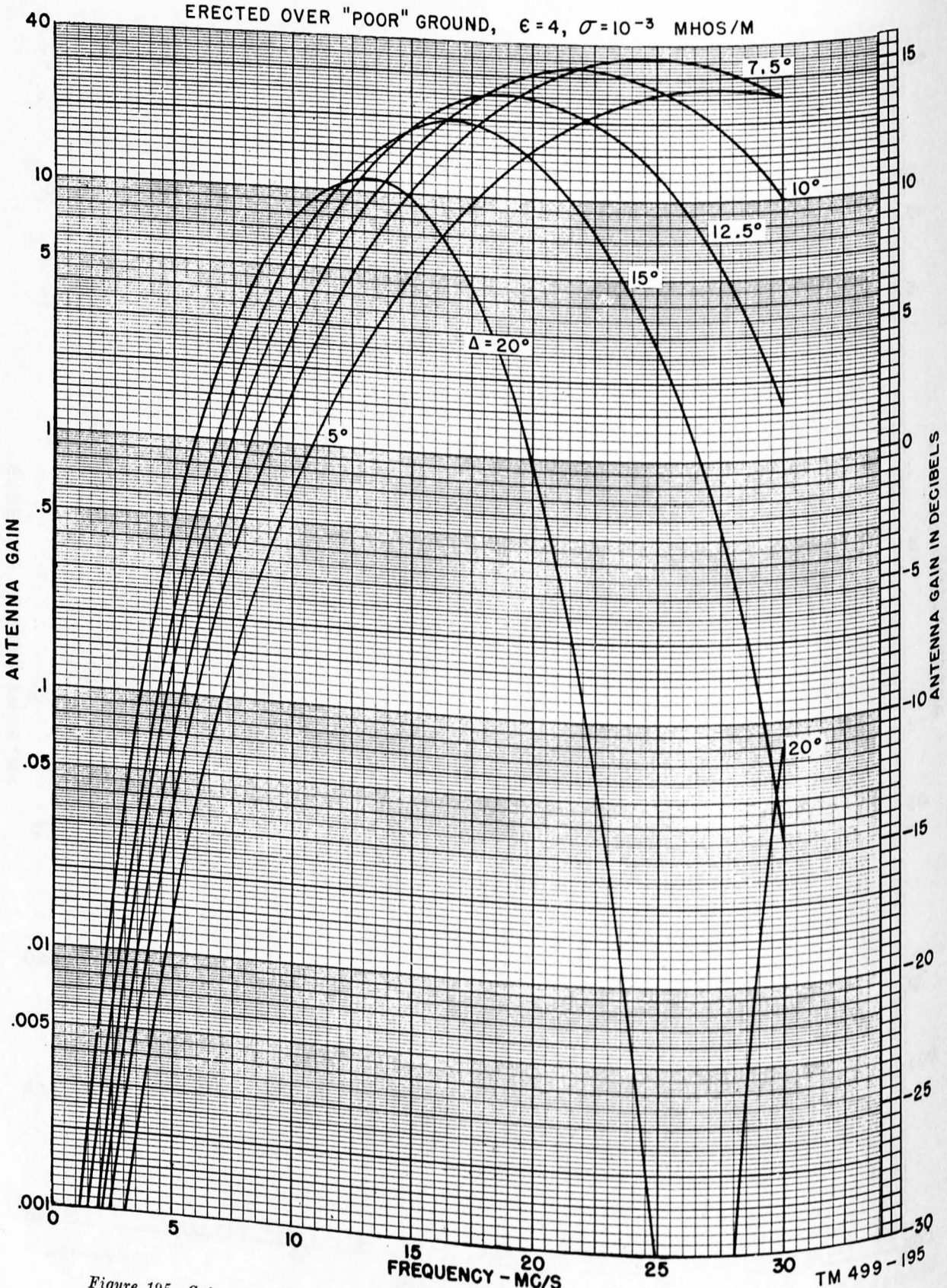


Figure 195. Gain curves, type C rhombic antenna erected above poor ground, angles from 5° to 20°.

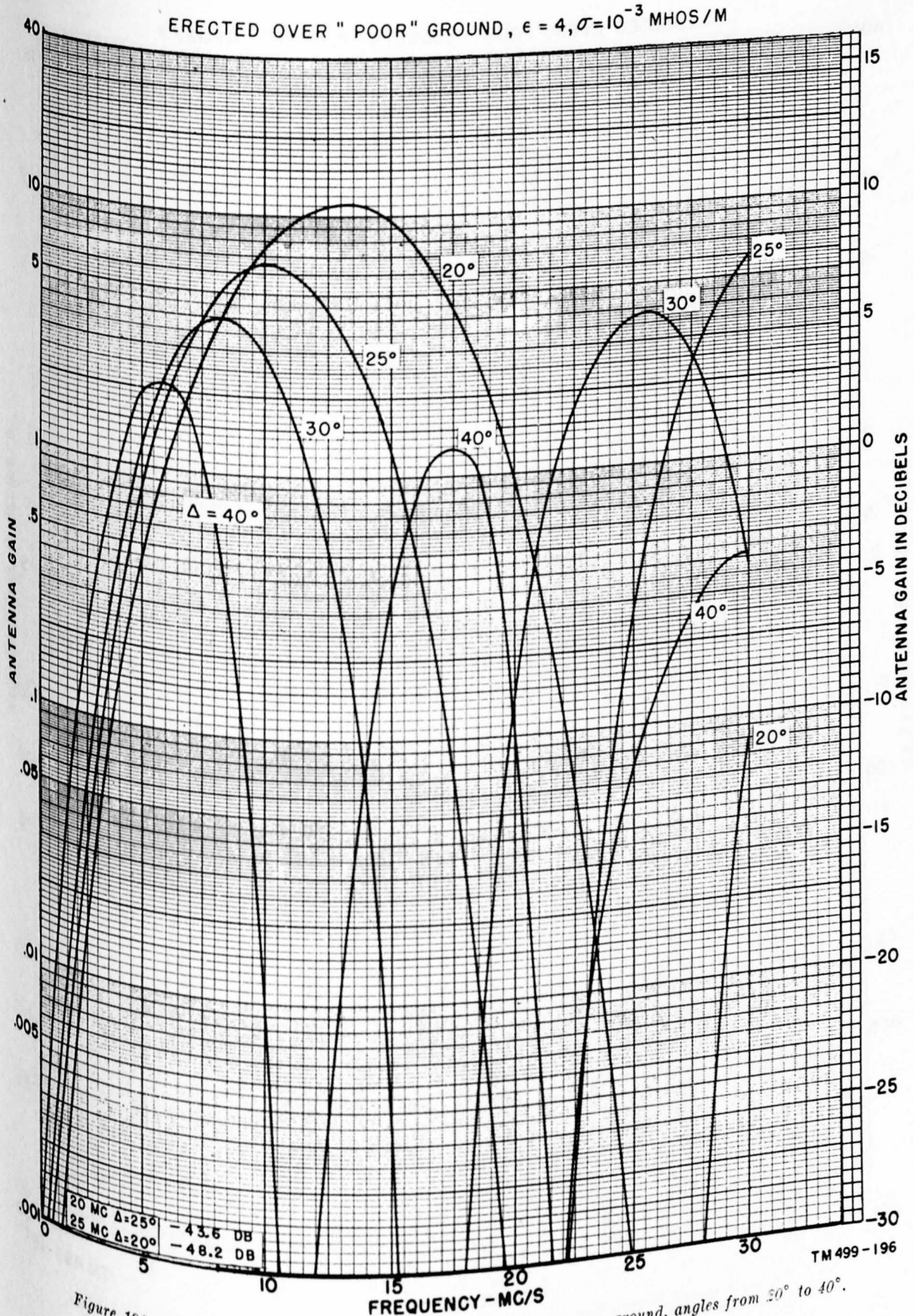


Figure 196. Gain curves, type C rhombic antenna erected above poor ground, angles from 20° to 40°.

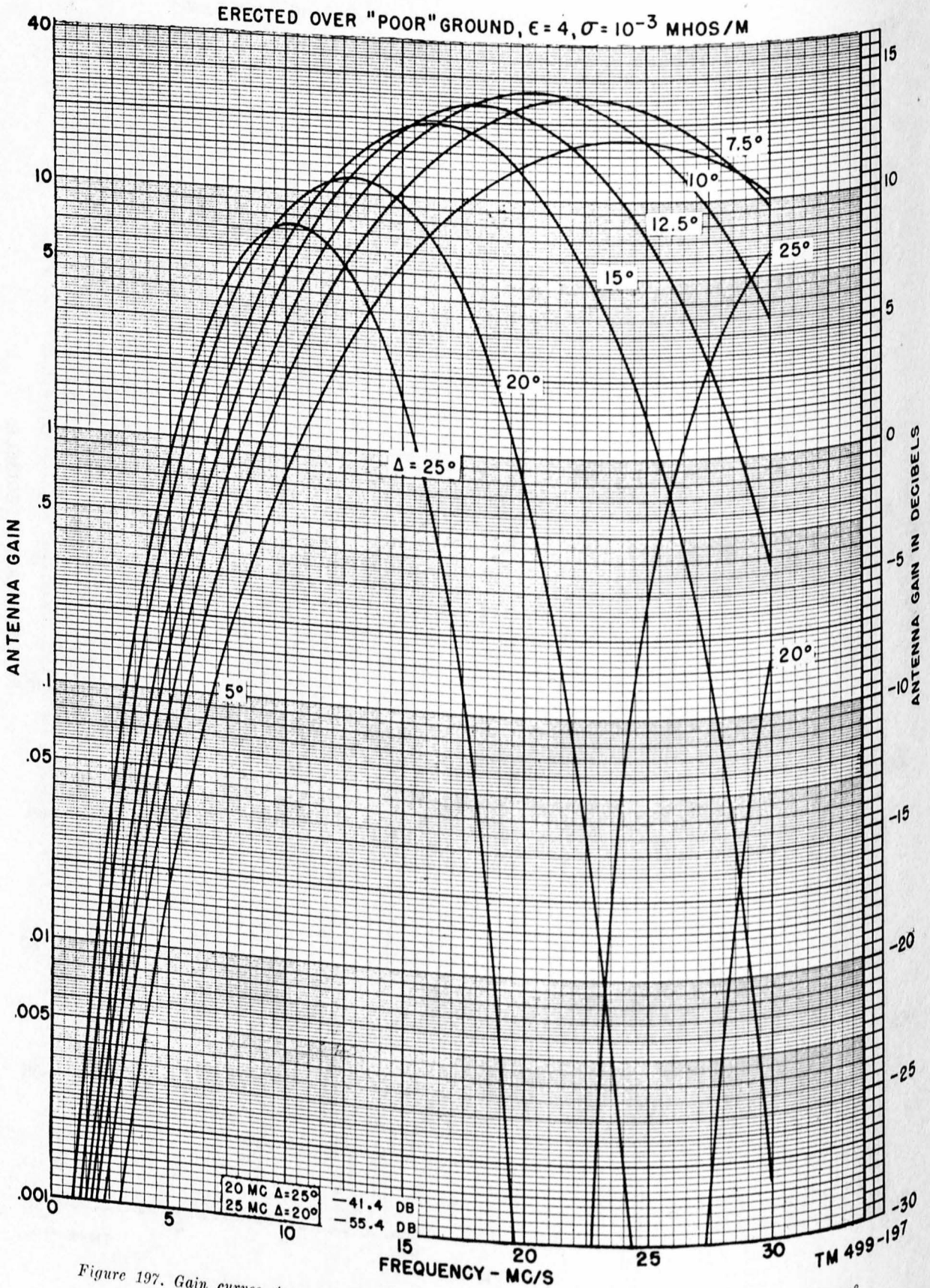


Figure 197. Gain curves, type D rhombic antenna erected above poor ground, angles from 5° to 20°.

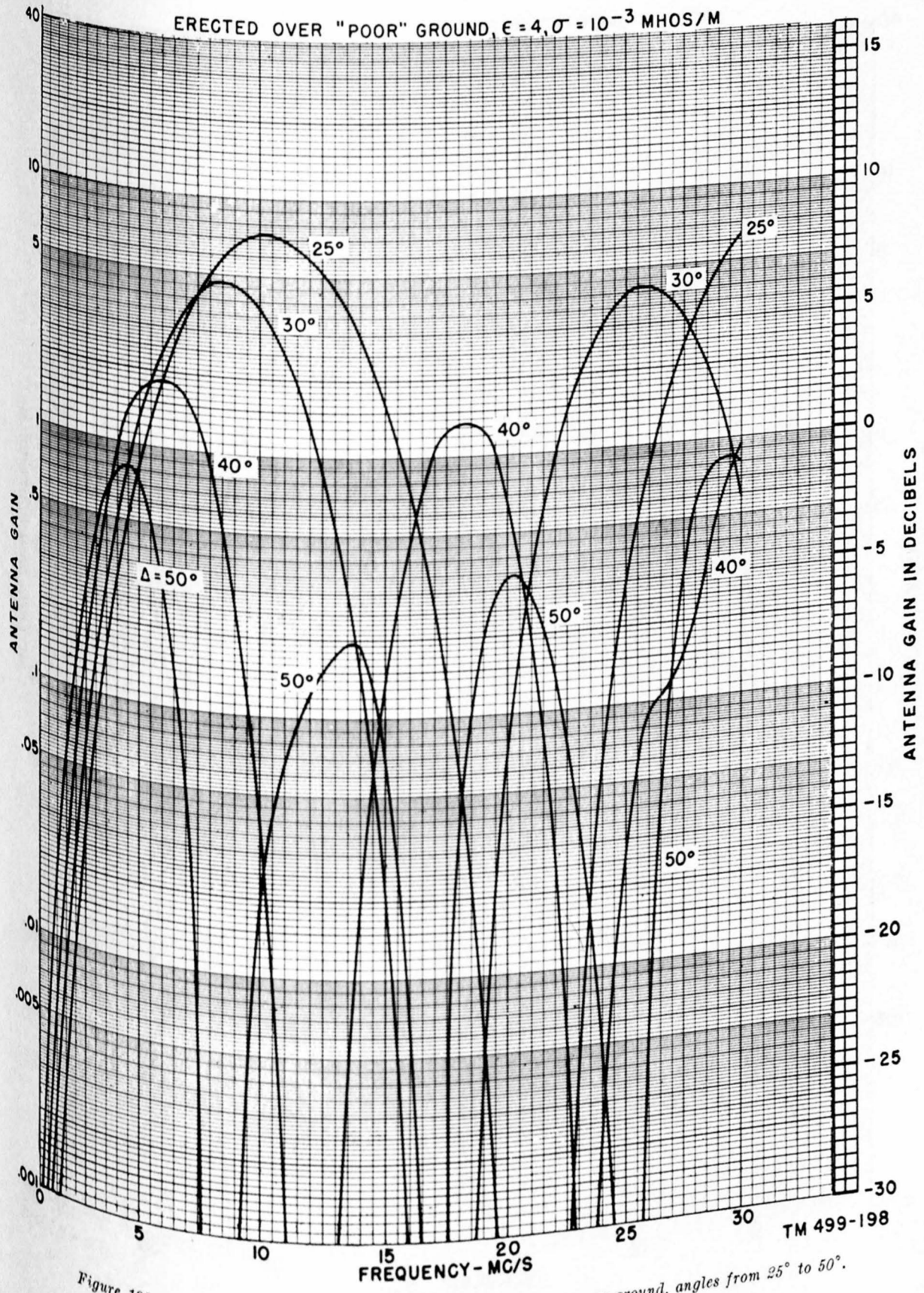


Figure 198. Gain curves, type D rhombic antenna erected above poor ground, angles from 25° to 50°.

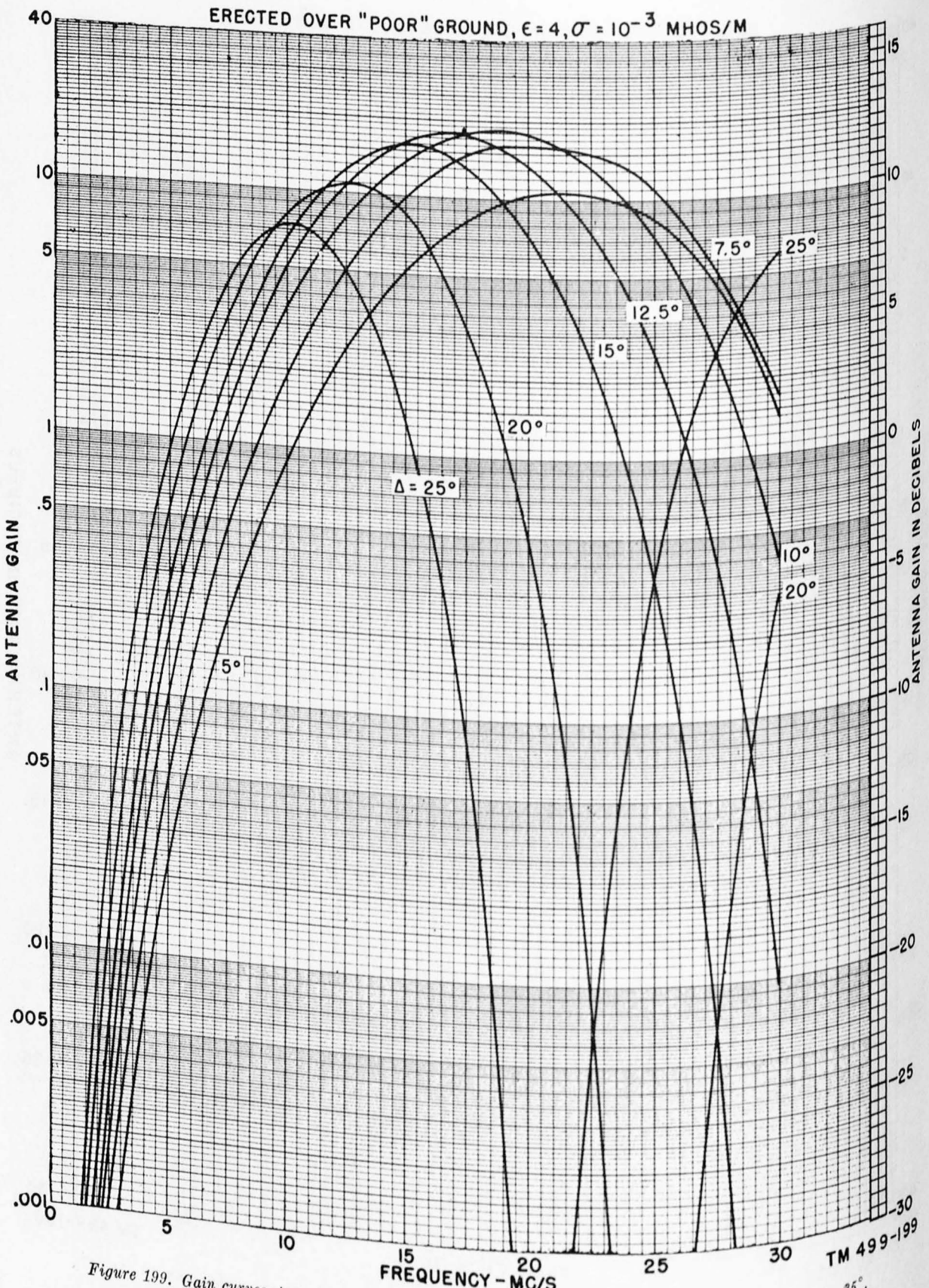


Figure 199. Gain curves, type E rhombic antenna erected above poor ground, angles from 5° to 25°.

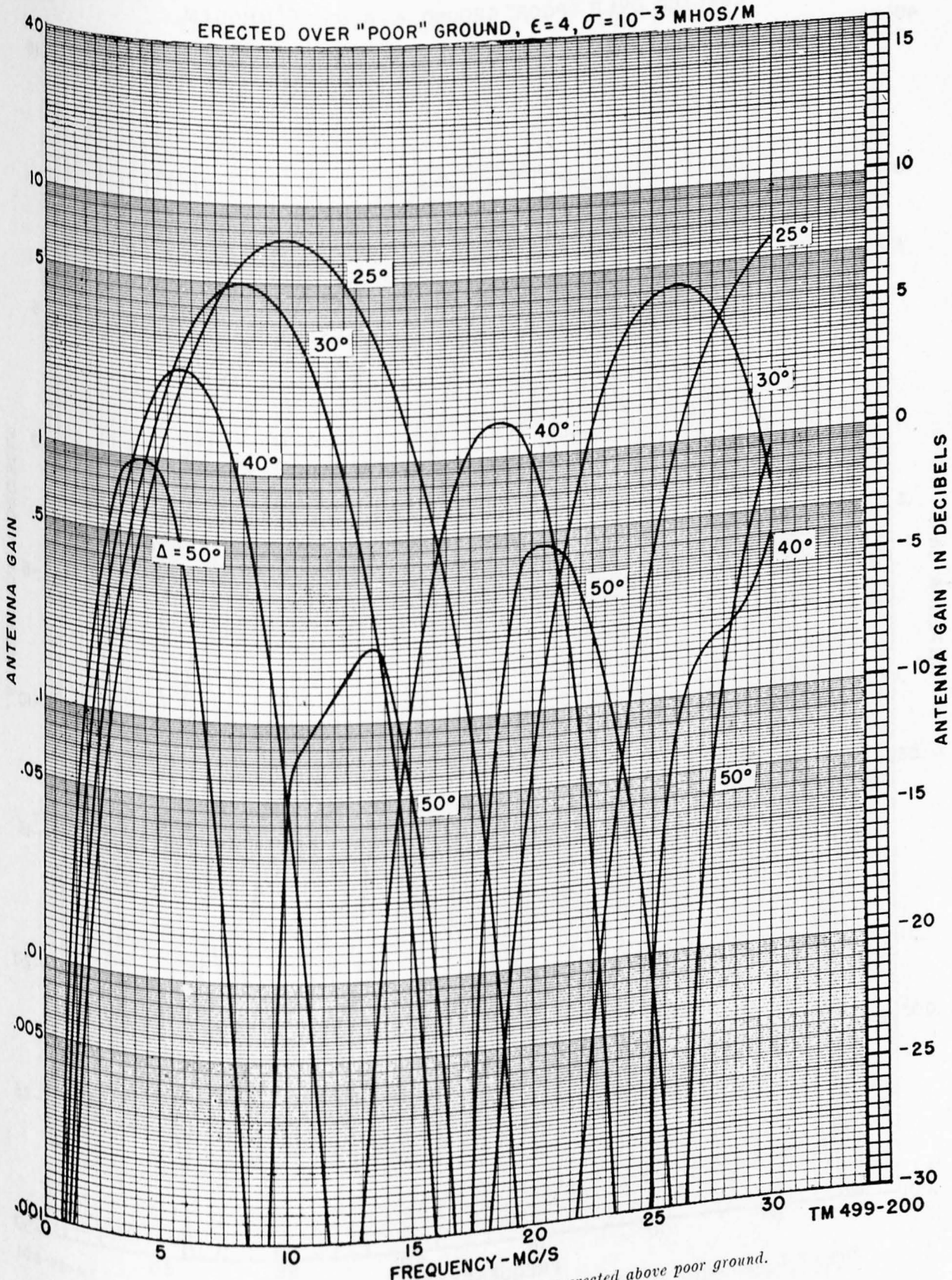


Figure 200. Gain curves, type E rhombic antenna erected above poor ground.

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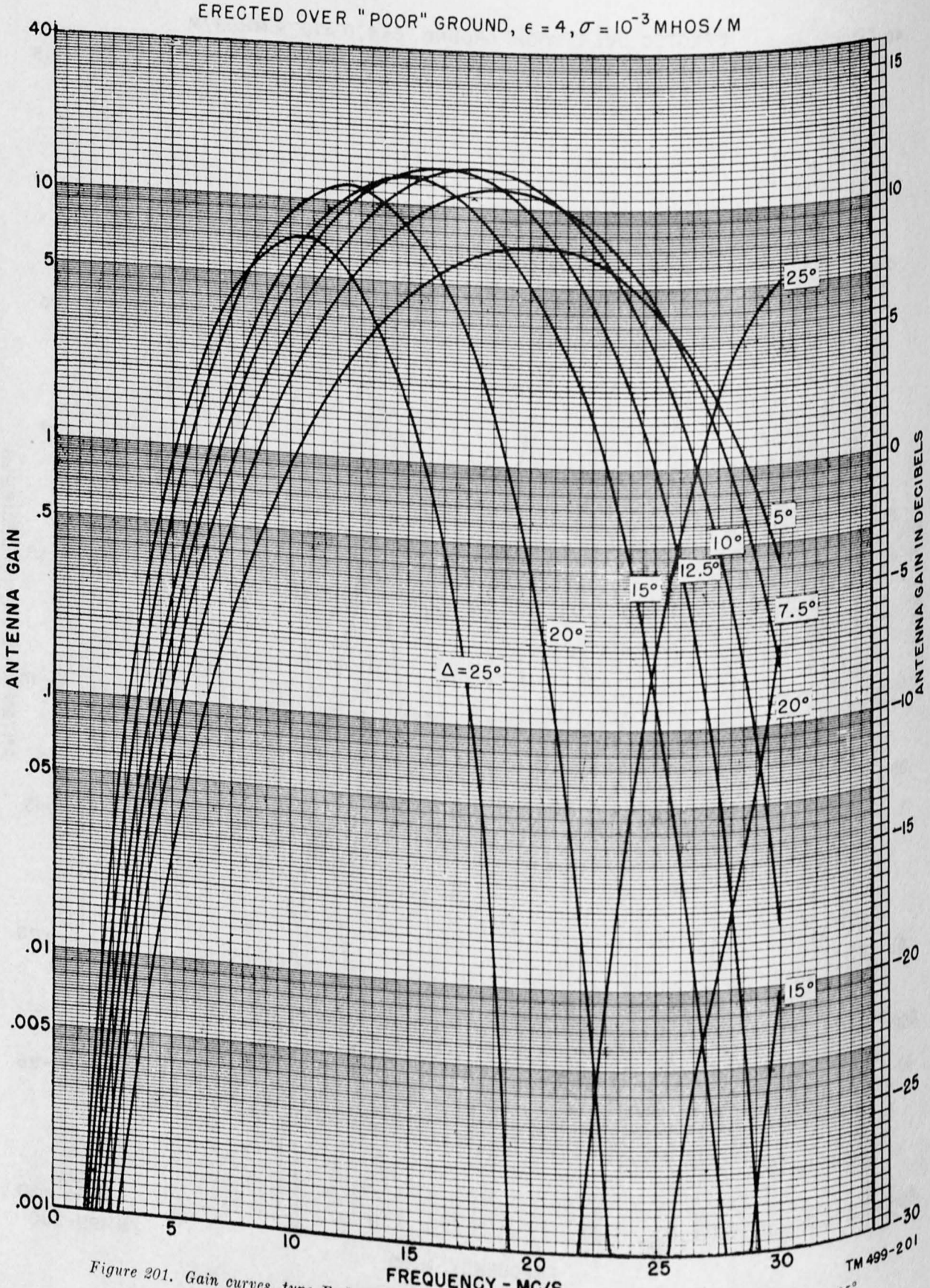


Figure 201. Gain curves, type F rhombic antenna erected above poor ground, angles from 5° to 25°.

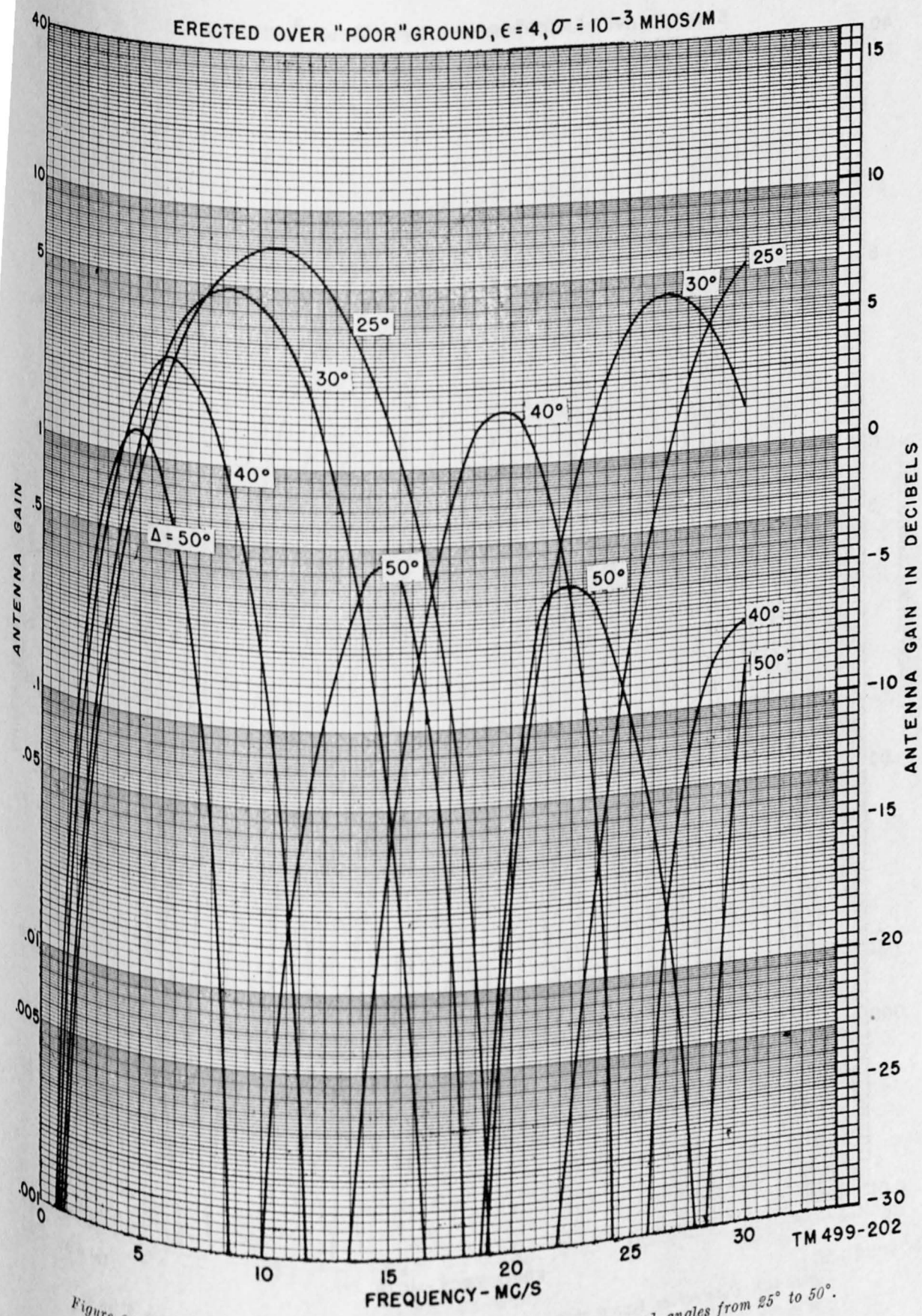


Figure 202. Gain curves, type F rhombic antenna erected above poor ground, angles from 25° to 50°.

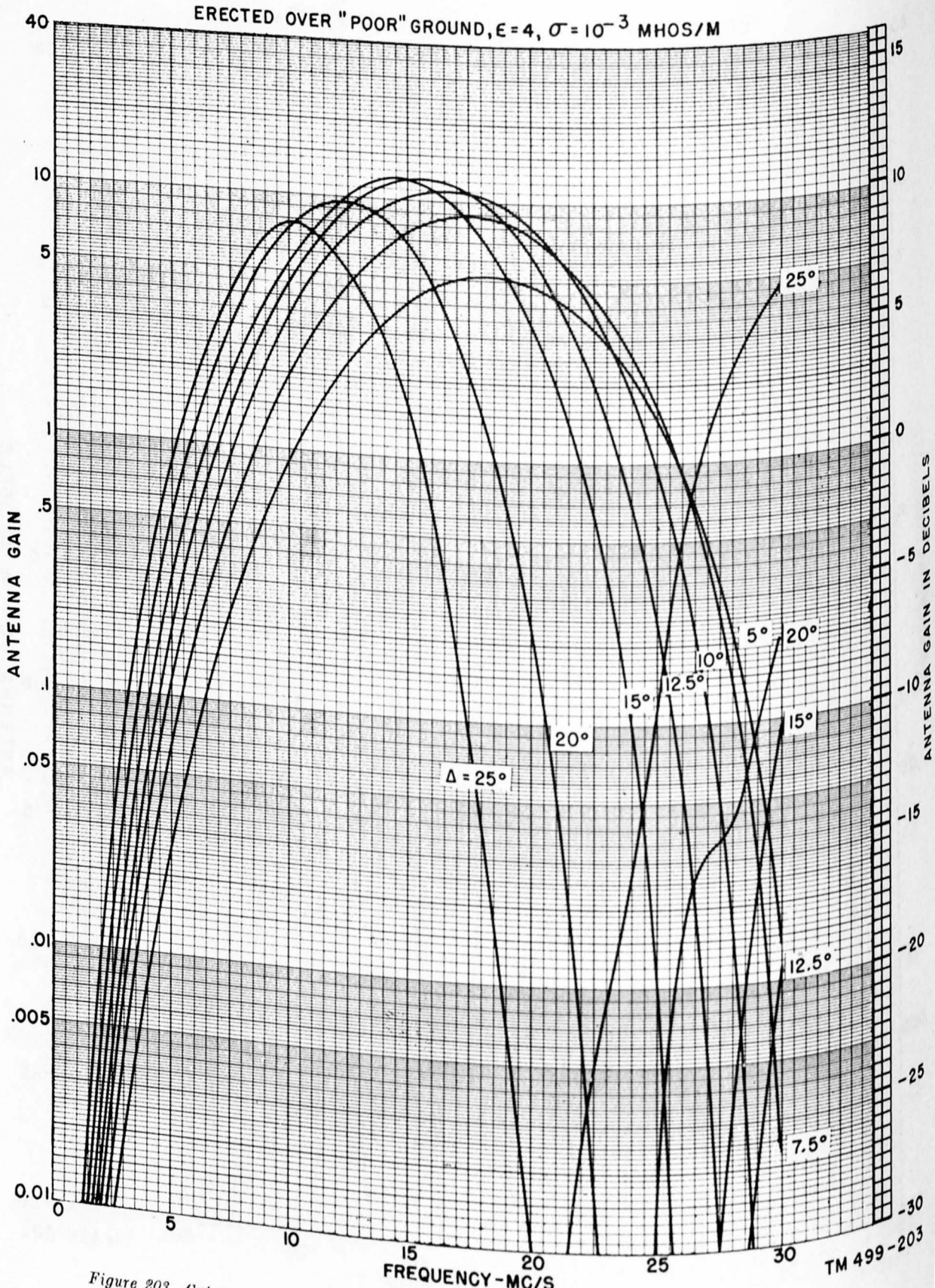


Figure 203. Gain curves, type G rhombic antenna erected above poor ground, angles from 5° to 25°.

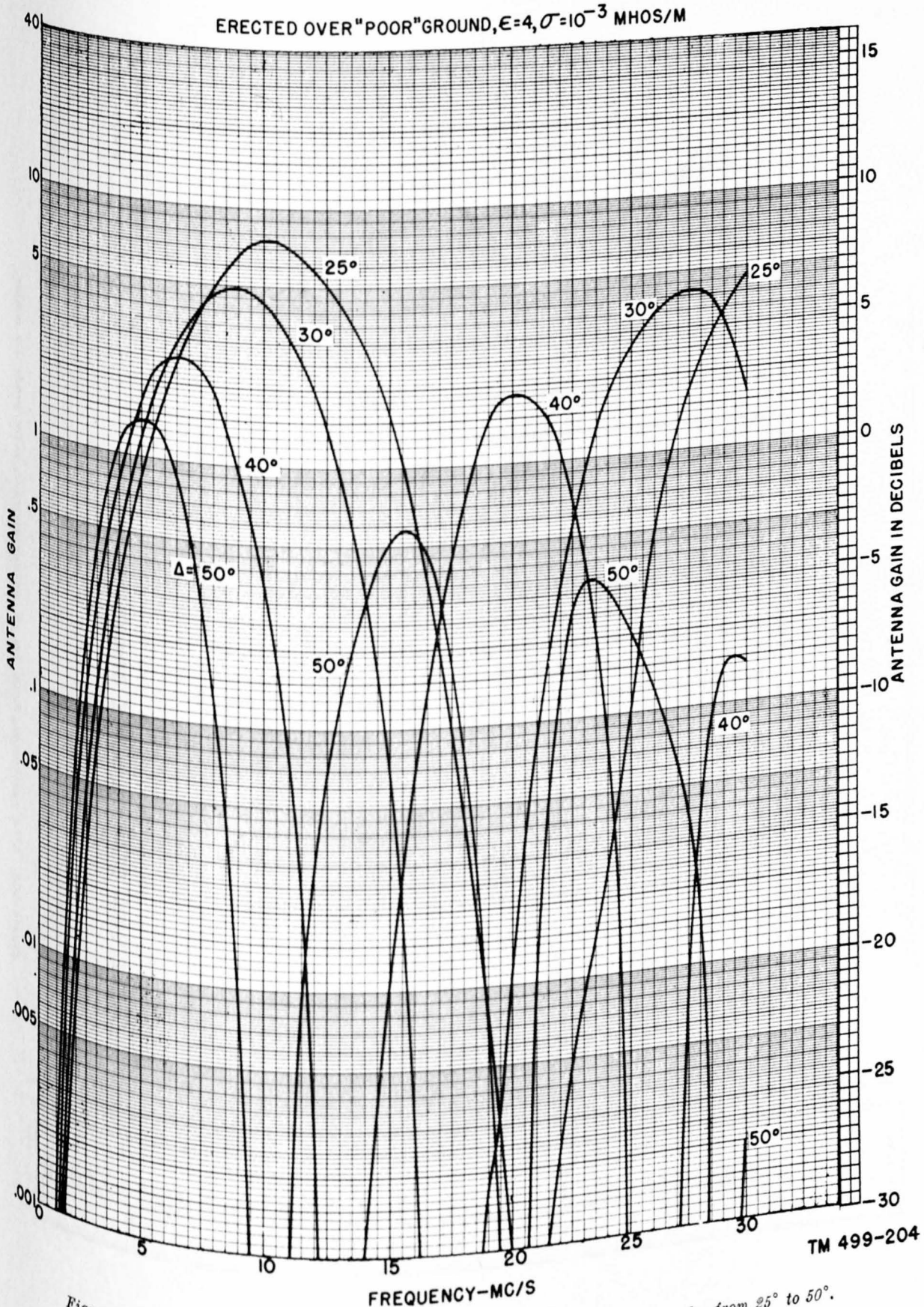


Figure 204. Gain curves, type G rhombic antenna erected above poor ground, angles from 25° to 50°.

Figure 205. LUF nomogram, 3,000 km or greater distance, noise grade 1.0 winter.

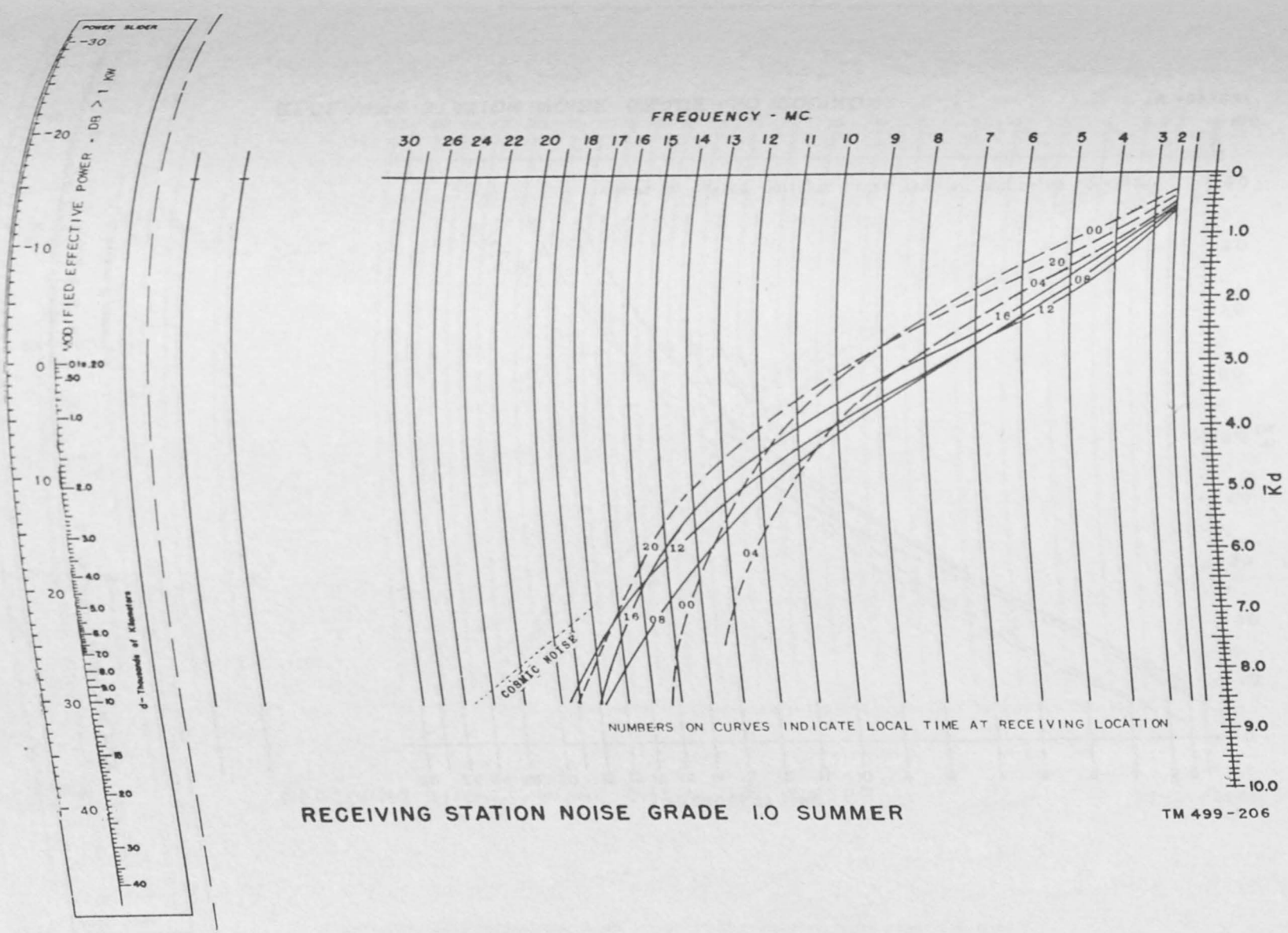


Figure 206. LUF nomogram, 3,000 km or greater distance, noise grade 1.0 summer.

Figure 207. LUF nomogram, 3,000 km or greater distance, noise grade, 1.0, equinox.

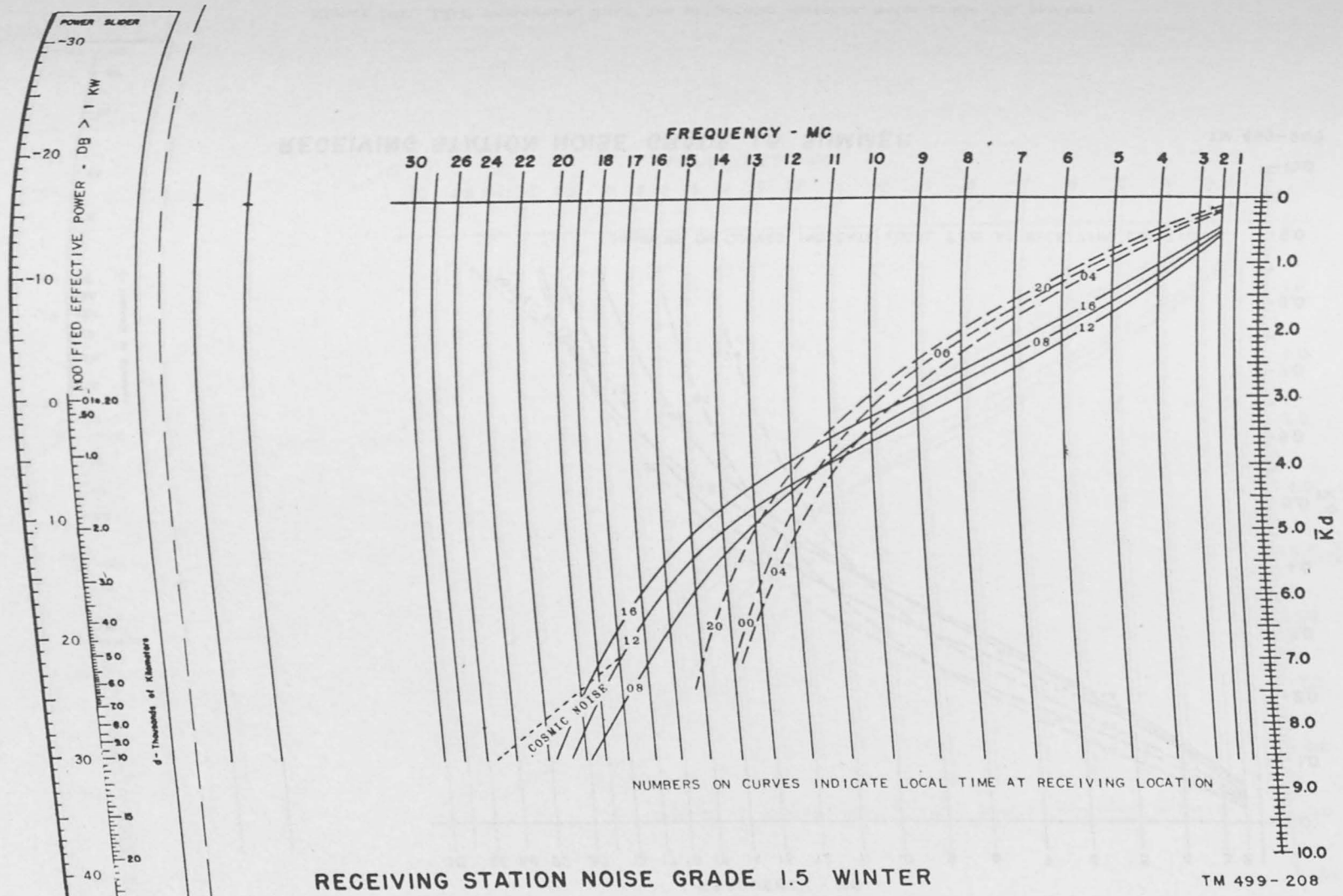


Figure 208. LUF nomogram, 3,000 km or greater distance, noise grade 1.5, winter.

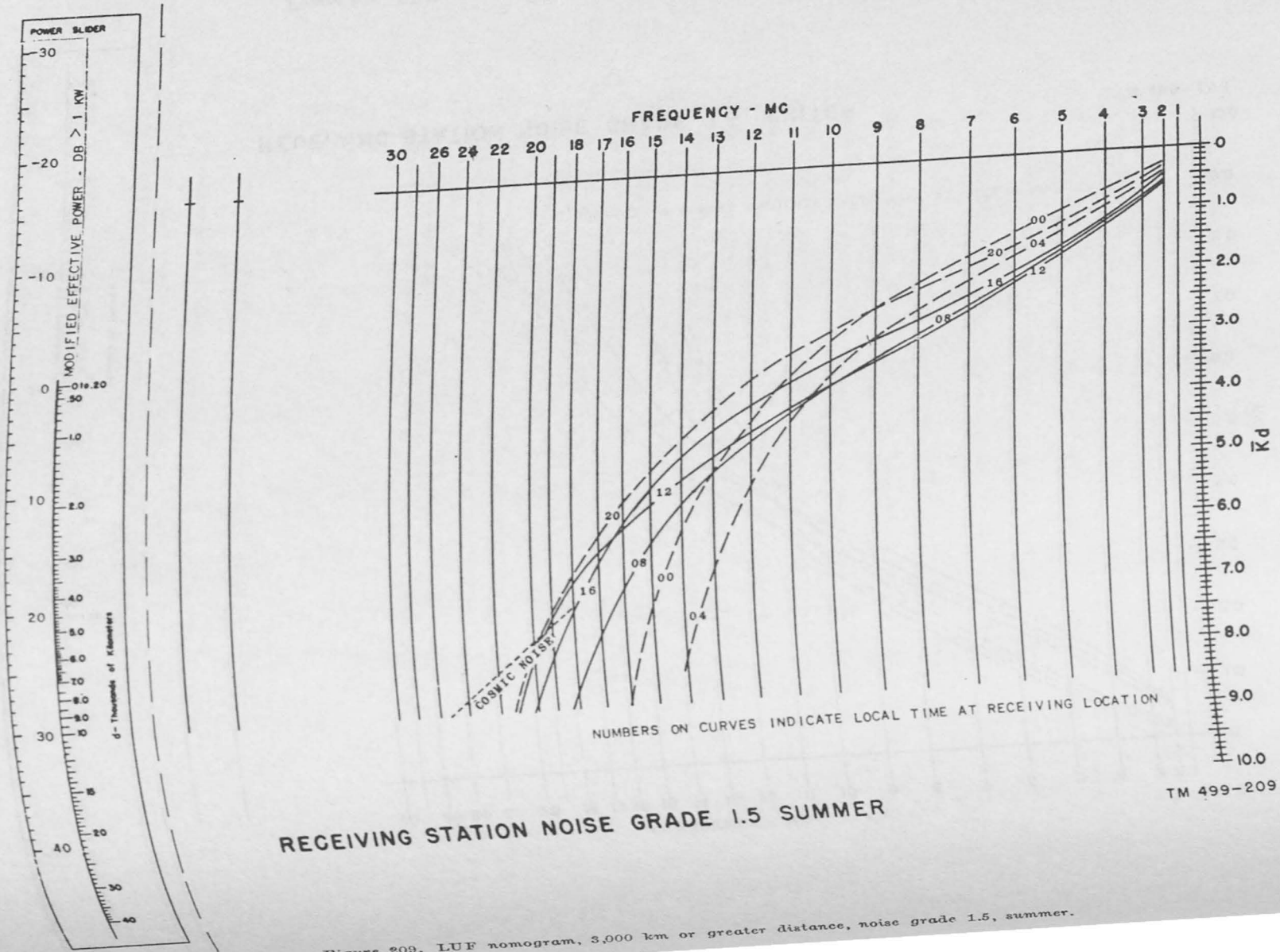


Figure 209. LUF nomogram, 3,000 km or greater distance, noise grade 1.5, summer.

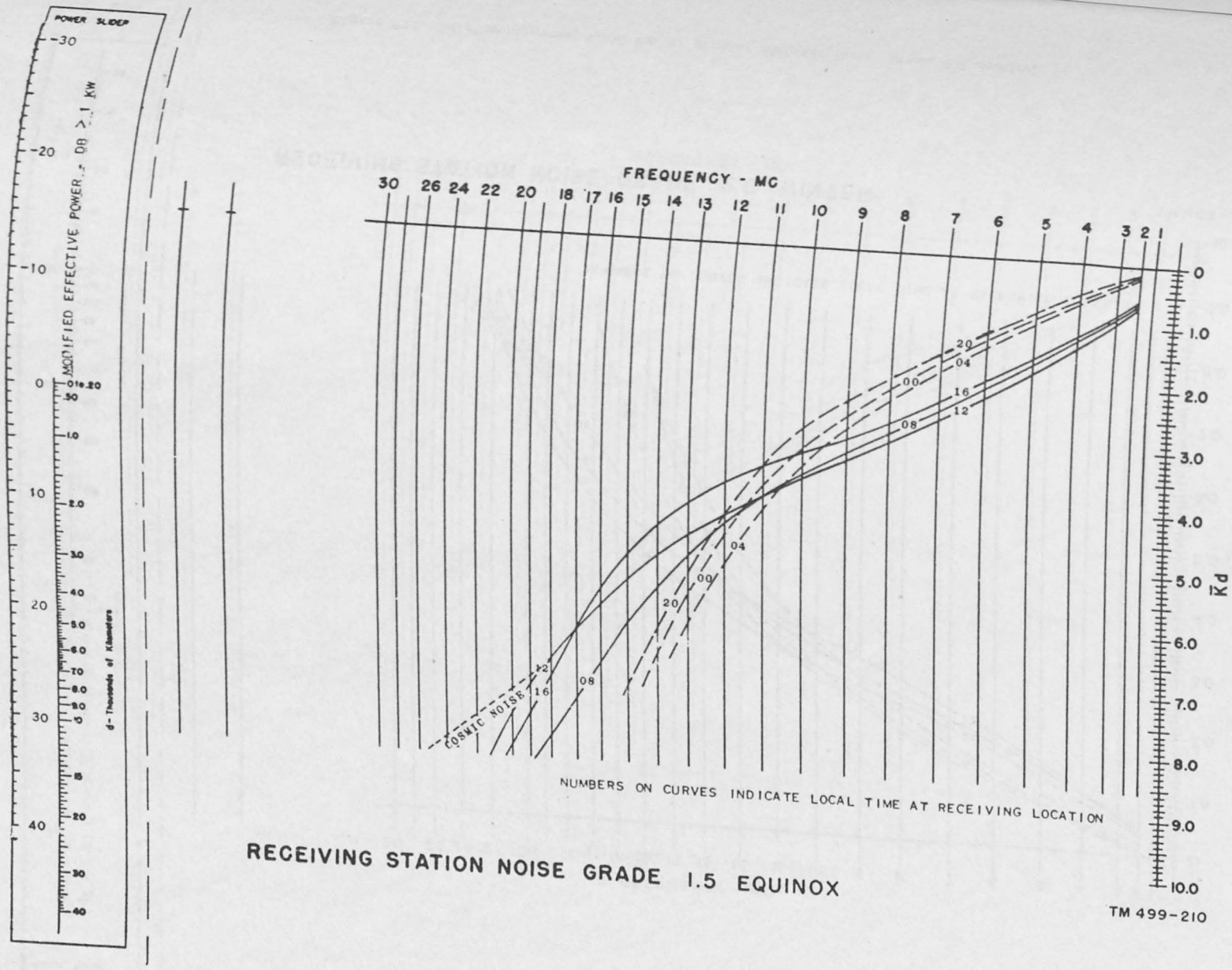


Figure 210. LUF nomogram, 3,000 km or greater distance, noise grade 1.5, equinox.

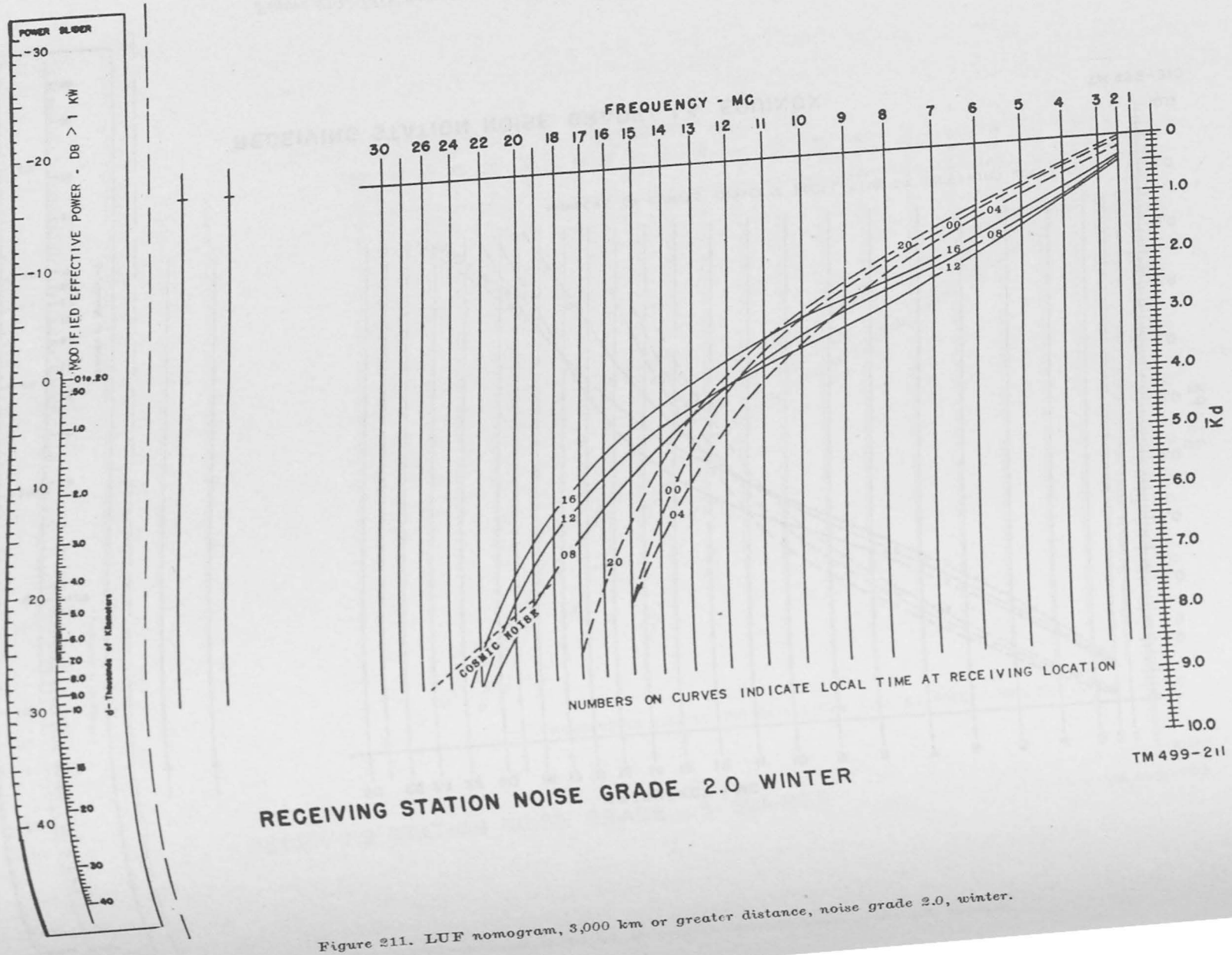


Figure 211. LUF nomogram, 3,000 km or greater distance, noise grade 2.0, winter.

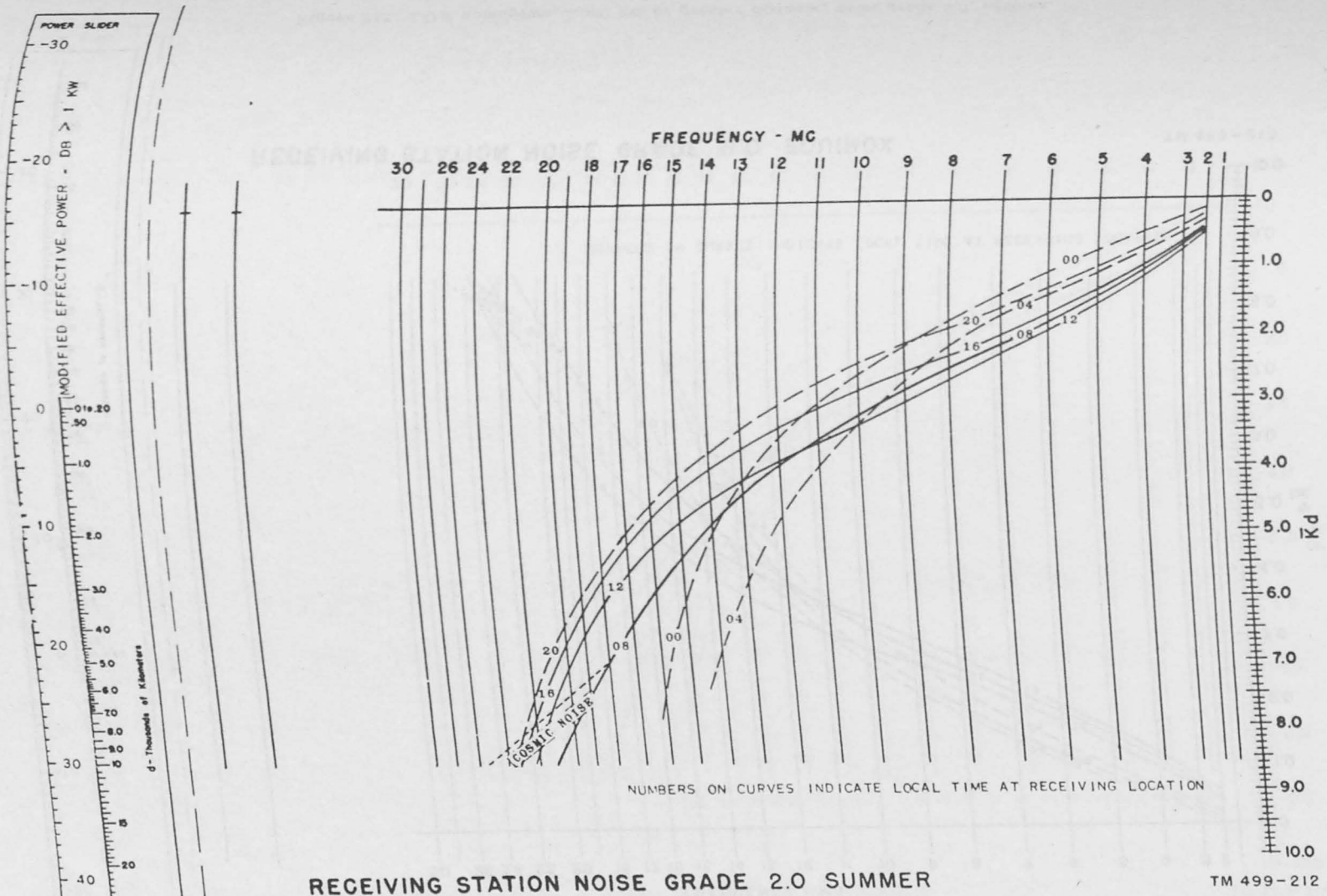


Figure 212. LUF nomogram, 3,000 km or greater distance, noise grade 2.0 summer.

Figure 213. LUF nomogram, 3,000 km or greater distance, noise grade 2.0, equinox.

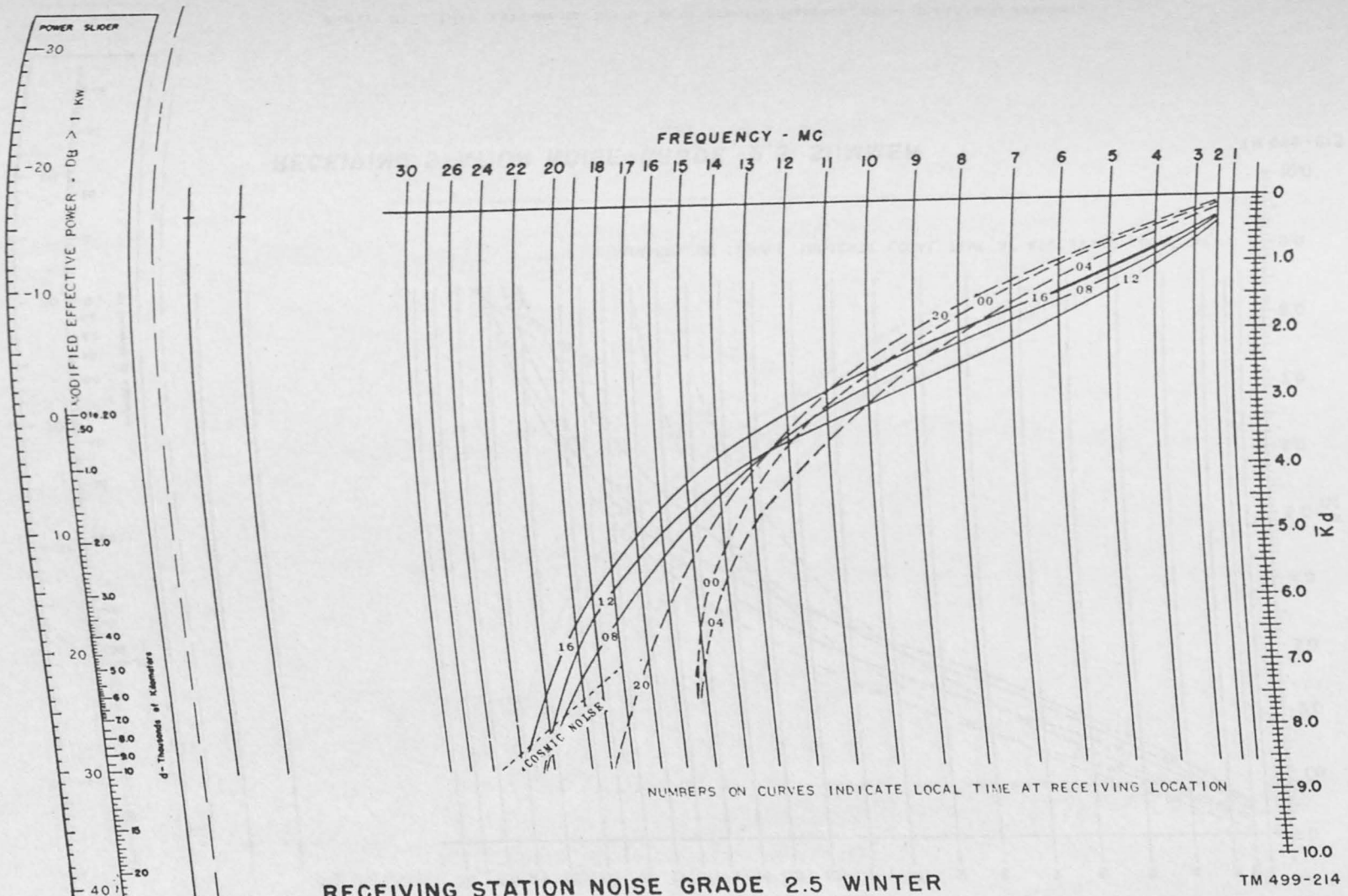


Figure 214. LUF nomogram, 3,000 km or greater distance, noise grade 2.5, winter.

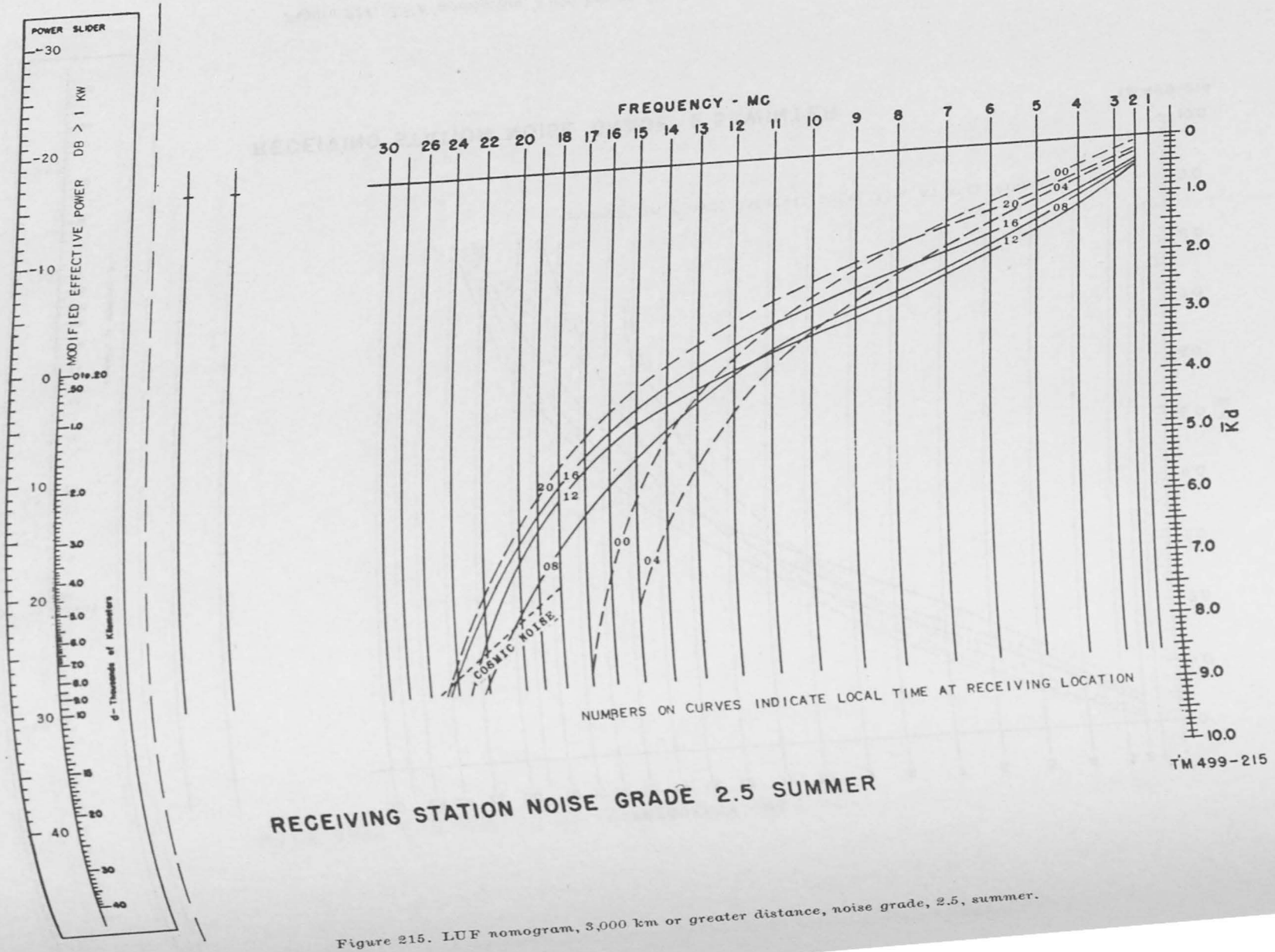


Figure 215. LUF nomogram, 3,000 km or greater distance, noise grade, 2.5, summer.

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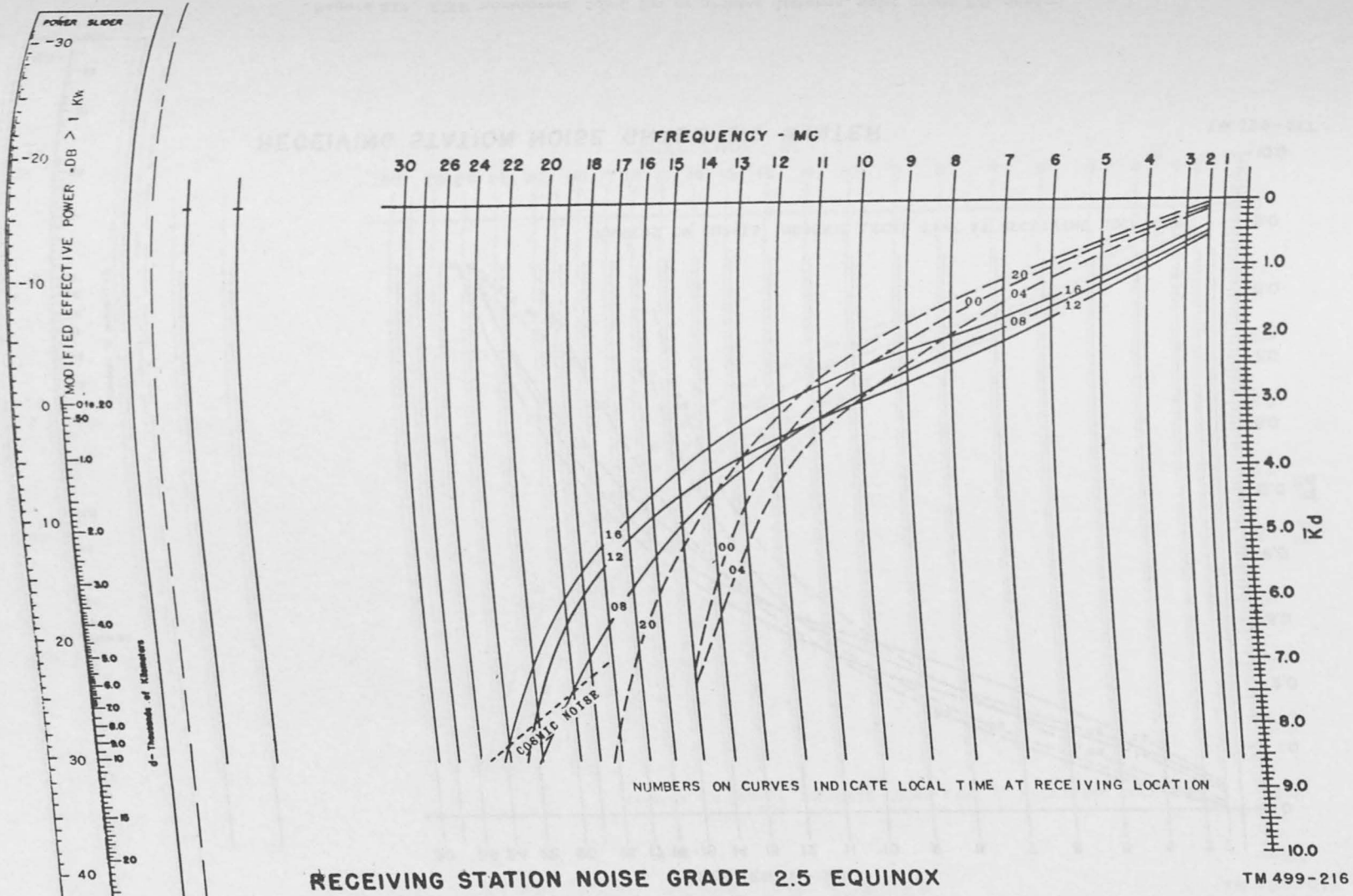
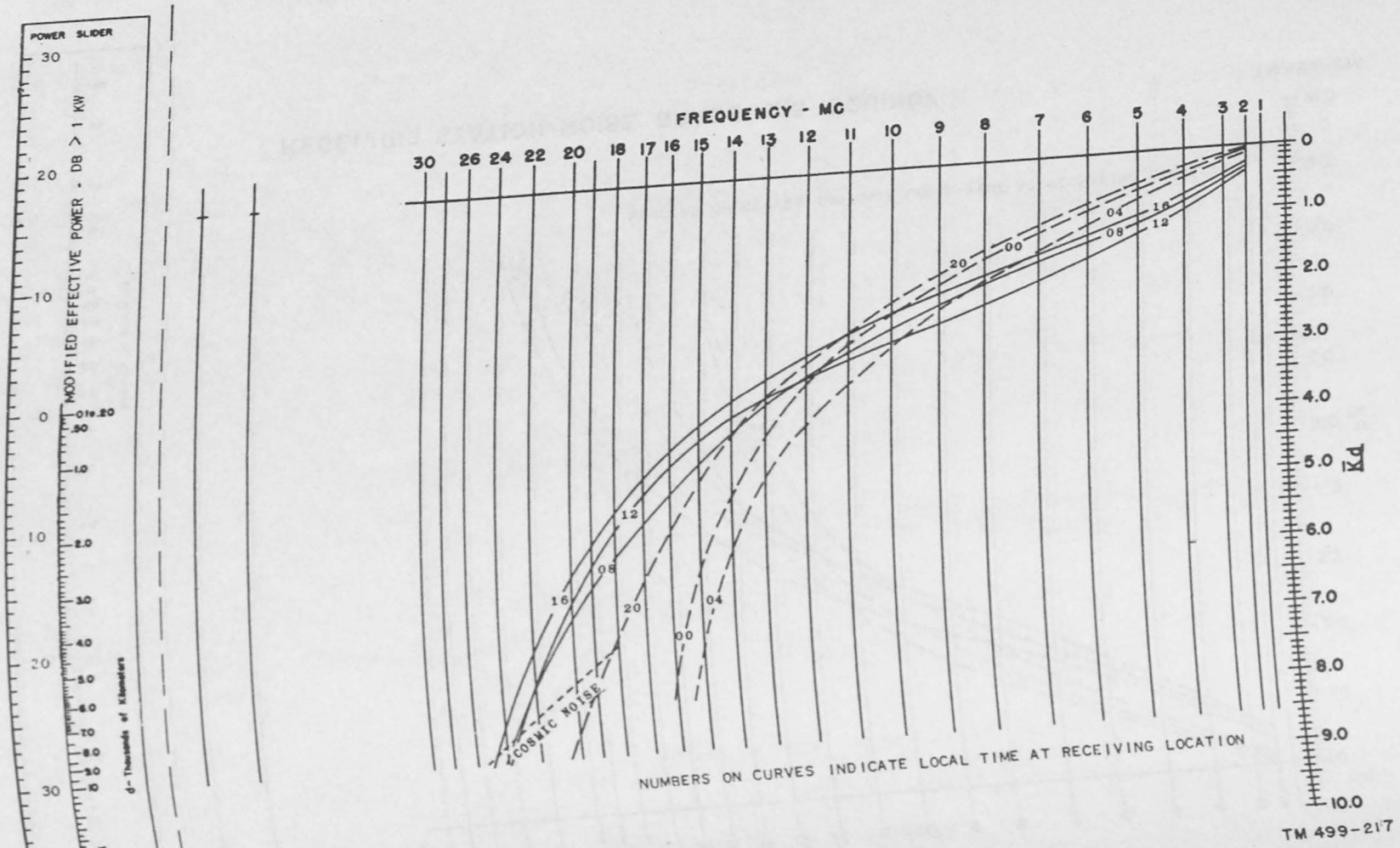


Figure 216. LUF nomogram, 3,000 km or greater distance, noise grade 2.5, equinox.



RECEIVING STATION NOISE GRADE 3.0 WINTER

Figure 217. LUF nomogram, 3,000 km or greater distance, noise grade 3.0, winter.

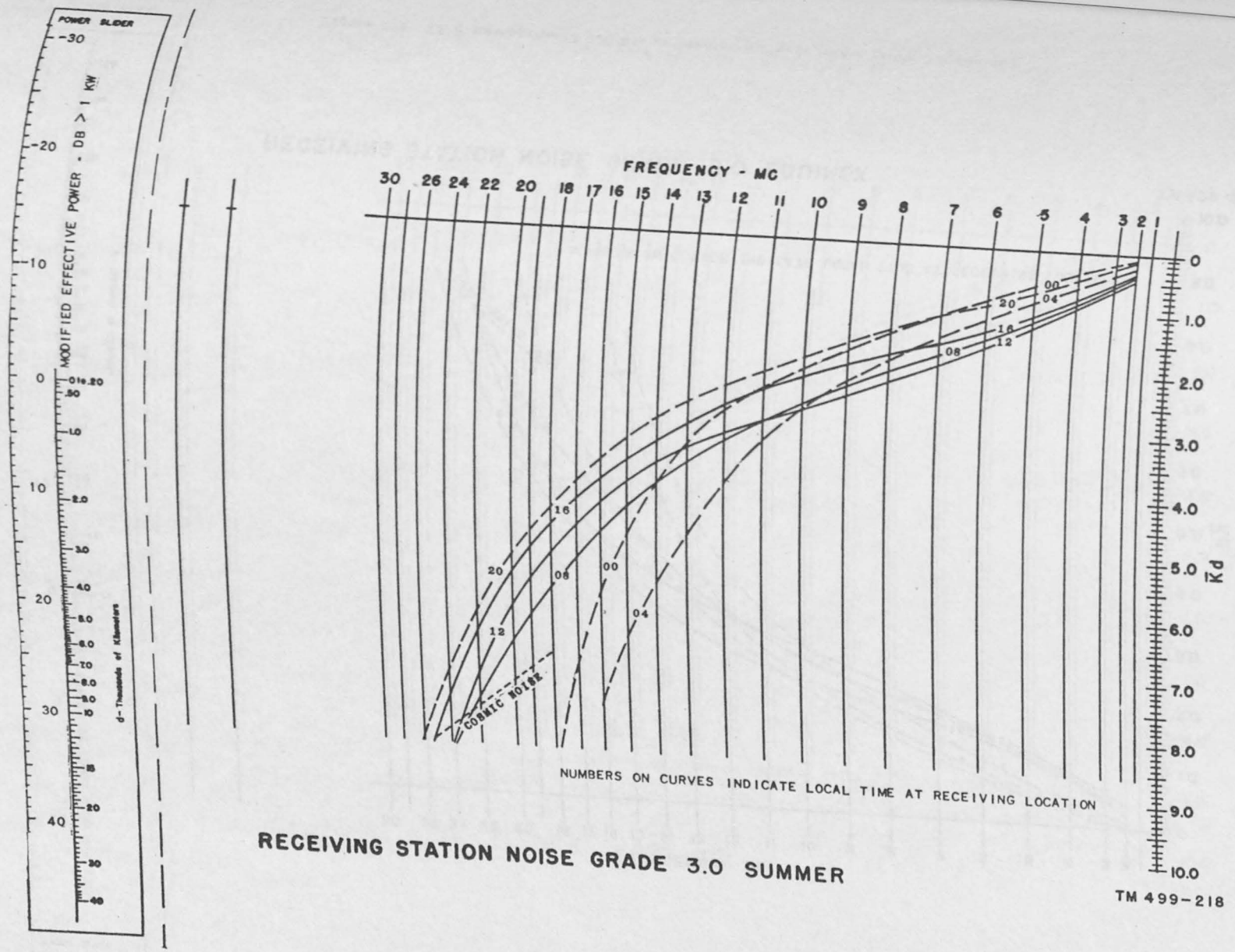
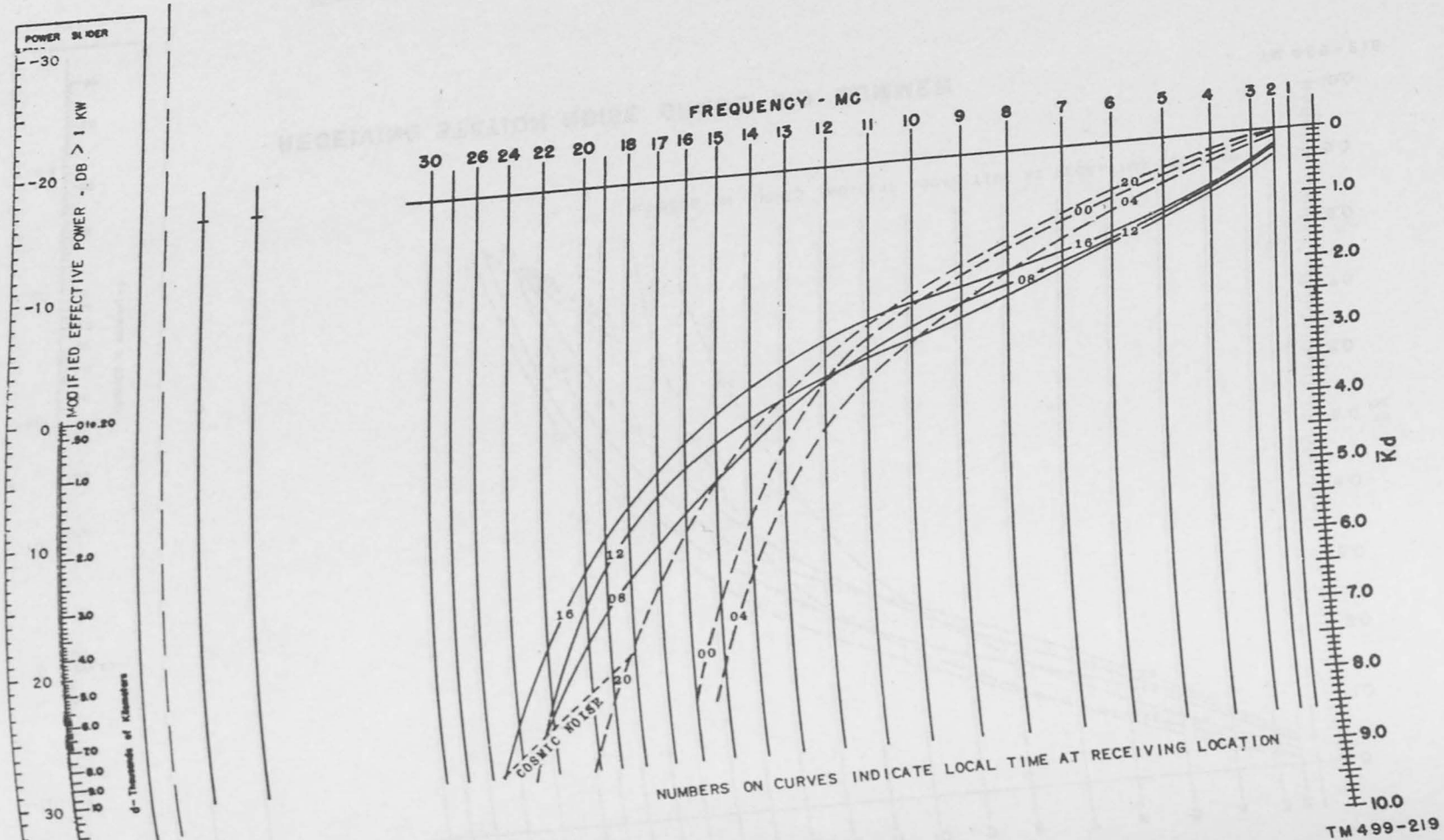


Figure 218. LUF nomogram, 3,000 km or greater distance, noise grade 3.0, summer.



RECEIVING STATION NOISE GRADE 3.0 EQUINOX

Figure 219. LUF nomogram, 3,000 km or greater distance, noise grade 3.0 equinox.

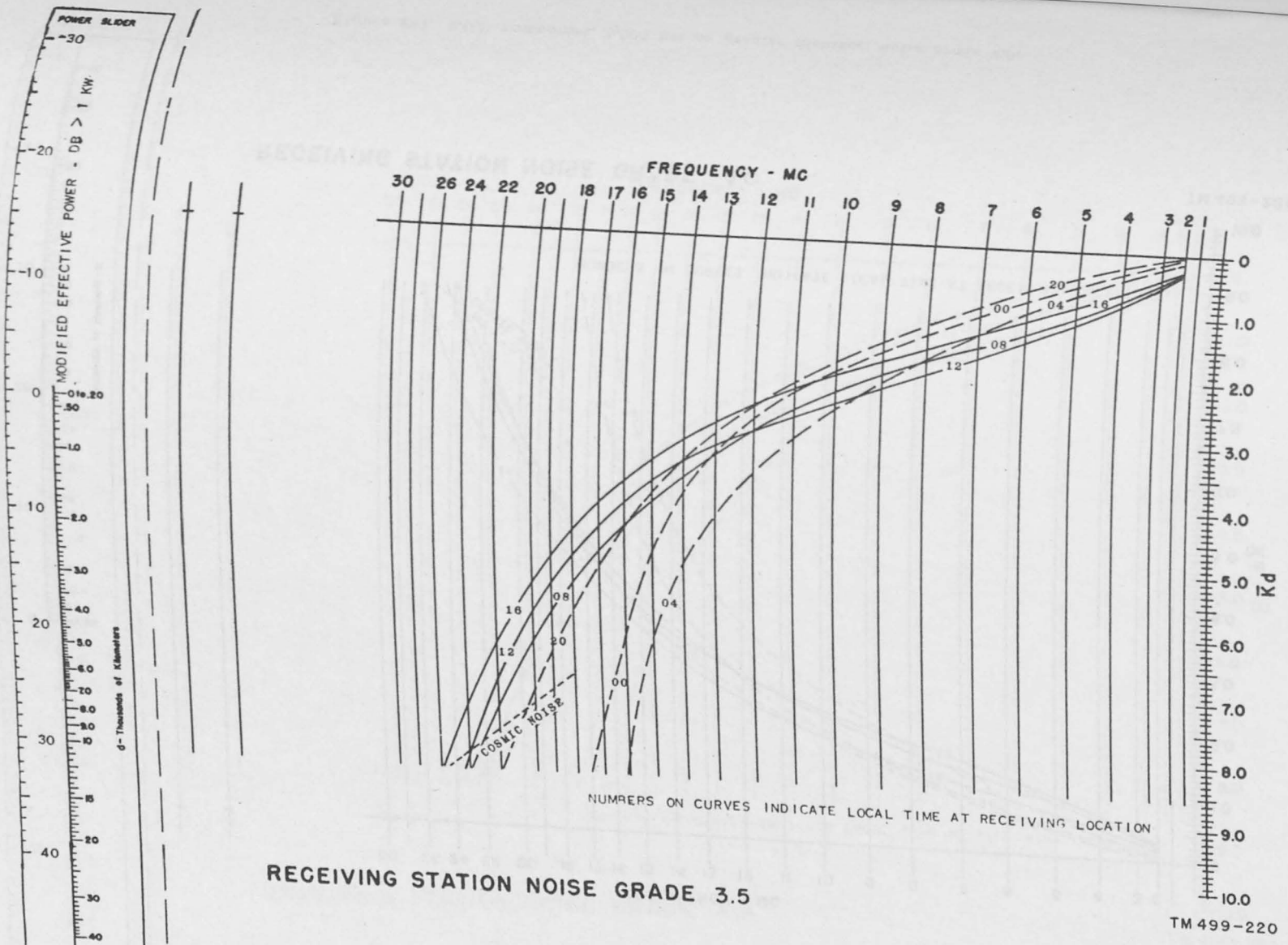
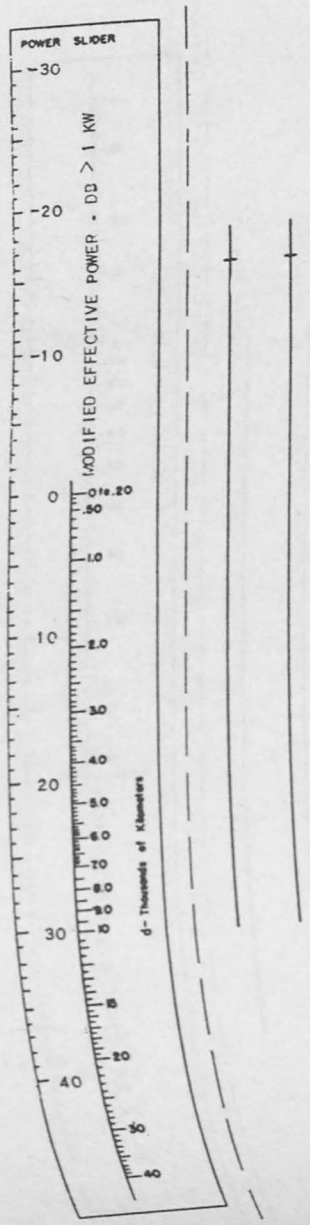
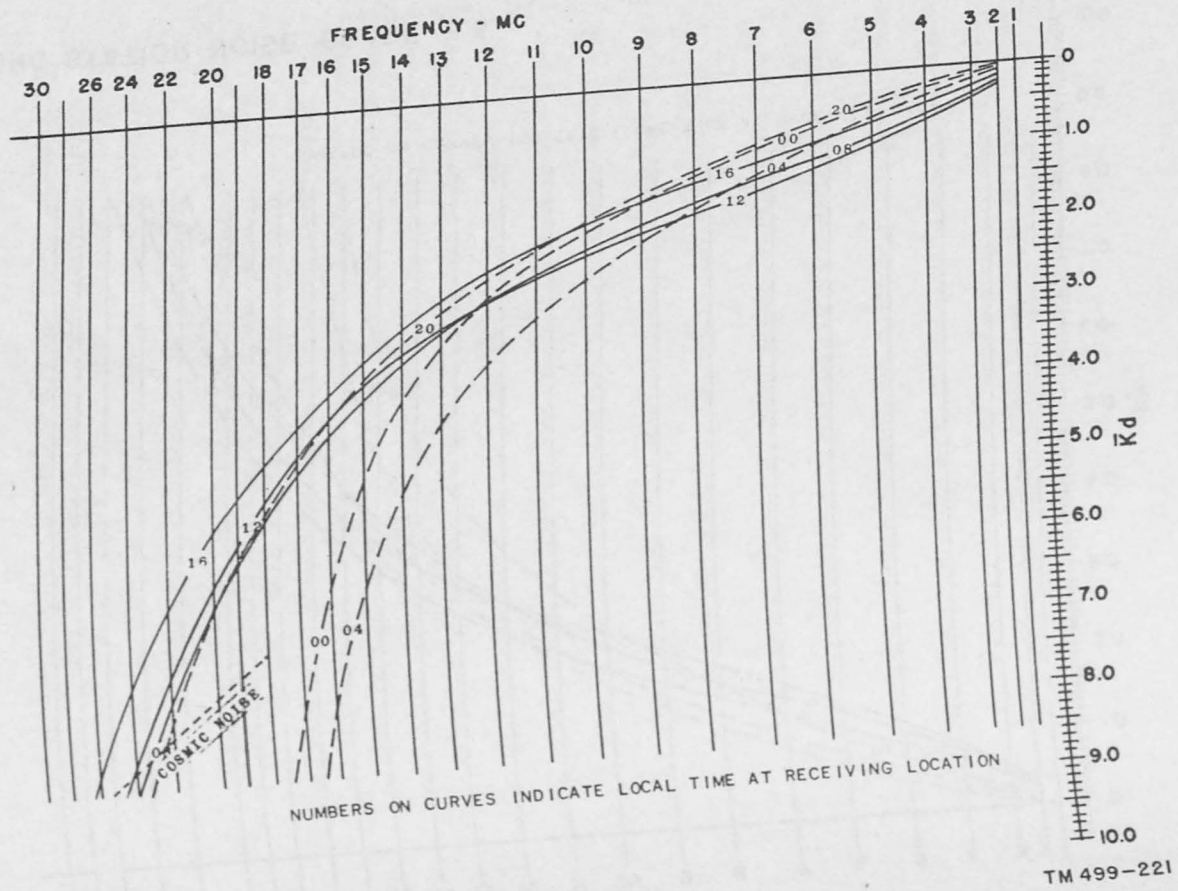


Figure 220. LUF nomogram, 3,000 km or greater distance, noise grade 3.5.





RECEIVING STATION NOISE GRADE 4.0

Figure 221. LUF nomogram, 3,000 km or greater distance, noise grade 4.0.

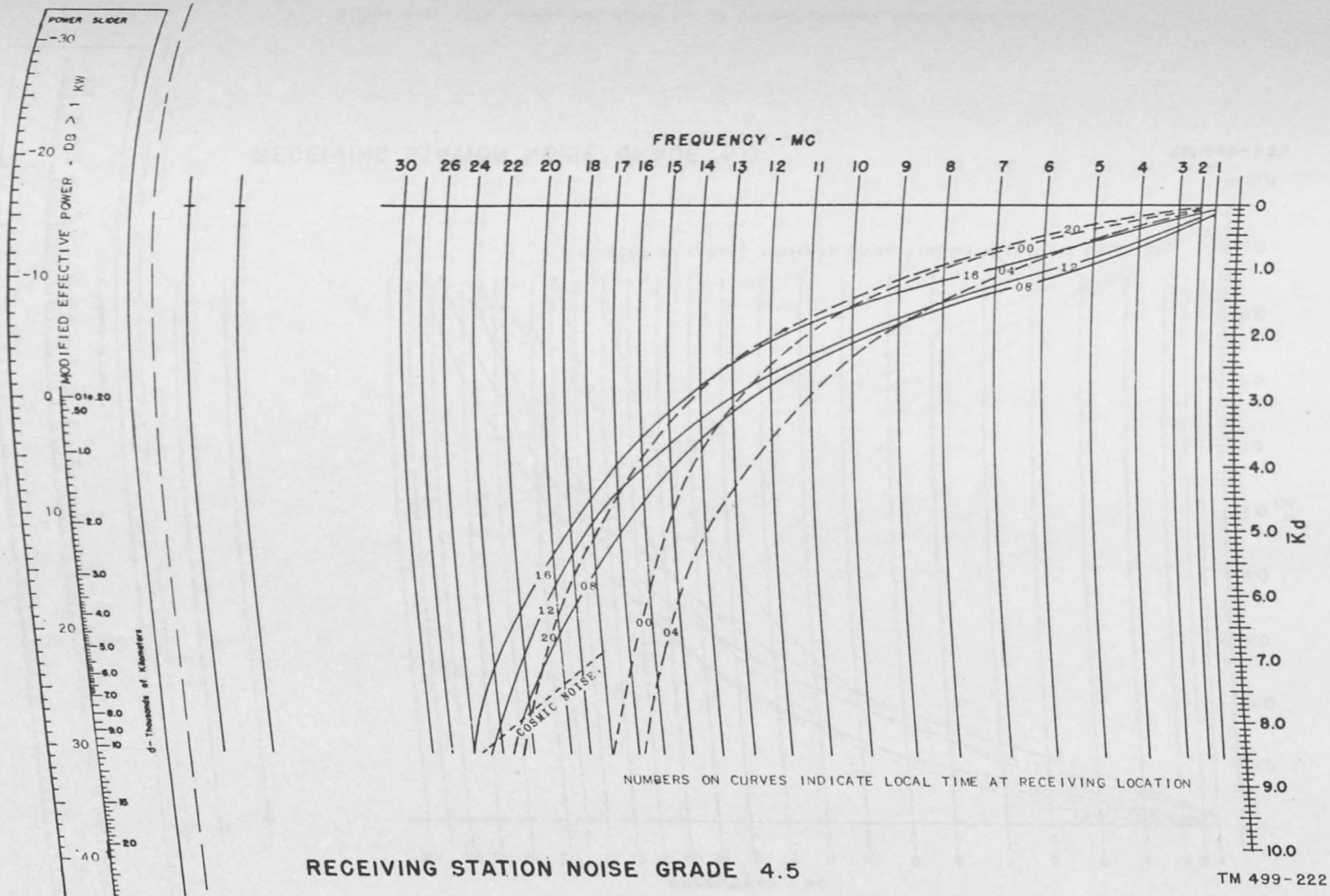
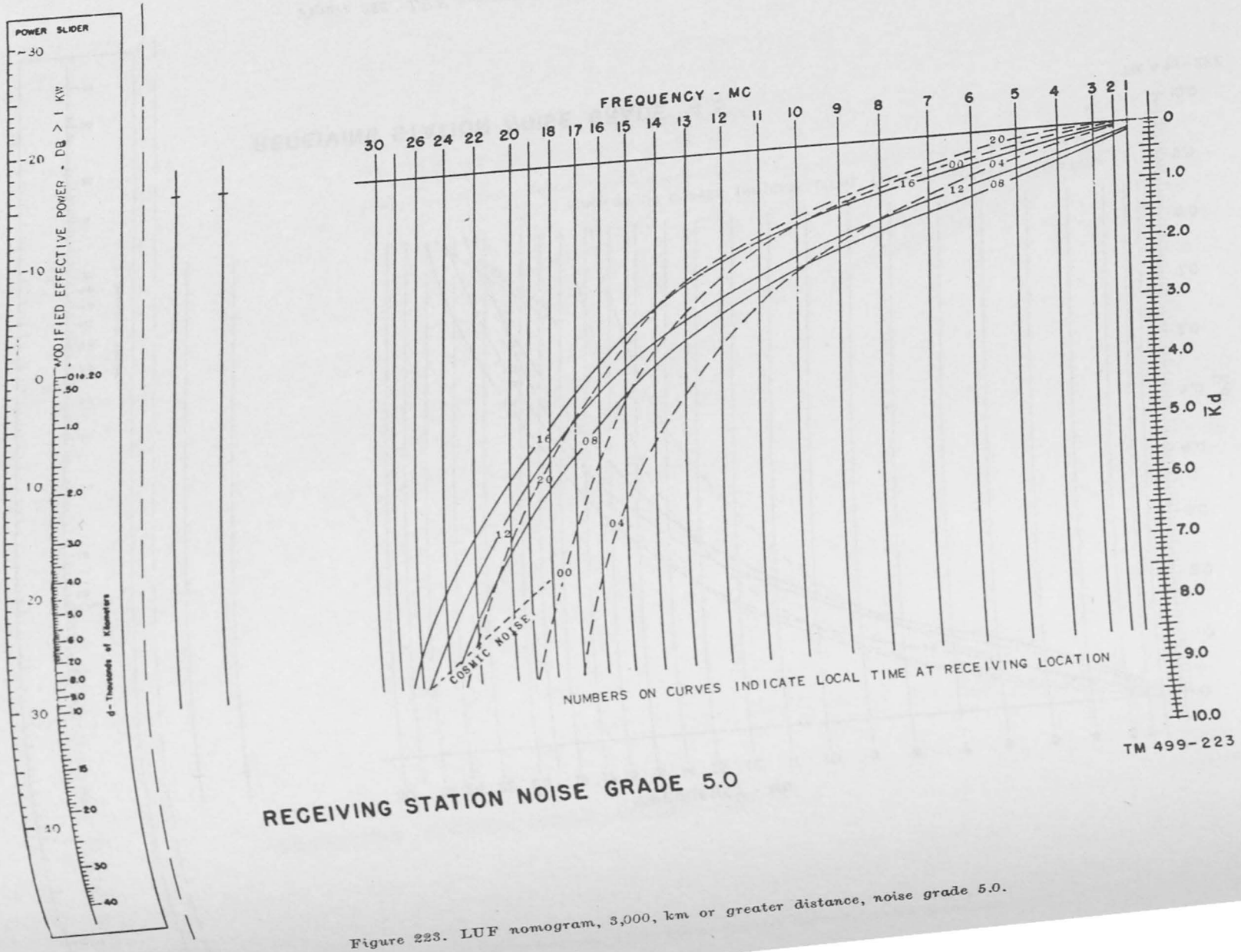


Figure 222. LUF nomogrma, 3,000 km or greater distance, noise grade 4.5.



RECEIVING STATION NOISE GRADE 5.0

Figure 223. LUF nomogram, 3,000, km or greater distance, noise grade 5.0.

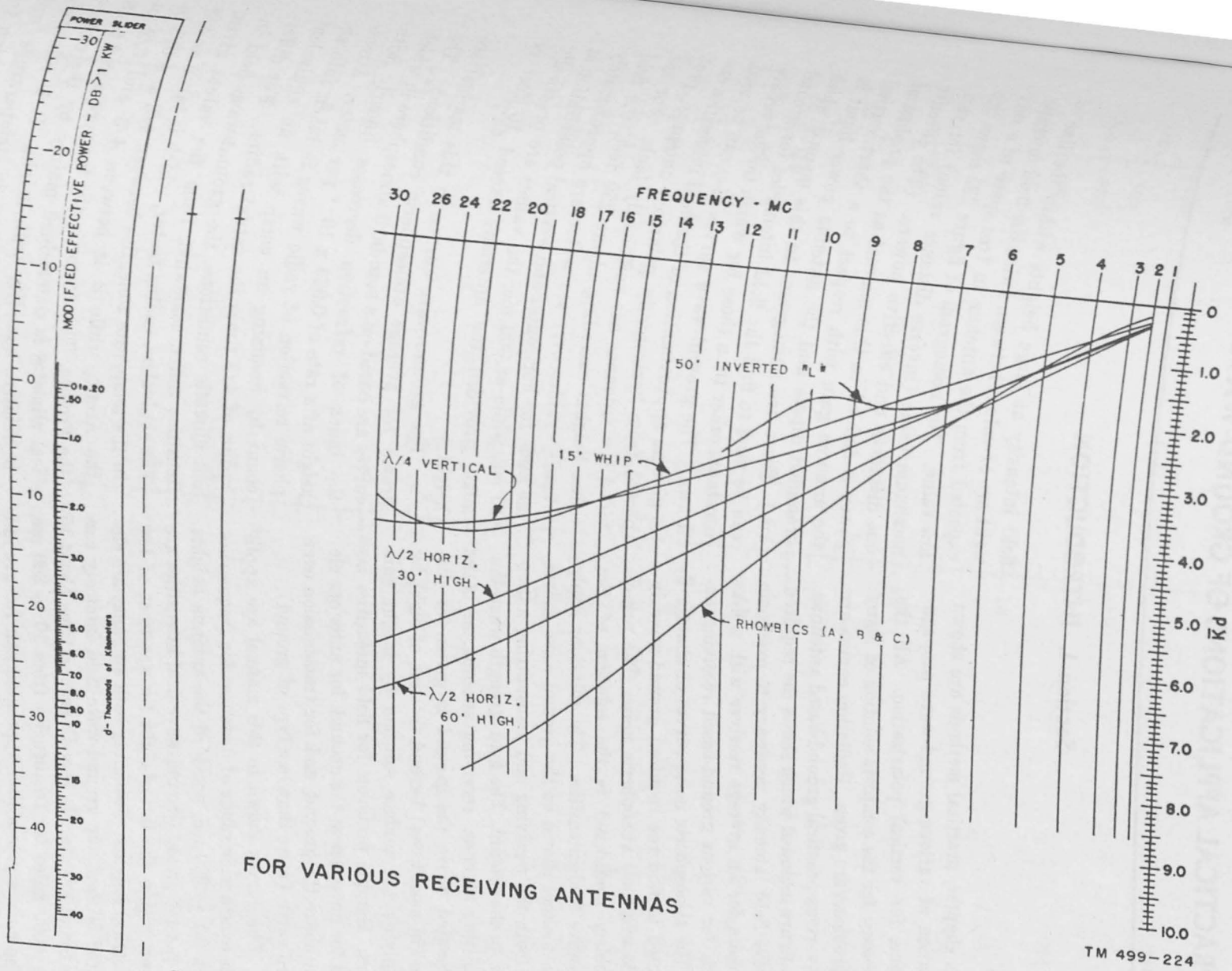


Figure 224. LUF nomogram, 3,000 km or greater distance, noise grade for various receiving antennas.

CHAPTER 4

PRACTICAL APPLICATIONS OF GROUND-WAVE THEORY

Section I. INTRODUCTION

94. Scope

a. In this chapter, practical methods are shown for the solution of various ground-wave propagation problems for vertical polarization. All the curves necessary for the complete solution of many practical problems are given. Radiation curves are shown for various practical ground-based antennas. There is a figure included which shows the required ground-wave field intensity necessary to overcome receiver noise for an average receiver with a 6-kc bandwidth for various ground-based receiving antennas. The atmospheric noise curves of chapter 3 can be used to find the required ground-wave intensity to overcome atmopheric noise. The principal problem considered is the solution of the ground-wave field intensities. The solutions apply for any distance shown on the ground-wave curves in case both the receiving and transmitting antennas are on the ground. The field strength when the transmitting antenna, receiving antenna, or both, are elevated above the ground is given for distances (in most cases) beyond the line of sight by multiplying the surface solution by height gain factors. Sample problems for field intensities are given for antennas at the ground, for antennas elevated above the ground, and for transmission over mixed earth (more than one type of ground).

b. The curves shown in this manual are applicable over a wide range of distances for frequencies from 0.1 to 300 mc, provided the antenna heights are not too great. Ground-wave field intensities are given within the line-of-sight for antennas of low electrical heights. Assuming both antennas are elevated 50 feet, the ground-wave field intensity can be found over fertile (good) ground from about 15 to 2,000 miles for frequencies from 10 to 300 mc. The curves give a first approximation for ground-wave field intensities for elevated antennas at points where the height gain factor limitations of this manual are not fulfilled. The ground-wave field intensity at large heights within the line of sight are of values between twice the field intensity expected from the antenna in free space to a very low value. The nomogram of figure 225 shows this maximum value (inverse distance value) for various distances and effective powers. (The effective power is defined in this manual as the product of the antenna gain with respect to a short vertical grounded dipole and the antenna power input in kw.) There are nomograms in this manual which can be used to find the field intensities for ground constants other than those for which the curves are drawn. The ground-wave curves also can be used to give an approximation of the field intensities expected from horizontally polarized antennas, provided the antennas are sufficiently high. For antenna heights exceeding about 250 feet, the field intensity values over sea water are approximately the same for horizontal and vertical polarization at 10 mc, while at 300 mc, the values are practically alike, provided the antennas exceed 10 feet in height.

c. The ground-wave curves in this manual are drawn for average atmospheric conditions. The curves are based on a standard atmosphere in which the index of refraction decreases linearly with height at a rate of 0.039×10^{-6} per meter. Atmospheric refraction of radio waves is taken into account by assuming an earth with an equivalen radius of 4/3 times the actual radius. For differ ent climatic conditions, the ground-wave field in tensities differ somewhat from the values give The equivalent radius factor, which is taken as 4 in the temperate zone, lies between 4/3 and 6/5 the Arctic, while it is between 4/3 and 3/2 the Tropics. This factor in the temperate and tr ical climates is determined mainly by the cha in relative humidity with height. It is relati insensitive to the change in temperature height. In the upper part of the very high quency band, there are, at times, exceptional

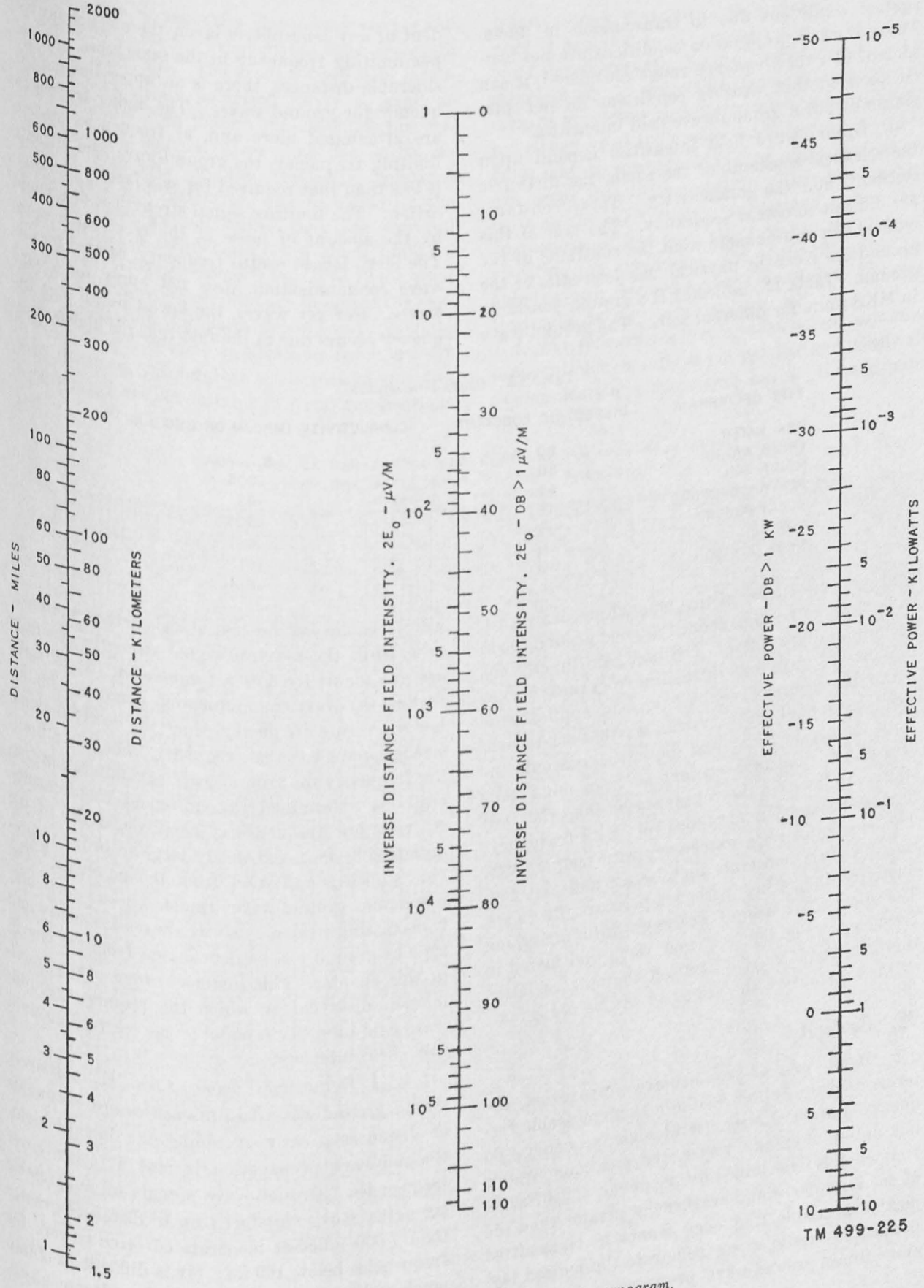


Figure 225. Inverse distance field intensity nomogram.

agation conditions due to transmission in ducts. These unusual propagation conditions are not consdered. For the frequency range considered, it can be assumed that weather conditions do not substantially affect ground-wave field intensities.

d. Ground-wave field intensities depend upon the electrical constants of the earth, the dielectric constant, and the conductivity. These constants are difficult to obtain accurately. The user of this manual can approximate what the constants of the ground are from the physical characteristics of the ground. Table IX indicates the ground constants in MKS units for different soils. The ground-wave field intensity curves of this manual are drawn for three types of terrain, defined as good ground, poor ground, and sea water. The user can directly obtain ground-wave field intensities from these curves within the accuracy required for most applications. The constants of soil vary with weather conditions. Both the conductivity and dielectric constants increase with moisture content. The ground constants are lower in the winter season than they are during the summer. They also vary with frequency. The constants of sea water vary with temperature, the dielectric constant diminishing and the conductivity increasing with temperature increases. The dielectric constant decreases with increasing frequency. For the frequency range considered in this manual, it can be assumed that the variation of the constants with frequency can be neglected.

Table IX. Ground Constants

TYPE OF TERRAIN	DIELECTRIC CONSTANT	CONDUCTIVITY (MHO/M OR EMU X 10^{-11})
SEA WATER	80	5.
FRESH WATER	80	.005
MOIST SOIL	30	.02
FERTILE GROUND	15	.005
ROCKY GROUND	7	.001
DRY SOIL	4	.01
VERY DRY SOIL	4	.001

95. General

a. In the case of ground-wave propagation, the terms used in chapter 3—the maximum usable frequency and the lowest useful high frequency—do not apply. For sky waves, the maximum usable frequency is determined by the extent of ionization of the ionosphere and frequencies greater than the maximum usable frequency cannot be transmitted because the radio waves penetrate the ionized layers. Since ground-wave propagation is independent of any ionospheric layer, there is not any upper limiting frequency in the same sense. At considerable distances, there is an upper limiting frequency for ground waves. The higher frequencies are attenuated more and, at frequencies above a limiting frequency, the ground-wave field intensity is less than that required for satisfactory communication. The limiting signal strength is determined by the amount of noise at the receiving location. The term, lowest useful frequency, as used for sky-wave communication, does not apply for ground waves. For sky waves, the lowest useful high frequency occurs due to the fact that the higher short-wave frequencies are less absorbed than the lower ones, while the required signal strengths generally are greater at the lower frequencies. Thus, satisfactory sky-wave communication is not possible below a limiting frequency, since the received signal strengths are less than required. The lower limiting frequency for ground-wave communication generally is determined by equipment requirements. At very low frequencies, the physical size of the antennas becomes extremely large in order to provide sufficient radiation from the antennas. The maximum ground-wave range for a particular transmitting station at a given wave frequency and type of ground can be determined from the curves in this chapter. This distance range is the transmission distance for which the required ground-wave field intensity is equal to the received ground-wave field intensity.

b. At frequencies below 1,500 kc, relatively strong ground-wave field intensities are obtainable at distances greatly exceeding the line of sight. Ground-wave propagation is best at these lower frequencies. Ground-wave signals of appreciable strengths can be produced up to distances greater than 1,000 miles at moderate effective powers for frequencies below 100 kc. (It is difficult to obtain much radiation from antennas of moderate physical size at these low frequencies.) The ground-wa

field intensity is primarily dependent on ground conductivity at the low frequencies, since the earth is a good conductor. The ground-wave field intensity for horizontally polarized waves is small at low frequencies even though the antennas are elevated to great heights. Over very dry earth, no effect is noticeable on the vertically polarized ground-wave field intensity, due to elevating the antennas above ground unless they are elevated about 200 feet at frequencies below about 1,500 kc.

c. *In the frequency range from 1.5 to 30 mc,* most of the communication circuits are designed for sky-wave propagation, although ground-wave communication is used in some applications for relatively short distances. Ground-wave circuits in this frequency range are not suitable in Army applications, wnere secrecy is required, because much of the energy is radiated as sky waves and can be of sufficient signal strength at considerable distances to be interceptible. Appreciable fading is possible for circuits operating in this frequency band. The signal strengths of the ground-wave and the sky-wave fields may be comparable in magnitude, and fading can occur due to the varying phase relationships between the arriving sky and ground waves. For frequencies of less than about 10 mc, the effect of elevating the antennas is not noticeable unless the antennas are elevated higher than 25 feet (for vertical polarization) over very dry soil.

d. *For frequencies greater than 30 mc,* sky-wave propagation generally is not possible and nearly all communication is by ground waves. Ground-wave

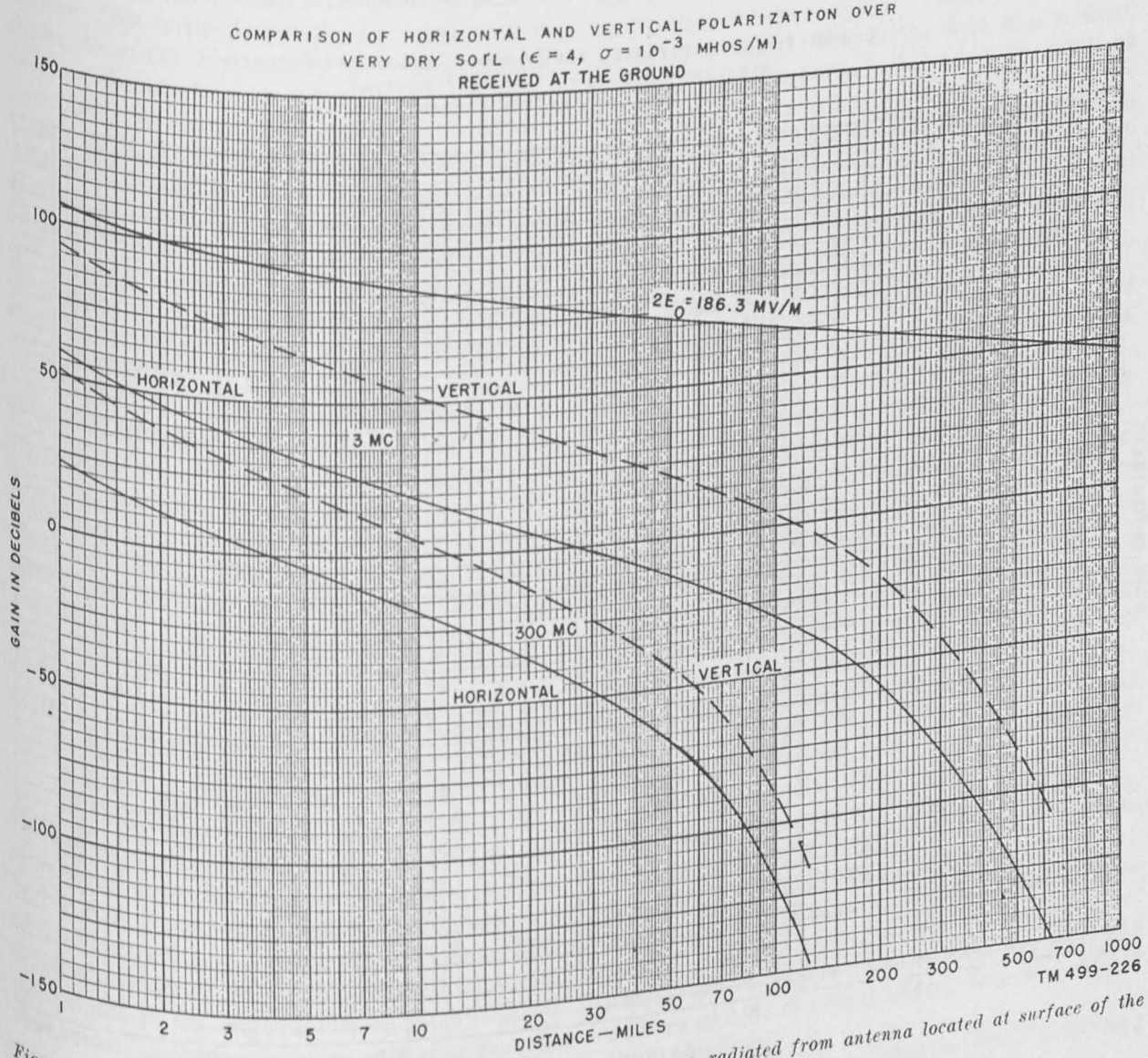


Figure 226. Ground-wave field intensity versus distance curves, for waves, radiated from antenna located at surface of the earth.

field strengths are very sensitive to changes in heights at these frequencies. Within the line of sight, the field intensity is determined by direct and ground-reflected waves. As the height of the receiving point is increased at distances near the transmitting antenna, the field intensity value fluctuates between larger and smaller values. At points exceeding the line of sight, the field intensities first rise linearly with height and then increase exponentially with heights until fluctuations are noticeable. For large antenna heights, the fields for horizontal and vertical polarization are nearly alike. Fading or rapid changing of field intensities is noticeable at higher frequencies at considerable distances from the transmitting antenna. Weather conditions produce variations in the rate at which the atmospheric index of refraction changes with height. These variations and tropospheric reflections cause fading.

96. Theoretical Basis

a. The optical ray theory cannot be used to calculate the ground-wave field intensities of antennas over finitely conducting earth. It has been shown that the field produced by an antenna can be evaluated with reasonable accuracy by ray theory for all cases except for the field in the immediate neighborhood of the earth. When the fields of an antenna are calculated mathematically, there are terms in the equations which vary in different manners with respect to distance. For ray theory, only the terms that decrease inversely with distance need to be considered, since these terms are much

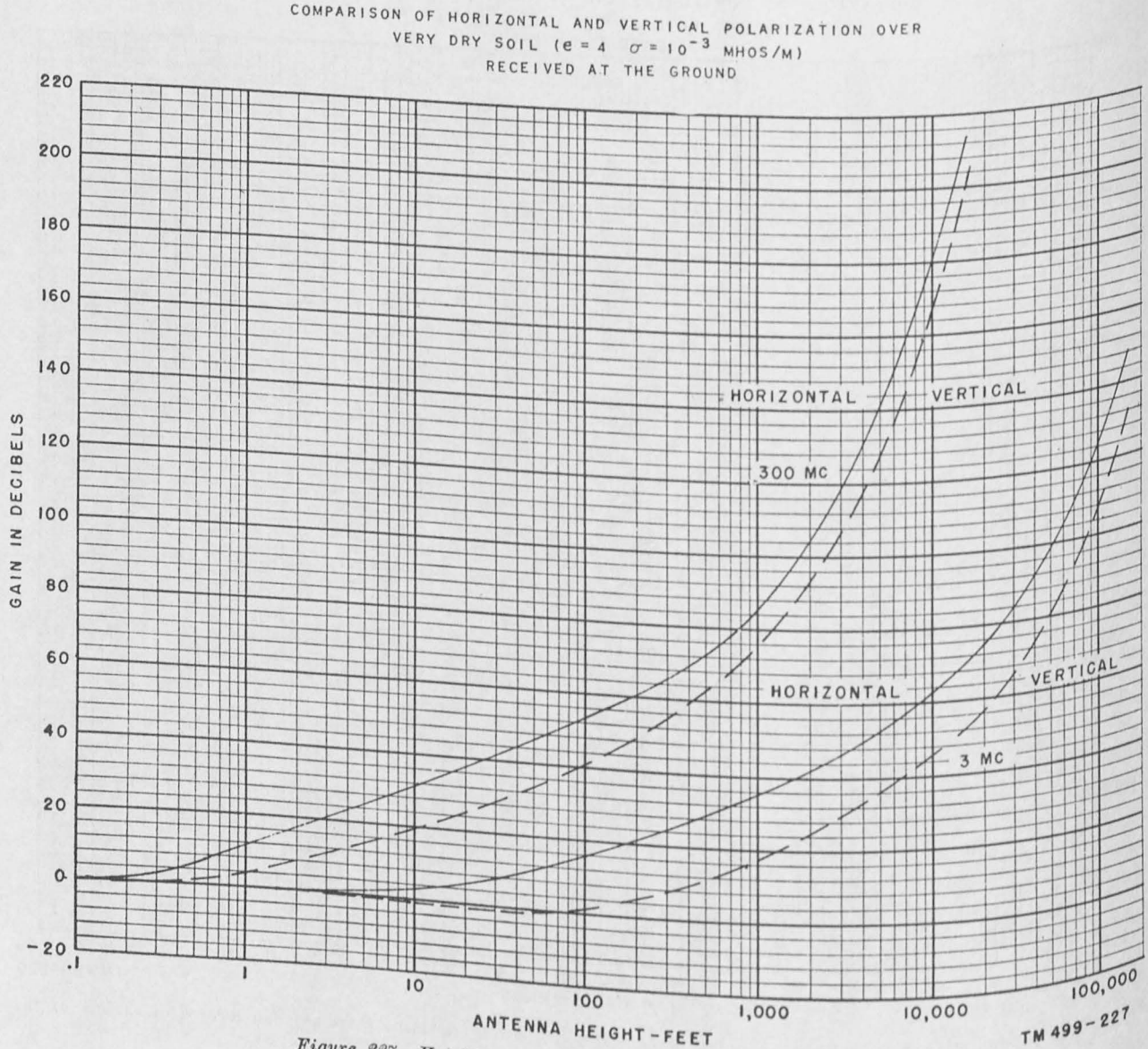


Figure 227. Height-gain factors for elevated vertical antennas.

greater than the others. In the case of an antenna erected near finitely conducting earth, only a small part of the field near the ground can be accounted for by terms that vary inversely with distance. It is necessary to account for terms that decrease inversely with distance squared ($1/r^2$). The earth attenuates the field in its neighborhood. Beyond a limiting distance, these fields decrease inversely with distance squared for cases where the curvature of the earth can be neglected. Ground-wave fields decrease more rapidly than inversely with distance squared at points beyond the horizon due to the curvature of the earth. The fields generated by the horizontal dipole antenna are attenuated at a greater rate than for a vertical dipole. In the case of a horizontal transmitting antenna, there is vertically polarized radiation in the direction of the wire. This vertically polarized ground wave is greater than the horizontally polarized ground wave at a distance from the antenna, the field component being greater in the direction of the antenna than in the direction at right angles to the antenna where the field is horizontally polarized. Figure 226 compares the ground-wave field intensities for both vertical and horizontal polarization over very dry earth for grounded antennas, and figure 227 compares the height-gain factors of elevated antennas over very dry earth for vertical and horizontal polarization.

b. The fields produced at various distances along the ground by ground-based antennas customarily are given by twice the field intensity expected in free space multiplied by an attenuation factor. The multiplying factor of 2 appears, due to the image effect of the earth. The field at the ground for a ground-based antenna is given by the following equation:

$$E = \frac{2 E_o A}{r}$$

where E_o is the field in free space at a unit distance;

r is the transmission distance; and

A is the attenuation factor.

The inverse distance field should be used in the above equation for the value of twice the free space field ($2 E_o$). The inverse distance field intensity is the field intensity that a transmitting antenna with a standard power input would produce at a standard distance in the required direction if no losses were present in the transmission path. For ground-wave radiation from a ground based antenna, it is the field intensity the antenna will produce in the ground plane at a standard distance over perfect (lossless) earth. The inverse distance value does not equal twice the free space value since the radiation resistance of an antenna is changed when it is placed near the vicinity of the earth. (The power per unit area radiated from a short, vertical dipole antenna is doubled when it is placed above perfect earth, since the energy is radiated into half the space. The image effect of the earth doubles the fields but the radiation resistance increases by a factor of 2. The field intensity increases by a factor of $\sqrt{2}$ instead of 2 as would be indicated by the image effect alone.) In the case of vertical polarization, antennas radiate perfect earth values for points very near the antenna.

c. The ground-wave field intensity curves are based on an inverse distance field intensity of 300 millivolts per meter at 1 km (186.3 millivolts per meter at 1 mile). This is the field that a short, lossless, vertical antenna with 1 km power produces over perfect earth at the standard distance in the ground plane. The ground-wave field intensity can be obtained in this manual for any vertically polarized antenna for which the inverse distance field intensity is known. The ground-wave field intensity is that for the short dipole multiplied by the ratio of the field intensity of the antenna used to that of the short dipole. The inverse distance field intensities in this manual are adjusted for heating losses. Since no antenna radiates all the power delivered to it, the values are multiplied by efficiency factors to account for these losses. In chapter 2, it was pointed out that the radiation resistance of an antenna is the resistance value such that, if it were substituted for the antenna, it would consume the same amount of power as actually is radiated. The heating losses in the antenna ground system can be represented similarly by a loss resistance. The smaller the loss resistance, when compared to the radiation resistance of the antenna, the greater the efficiency. The antenna ground system loss varies with the type of earth over which the antenna is erected. These losses can be reduced by using suitable grounding systems. For most Army applications, a counterpoise ground with radially directed ground wires, equal to or greater than the antenna heights, is recommended. Figures 246–249 give the inverse distance intensities for various ground-based vertical and inverted L antennas in gains with respect to the short dipole both in numbers and in decibels.

d. The ground-wave field intensities for elevated

are given for distances greater than certain distance limitations determined by the line of sight distance and the electrical heights of the antennas. The vertically polarized ground-wave field intensity for antennas fulfilling these limitations is given by the following equation:

$$E = \frac{2 E_o A F_{h1} F_{h2}}{r}$$

where $2E_o$ is the inverse distance field at a unit distance;

r is the transmission distance;

F_{h1} is the height gain factor for the transmitting antenna;

F_{h2} is the height gain factor for the receiving antenna; and

A is the attenuation factor.

The inverse distance field intensity to be used in the equation is the field that the antenna would produce at a standard distance over perfect earth adjusted by an efficiency factor. The inverse distance field intensities shown in figure 250 are for a vertical half-wave antenna at various heights above earth based on the perfect earth radiation resistance. If the vertical half-wave antenna is placed at the ground, the inverse distance field intensity in the ground plane is 236.3 millivolts per meter at 1 mile. The inverse distance field intensity at heights greater than one-half wavelength is approximately twice the field intensity that the antenna would produce in free space. For antennas elevated by more than one wavelength, twice the free space field intensity at standard distance can be used as an inverse distance field intensity. The inverse distance field intensity for antennas other than a half-wave antenna can be obtained, provided the antenna gain is known.

97. Types of Intervening Terrain

a. The ground-wave field intensity curves (figs. 235–240) are calculated for three types of terrain. These curves are theoretical average curves that are calculated for a smooth spherical earth and do not account for variations such as buildings and high hills. The effects of tropospheric reflections are ignored in the calculations. No account is made of the effects of cities, these effects being more noticeable in the v-h-f band. Multiple paths may arise due to reflections from the surfaces of the buildings. Multipath transmission occurs more frequently at higher frequencies since a smaller area can act as a reflector. Trees and foliage decrease the field intensities, the absorption increasing with frequency. Hills and obstructions produce shadow effects which also are more noticeable at the higher frequencies (smaller field strengths immediately behind an obstacle than at some distance beyond it). The types of ground generally encountered approximate the types given in this manual. The dielectric constant and conductivity of ground vary with the moisture content, thickness of the soil layers, and soil consistency. Ground which has a high conductivity usually also has a high dielectric constant.

b. Sea water has a conductivity of 5 and a dielectric constant of 80 in MKS units. Ground-wave propagation is better over sea water than over any type of ground. Ground with a conductivity of 10^{-2} and a dielectric constant of 15 is defined in this manual as good ground. Rich soil similar to that found in Ohio and Illinois has characteristics which approximate this. It is characterized by pastoral land having low hills and deep, rich, loamy soil. Ground having a conductivity of 10^{-3} and a dielectric constant of 5 is defined as poor ground. The ground constants in industrial areas of cities have been measured to have approximately these values. Very dry earth has these constants. Country typical of coastal areas with sandy, dry, rocky, or shallow soil has ground constants slightly higher than the poor ground values given. The majority of continental United States can be considered to be poor ground since trees and other foliage tend to increase ground-wave absorption and the ground constants should be adjusted for this. Figure 241 shows vertically polarized ground-wave field intensities in the dense New Guinea jungle. Abnormal absorption is experienced in jungle areas due to the extremely heavy foliage. The amount of attenuation is dependent on the density of foliage, and ground-wave communication is limited to a mile or so for normal transmitter powers in dense jungles when the antennas are located below the jungle growth. Ground-wave communication is improved if the antennas are elevated above the jungle growth. At times, better communication may be obtained by using horizontally polarized antennas.

c. The ground-wave field intensity curves can be used for ground with constants other than those for which the curves are drawn. Figures 260 and 261 are nomograms by which one can obtain ground-wave field intensities for surface antennas for transmission over earth with constants other than those shown in the curves. The ground-wave

...pend mainly on the conductivity ...er frequencies while mainly on the dielectric constants at higher frequencies. An equivalent operating frequency is obtained based on the particular ground constants and the ground-wave field intensities are read at the values of the equivalent operating frequency from the ground-wave curves. Figures 262 and 263 are nomograms with which the height gain factors can be determined for earth of other constants than those shown on the curves. Equivalent operating frequencies are obtained and the ground height gain curves are read at these values.

98. Limitations on Height-Gain Factors

a. As stated previously, the ground-wave field intensities for elevated antennas are obtained in this manual from the field intensities for the antennas at the earth's surface by multiplying by height-gain factors. The average level of the terrain between the transmitting and receiving antennas is taken as the surface, and the antenna heights are measured from this surface to the center of the antennas. The height-gain factors can be used only at distances sufficiently exceeding the line of sight distance or for antennas with sufficiently low electrical heights. For low frequencies, higher heights are usable than for higher frequencies. In order to determine whether the height-gain factors of figures 253–255 can be used, it first is necessary to see whether the transmission distance is greater than a spherical earth limiting distance. The limiting distance is equal to the line of sight distance plus an additional factor accounting for the bending of radio waves around the earth. Written in the form of an equation—

$$d_m = d_e + d_a$$

where d_m is the spherical earth limiting distance;
d_e is the line of sight distance from nomograms (figs. 251 and 252); and
d_a is an auxiliary distance accounting for the bending of radio waves around the bulge of the earth as obtained from figure 256.

b. In case the transmission distance is less than the minimum distance determined by the line of sight, the height-gain factors still may be used, provided neither antenna exceeds a particular value of height given by the equation—

$$h = 2000/f^{2/3}$$

where f is the frequency in mc; and
h is the limiting height in feet.

The height-gain factors can be used when the antennas are lower than the value given in the preceding equation at distances greater than a plane earth limiting distance which is determined for the frequency range in this manual by the sum of antenna heights and a minimum distance range. Figures 257–259 can be used to obtain the plane earth minimum distance limitation; the greater of the two limiting values is the distance limit.

Section II. CALCULATION OF GROUND-WAVE FIELD INTENSITIES

99. Ground-Wave Field Intensities at the Surface of the Earth

a. The ground-wave field intensities can be directly obtained for points on the surface of the earth for ground-based antennas having an inverse distance field intensity of 300 millivolts per meter at 1 km (186.3 millivolts per meter at 1 mile) from figures 235–241. Ground-wave field intensities for any other antennas for which the inverse distance field are known can be found easily. The values of the curves are defined by the following equation:

$$E = \frac{186.3}{r}\sqrt{P}\,A$$

where E is the ground-wave field intensity in microvolts per meter as taken from the curves;
r is the transmission distance in miles;
P is the antenna input in kw; and
A is the attenuation factor included in the curves.

b. Figures 246–250 give the inverse distance field intensities of various antennas in ratios squared to the reference dipole inverse distance field intensity (antenna gains with respect to the short dipole). The field intensity produced by any antenna is given by the following equation:

$$E = \frac{2E_o}{r}\sqrt{P}\,A$$

where $2E_o$ is the inverse distance for 1 kw input

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power field intensity of the antenna used. Since the gain of the antenna is equal to $(2\ E_o/186.3)^2$, the ground-wave field intensities for any antenna can be given by the equation—

$$E = \frac{186.3}{r} \sqrt{GP}\ A$$

Thus, the ground-wave field intensity values can be obtained from the curves by multiplying by the square root of the product of the gain and the power input in kw to obtain values in microvolts per meter. Expressing this relationship in db, the field intensity is given by—

$$20 \log_{10} E = 20 \log_{10} E_c + 10 \log_{10} G + 10 \log_{10} P$$

or

$$E \text{ db} = E_c \text{ db} + P \text{ db} + G \text{ db}$$

where E is the ground-wave field intensity;

E_c is the field intensity in decibels referred to 1 microvolt per meter based on an inverse distance field intensity of 186.3 millivolt per meter at 1 mile;

P is the antenna input power in kw; and

G is the antenna gain.

Thus, the field intensity expressed in db referred to 1 microvolt per meter is equal to the sum of the field intensity value obtained from figures 235–241, the antenna gain, and the antenna input power.

100. Example of a Calculation for Ground-Wave Field Intensity at the Surface of the Earth

The ground-wave field intensity is required at the ground for the following circuit:

Transmission distance	22 miles
Wave frequency	0.5 mc
Type of intervening ground	Good
Transmitting antenna type	$\lambda/2$ vertical
Transmitting antenna input power	250 watts

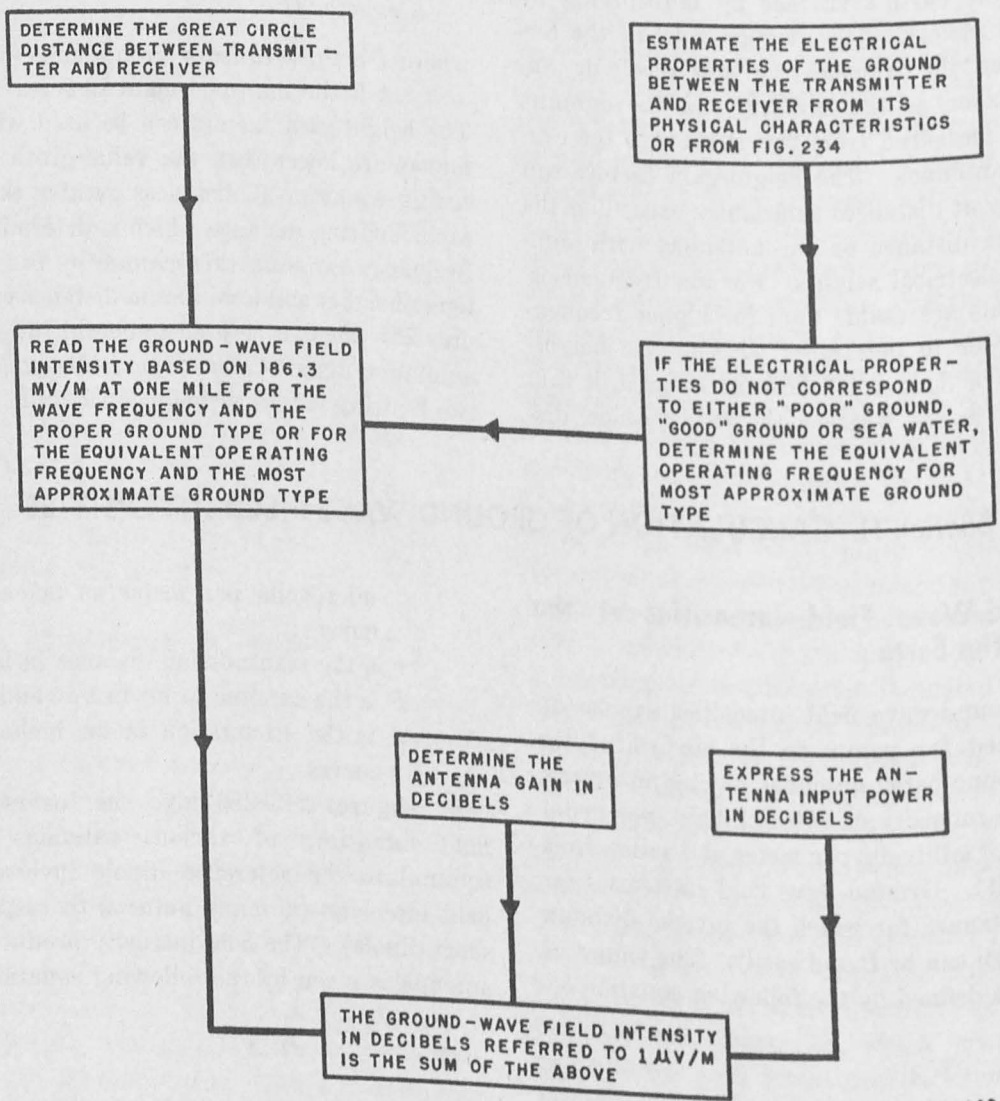


Figure 228. Flow chart for calculating ground-wave field intensities for antennas located at the surface of the earth.

a. Read the ground-wave field intensity from figure 237 (good ground) at 22 miles from the 0.5-mc curve. Ground-wave field intensity, based on an inverse distance field intensity of 186.3 millivolts per meter at 1 mile, is 76.0 db above 1 microvolt per meter. These curves can be read either in db or in microvolts per meter, but the values can be read in db much more easily and accurately.

b. Read the antenna gain for a vertical half-wave antenan from figure 246. The antenna gain expressed in db is 2 db. The power input of 250 watts expressed in db (fig. 266) is —6.0 db referred to 1 kw.

c. The ground-wave field intensity for the circuit is equal to the sum of the value from the curve (76 db), the antenna input power (—6.0 db), and the antenna gain (2 db). This field intensity is 72 db or 4 x 10^3 microvolts per meter (fig. 267).

101. Ground-Wave Field Intensities for Elevated Antennas

a. Ground-wave field intensities can be found for elevated antennas by multiplying the surface solution by height-gain factors beyond certain distance limitations. The factor can be used, provided the transmission distance is greater than either or both of two limiting distances. The height-gain factors can be used in case the transmission distance sufficiently exceeds the line of sight. This spherical earth limitation is the sum of the line of sight distance determined by the heights above earth of both the transmitting antenna and the receiving location and an auxiliary distance accounting for the bending of the radio wave around spherical earth. The line of sight distance is obtained from figure 251 or 252 by laying a straightedge at the height values and reading the line of sight distance at the center scale. The auxiliary distance is read from figure 256 for the particular type of ground and the operating frequency. The height-gain factors still can be used even though the transmission distance is less than the spherical earth limiting distance, provided neither the transmitting nor receiving antenna height exceeds a limiting height ($h = 2000/f^{2/3}$ in feet) for distances greater than the plane earth limitation. Figures 257–259 can be used to determine the plane earth limitation for good ground, poor ground, and sea water. The top horizontal scale of any of these figures indicates the maximum antenna height limitation corresponding to the frequencies on the lower horizontal scale. The figures can be entered at the point corresponding to the wave frequency and the sum of the transmitting and receiving antenna heights, and a distance limitation can be read at the left vertical scale. The minimum range can be found from the figure at the intersection of the minimum range line and the vertical line corresponding to the wave frequency. The greater of these two distance limitations is the plane earth limitation. In using these figures, it is not necessary to determine exactly the plane earth limitation. If the figures are entered at the sum of the antenna heights and the wave frequency, one immediately notes whether the distance corresponding to these values exceeds the transmission distance and also notes whether the intersection of the vertical frequency lines with the minimum range line exceeds the transmission distance. If the transmission distance exceeds either or both of the plane earth or spherical earth limiting distances, the height-gain factors can be used. In nearly all cases over sea water, the spherical earth limiting distance is less than the plane earth limiting distance.

b. In case the height-gain factors are applicable, the ground-wave field intensities for elevated antennas can be found from the product height-gain factors and the solution based on the transmitting and receiving antennas located on the ground. Figures 255, 254, and 253 give the height-gain factors over sea water, good ground, and poor ground for various heights above the ground, both in numbers and in db referred to 1. The factors for either the transmitting or receiving antennas can be read from these curves (factors for the transmitting and receiving heights are equal at equal heights). In decibels, the ground-wave field intensities for elevated antennas can be given by—

$$E_e \text{ db} = E_s \text{ db} + F_{h1} \text{ db} + F_{h2} \text{ db}$$

where E_e is the ground-wave field intensity for the antennas elevatd above the earth;
E_s is the ground-wave field intensity for the antennas at the surfaces;
F_{h1} is the height-gain factor for the transmitting antenna; and
F_{h2} is the height-gain factor for the receiving height.

102. Example of Calculation for Ground-Wave Field Intensity for Elevated Antenna

The field intensity is required at the receiving location for the following circuit:

Transmission distance	50 miles
Wave frequency	20 mc
Type of intervening ground	Good
Transmitter power	500 watts
Type of antenna	λ/2 vertical
Transmitting antenna height	100 feet
Receiving height	150 feet

a. It first is necessary to find out whether transmission distance exceeds either the spherical earth limitation, or the plane earth limitation, or both. The spherical earth limitation is equal to 91.4; the sum of 31.4 miles, the line of sight distance for the antenna heights of 150 and 100, from figure 251 and 60 miles, the auxiliary distance for good earth at 20 mc, from figure 256. The transmission distance is less than the spherical earth limiting distance, making it necessary to find out whether the transmission distance exceeds the plane earth limitation. The plane earth limitation is obtained from figure 258 for good ground. It can be noted from the upper horizontal scale that the higher of the two antennas (150 feet) is less than the height limitation for the wave frequency of 20 mc, 270 feet. A further check is required. Therefore, enter the figure at the sum of the antenna heights, 250 feet, and the wave frequency, 20 mc. It can be noted that the limitation based on the sum of the heights is 42 miles. The minimum distance range obtained from the minimum range line at the wave frequency is 1.1 miles. The plane earth limitation is the greater of these two distances, or 42 miles. Since the transmission distance is greater than the plane earth limitation and the antennas do not exceed the plane earth antenna height limitation, the height-gain factors can be used.

b. Read the height-gain factors from figure 254 for good earth on the curve for the wave frequency at the antenna heights of 100 and 150 feet. These values are 9 and 12 db, respectively.

c. Find the ground-wave field intensity for antennas at the surface, based on the inverse distance field intensity that the transmitting antenna has in its elevated position. This field intensity is obtained by reading the field intensity at 50 miles on the curve for the wave frequency of 20 mc from figure 237 and correcting for the actual antenna radiation. The figure shows that the ground-wave field intensity for an inverse distance field value is 186.3 millivolts per meter is —0.8 db. The transmitting antenna height expressed in fractions of a wavelength is shown by nomogram (fig. 265) to be at a height of 3.1 λ for the wave frequency of 20 mc and the physical height of 150 feet. The inverse distance field intensity for the half-wave transmitting antenna is equal to twice the free space value, or 275.2 millivolts per meter at 1 mile, at this height above ground. The antenna gain is 3.4 db compared to the standard field of 186.3 millivolts per meter at 1 mile. The input power of 500 watts is —3 db, expressed in decibels referred to 1 kw from figure 266. The surface solution is the sum of these values or —0.4 db.

d. Ground-wave field intensities for the elevated position now can be determined. The field intensity for the elevated solution in microvolts per meter is the surface solution multiplied by the height-gain factors. In decibels, it is equal to the sum of the surface solution and the height-gain factors. The ground-wave field intensity for the elevated antennas is equal to —0.4 db +9 db +12 db or 20.6 db above 1 microvolt per meter (11.0 microvolts per meter). Figure 267 is used to convert field intensities in db referred to 1 microvolt per meter to microvolts per meter.

103. Transmission Over Mixed Earth

a. The constants of the ground vary greatly in different locations. Figure 234 is a world map which approximately indicates the various types of terrain at different locations. The type of ground between transmission points of a ground-wave circuit may vary greatly. In the case, the ground varies in such a manner in its characteristics that no large distances are of the same type, the averages of the ground constants over the path can be taken as the constants for the circuit. The ground-wave field intensities can be obtained from figures 235–240 for various types of earth by using figure 260 or 261. These nomograms give equivalent operating frequencies at which the ground-wave field intensity curves are read to obtain the values for other ground constants. In case the ground varies in a discontinuous manner with large stretches having different characteristics such as a radio path first over land and then over sea water, the averages of the ground constants are not applicable. The method for transmission circuits of this type uses the curves corresponding to the types of ground over which the radio waves travel. As an illustration, a circuit with the first 10 miles over poor ground and the following 20 miles over sea water can be assumed. The poor ground curve is used for the first 10 miles and the sea water curve

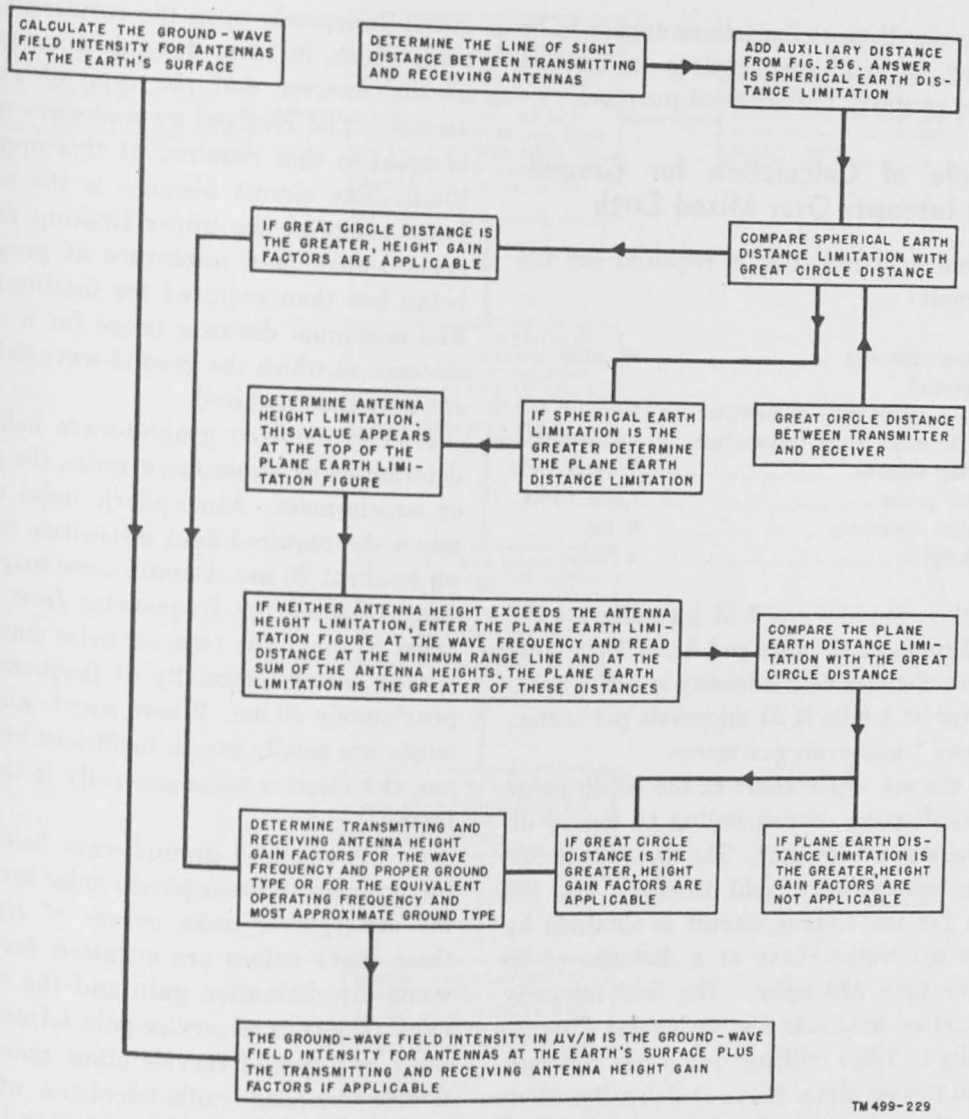


Figure 229. Flow chart for calculating ground-wave field intensities for antennas elevated above the surface of the earth.

is used for 20 miles from the distance value at which the sea water curve has the same field intensity value as the poor ground curve has at 10 miles. This is a horizontal curve sliding method. One curve is placed over another with the field intensity scales being in the same vertical positions above one another. The second curve is slid horizontally until the curves for the wave frequency meet at the distance value on the first curve where the ground type changes.

b. For elevated antennas for a mixed earth transmission path, the ground-wave field intensities are obtained by the solution of surface antennas as indicated above multiplied by height-gain factors. If the ground is of one type up to or beyond the horizon distance, the height-gain factor for the particular type of ground is used. To obtain the horizon distance for each antenna, use the nomogram (fig. 251), taking the height of the other antenna as zero feet. If more than one type of ground is included within the distance from the horizon to the antenna, determine the height-gain factor for the average of the ground constants within this distance. Figures 267 and 268 can be used to determine equivalent frequencies with which one can obtain the height-gain factors from the curves of this manual for ground constants other than those of the curves. Minimum limiting distances at which height-gain factors can be used are given in this manual for three types of earth. If the earth has other constants than these, the limiting distance can be approximated by using the values for the types of earth given. The limiting distances are less for smaller earth constants. In

case the minimum distance limitations appear to be nearly fulfilled, the height-gain factors can be used with sufficient accuracy for practical purposes.

104. Example of Calculation for Ground-Wave Field Intensity Over Mixed Earth

The received field intensity is required for the following circuit:

Transmission distance	40 miles
Type of ground	
First 15 miles from transmitter	Poor
Next 25 miles from transmitter	Sea water
Transmitting antenna	λ/4 vertical
Transmitter power	1,000 watts
Transmission frequency	5 mc
Antenna heights	0 feet

a. Read the ground-wave field intensity on the poor ground curve at 15 miles and 5 mc. This value for an inverse distance field intensity of 186.3 millivolt per meter at 1 mile is 31 microvolt per meter, or 30 db above 1 microvolt per meter.

b. Enter the sea water chart at the 30 db value and note the distance corresponding to the 30 db value for the wave frequency. The distance is 320 miles. The ground-wave field intensity for the mixed path for the 40-mile circuit is obtained by reading the sea water curve at a distance of 25 miles greater than 320 miles. The field intensity value for surface antennas for an inverse distance field intensity of 186.3 millivolt per meter at 1 mile is read from the sea water curve at 345 miles. This value is 26 db.

c. The received field intensity for the circuit is obtained from the above value by correcting for the transmitting antenna radiation. The transmitting antenna input power in db referred to 1 kw is 0 db and the antenna gain is 0 db. Thus, the received field intensity is 26 db, the sum of the ground-wave field intensity for an inverse distance field intensity of 186.3 millivolt per meter at 1 mile, the antenna gain, and the antenna input power.

105. Maximum Distance Range

a. It has been mentioned previously that, at considerable distances, there is an upper limiting frequency for ground-wave propagation, since the ground-wave field intensity decreases with increasing frequency. This upper limiting frequency is determined by the signal strength required for satisfactory communication. The required signal strength depends upon the required signal-to-noise ratio which, in turn, depends upon the noise level at the receiver and the type of communication service. The received ground-wave field intensity is equal to that required at this upper frequency limit. The circuit distance is the maximum distance range at the upper limiting frequency, the ground-wave field intensities at greater distances being less than required for intelligible reception. The maximum distance range for a circuit is that distance at which the ground-wave field intensity is equal to that required.

b. The required ground-wave field intensity is determined by atmospheric noise, the receiver noise, or cosmic noise. Atmospheric noise usually determines the required field intensities for frequencies up to about 20 mc. Cosmic noise may be the determining factor for frequencies from 20 mc up to about 50 mc. The receiver noise may be the determining factor, especially at frequencies above approximately 40 mc. Where cosmic and atmospheric noises are small, due to inefficient receiving antennas, the receiver noise generally is the determining factor.

c. The required ground-wave field intensities in the presence of atmospheric noise are obtaind from the atmospheric noise curves of chapter 3 after these curve values are adjusted for receiving antenna discrimination gain and the type of service gain. The type of service gain adjustment is necessary for types of service other than speech grade double sideband radio-telephone of a 6-kc total bandwidth. The discrimination gain is added to account for the improvement in signal-to-noise ratio due to the receiving antenna. Figure 242 can be used to find the discrimination gains for various ground-based vertical polarized receiving antennas. Figure 245 can be used to find the type of service gain (the relative signal strengths in reference to the base type of communication service). Fading adjustments are not included in this table since it is assumed that the minute-to-minute variation in ground-wave field intensities are not excessive.

d. The cosmic noise may be the determining factor on the required field intensity on frequencies between 20 and 50 mc. The extent of knowledge about the required intensities in the presence of cosmic noise is limited at the present time. Figure 244 shows approximately the required field intensities in the presence of cosmic noise for an antenna with the directivity of half-wave antenna. The user may or may not wish to use this curve which is

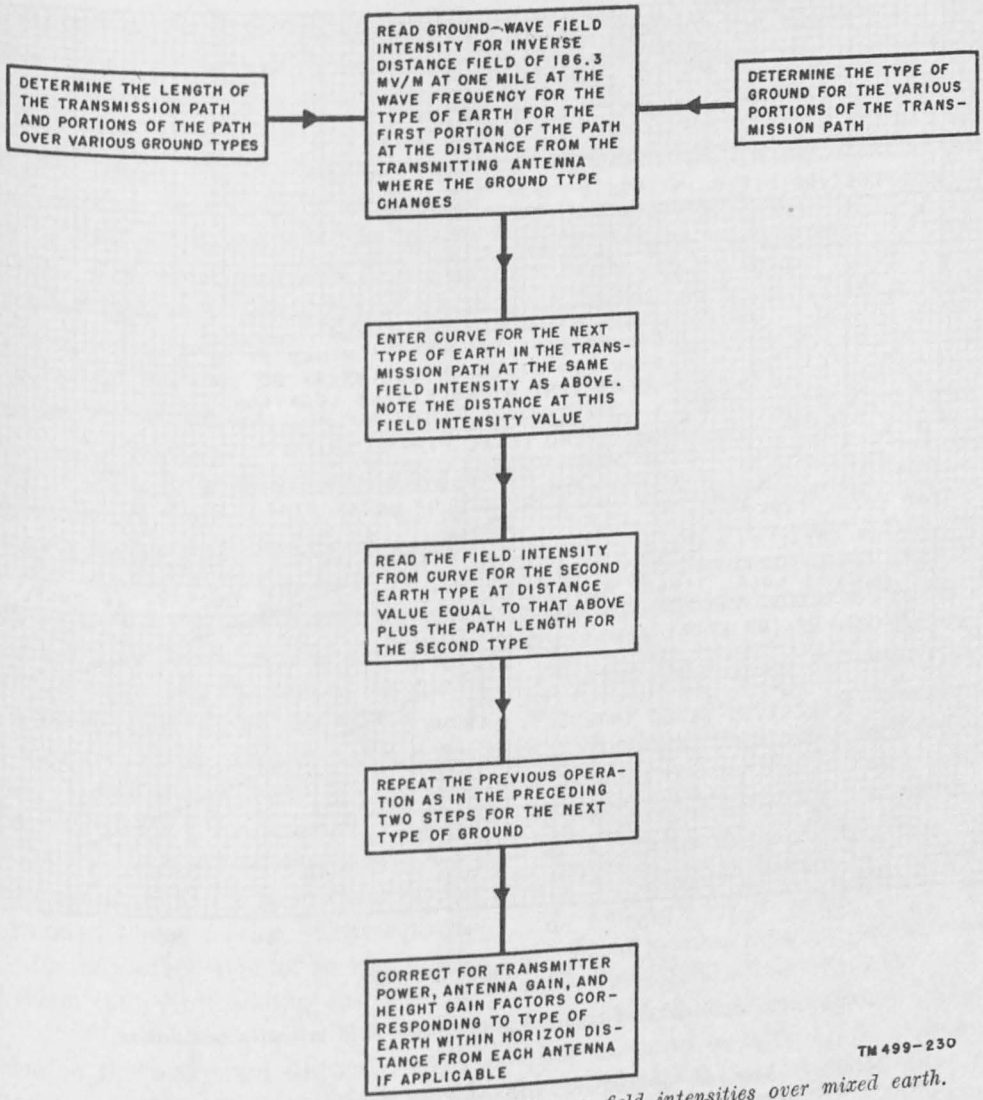


Figure 230. Flow chart for calculating ground-wave field intensities over mixed earth.

drawn for speech grade radiotelephony with a receiver bandwidth of 6 kc. The required field intensity for reception with a half-wave antenna in the presence of cosmic noise is the value from the curve to which is added the type of service gain.

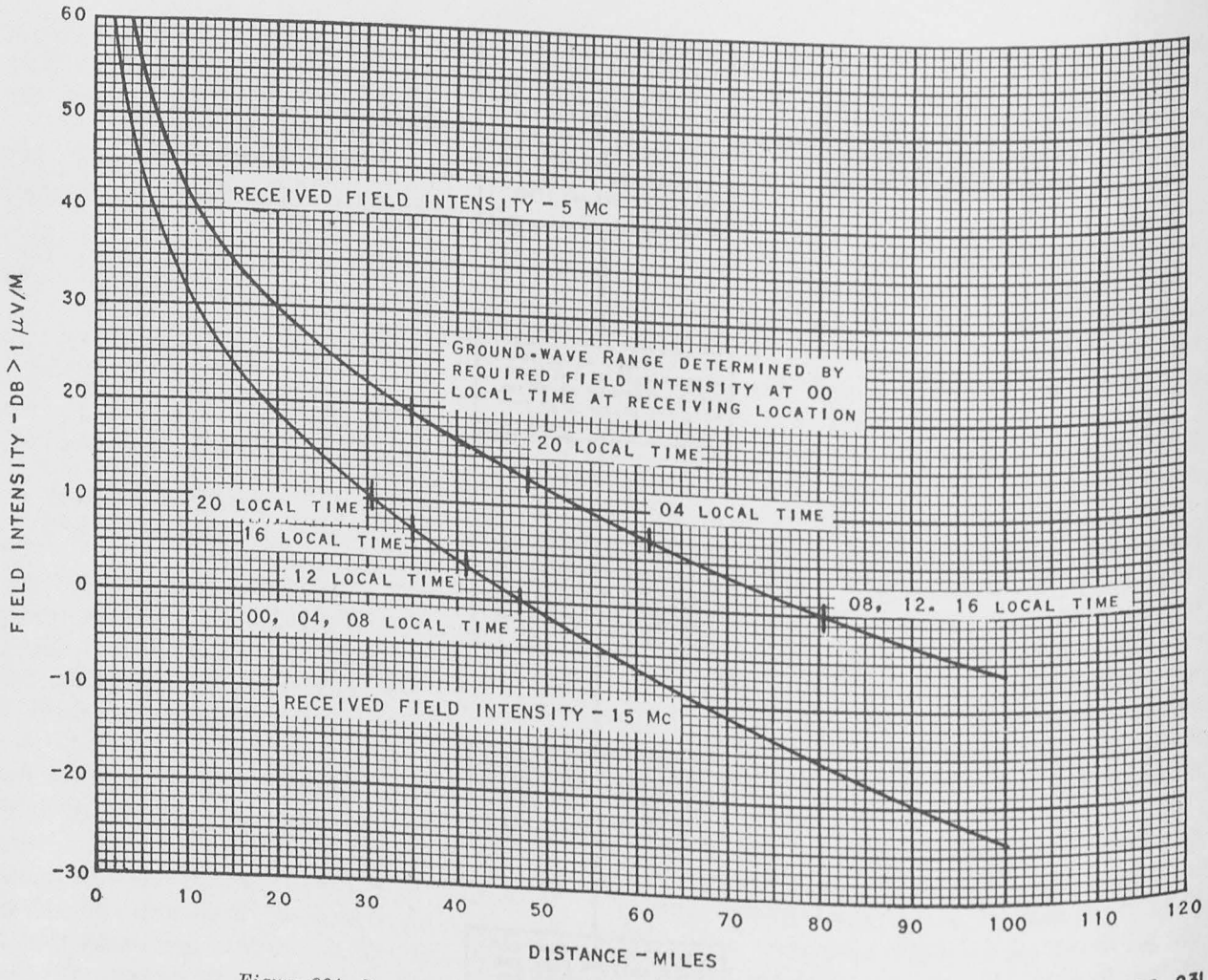
e. The required field intensity in the presence of receiver noise can be obtained from figure 244 for frequencies from 20 to 300 mc. This figure shows the required field intensities for a rms signal carrier-to-rms noise ratio of 15 db (speech grade double sideband radiotelephony) for a receiver bandwidth of 6 kc. This curve is based on a half-wave receiving antenna sufficiently elevated above the surface of the earth. The effective noise figure (ch. 2) can be written as—

$$F' = \frac{F}{L}(EN - 1) \qquad \text{(Eq 43)}$$

where F' is the effective noise figure of the system;
F is the noise figure of the receiver;
L is the attenuation loss of the transmission line; and
EN is the external noise figure,

$$\frac{\text{available noise power from the antenna.}}{\text{ideal available noise input power}}$$

It can be seen from the above that the effective noise figure for a receiving system depends on the receiver noise figure, the transmission line losses, and the external noise figure. At high frequencies, it can be assumed that the external noise figure is approximately one and the effective noise figure of the receiving system is dependent mainly on the receiver noise figure and the losses. The noise figure of a receiver depends largely on the receiver design. At frequencies below about 30 mc, noise figures of the order of 3 db may be obtained by using a stage of tuned r-f amplification with a triode tube. Pentode amplifier tubes often are satisfactory since



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Figure 231. Received and required ground-wave field intensity calculation.

Table X. Received and Required Ground-Wave Field Intensity Calculations.

	GROUND-WAVE RECEIVED FIELD INTENSITY					GROUND-WAVE REQUIRED FIELD INTENSITY							
	DISTANCE IN MILES	FIELD INTENSITY FIG. 235	TRANSMITTER ANT. GAIN FIG. 250	2 KW INPUT POWER IN DB > 1 μV/M	RECEIVED FIELD INTENSITY (2) + (3) + (4)	LOCAL TIME AT REGG LOCATION	REQ FIELD INT TO OVERCOME ATMOS NOISE	REGG ANTENNA DISC GAIN FIG. 242	(7) - (8)	REQ FIELD INT TO OVERCOME SET NOISE FIG. 242	LARGER OF (9) OR (10)	TYPE OF SERVICE GAIN FIG. 245	RECEIVED FIELD INTENSITY (11) + (12)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
5 Mc	5	49.7	2.1	3.0	54.8	00	24.7	5.4	19.3	-0.4	19.3	0	19.3
	10	37.2	2.1	3.0	42.3	04	12.0	5.4	6.6	-0.4	6.6	0	6.6
	20	24.8	2.1	3.0	29.9	08	0	5.4	-5.4	-0.4	-0.4	0	-0.4
	50	6.5	2.1	3.0	11.6	12	-4.1	5.4	-9.5	-0.4	-0.4	0	-0.4
	70	-1.5	2.1	3.0	3.6	16	4.4	5.4	-1.0	-0.4	-0.4	0	-0.4
	100	-11.3	2.1	3.0	-6.2	20	18.2	5.4	12.8	-0.4	12.8	0	12.8
15 Mc	5	39.0	2.1	3.0	44.1	00	-2.0	5.1	-7.1	-0.1	-0.1	0	-0.1
	10	26.8	2.1	3.0	31.9	04	-17.7	5.1	-22.8	-0.1	-0.1	0	-0.1
	20	13.8	2.1	3.0	18.9	08	3.4	5.1	-1.7	-0.1	-0.1	0	-0.1
	50	-6.5	2.1	3.0	-1.4	12	8.6	5.1	3.5	-0.1	3.5	0	3.5
	70	-16.0	2.1	3.0	-10.9	16	12.6	5.1	7.5	-0.1	7.5	0	7.5
	100	-28.5	2.1	3.0	-23.4	20	15.1	5.1	10.0	-0.1	10.0	0	10.0

TABLE X

the noise introduced by them does not greatly exceed that of a triode. Practical radio receivers generally are not designed to have low noise figures for low frequencies since the externally induced noises are large. At frequencies greater than 30 mc, a low noise figure may be obtained by using tuned r-f amplification, and low noise mixing stages. The noise figure increases with frequency and, for the higher frequencies, no improvement is obtained by using r-f amplification. The user of this manual generally will not know the effective noise figure to use with figure 244. An assumption can be made that the effective noise figure is approximately 10 db. This value would correspond to a relatively good receiver and account for some externally induced noise in addition to transmission line losses. The required field intensity for frequencies from 20 to 300 mc is obtained for half-wave receiving antennas several wavelengths above the surface of the earth from the sum of the curve value for the effective noise figure and the type of service gain. For frequencies less than 30 mc, figure 242 shows the ground-wave field intensity required to overcome receiver noise for an average receiver, for various ground-based vertically polarized receiving antennas, and for speech grade double sideband radiotelephone service. The required field intensity for any other type of service is obtained from these values by adding the type of service gain.

f. To determine the maximum distance range, plot the ground-wave field intensity against a distance corresponding to the wave frequency. These field intensities are drawn for the type of the transmission path and account for the transmitting antenna radiation and the height-gain factors for the transmitting and the receiving antennas. The required field intensity for the circuit then is obtained from the atmospheric noise curves, the receiver noise curves, and the cosmic noise curve (if the user desires to use an approximation of its effects). The atmospheric noise curve is read at the desired hour and wave frequency. To this is added the receiving antenna discrimination gain with its sign changed and the type of service gain to obtain the required ground-wave field intensity in the presence of atmospheric noise. The required ground-wave field intensity is the higher of the receiver and atmospheric noise limitations. The maximum distance range is the distance where the received ground-wave field intensity is equal to the required field intensity.

106. Example of Calculation for Maximum Distance Range

The maximum distance range is required for the following transmission conditions:

Transmitting antenna	Half-wave vertical
Transmitter input power	2 kw
Frequency	5 and 15 mc
Receiving antenna	15-foot whip
Receiving location	40° north, noise grade 2.5
Type of service	Radiotelephone
Time	Month of June
Type of ground	Poor

a. Ground-wave intensities are plotted in db above 1 microvolt per meter against distance, using figure 235 corresponding to poor ground. The groundwave field intensity values for each distance are the sum of the values from the curve, the transmitting antenna gain, and the transmitter input power, all of these being expressed in db. Columns 1–5 of table X show the calculations. Since the antennas are at the surface, no height-gain factors are required. The ground-wave field intensities are plotted against distance for the wave frequencies of 5 and 15 mc on figure 231.

b. The required ground-wave field intensities for satisfactory communication are obtained for 0000, 0400, 0800, 1200, 1600 and 2000 local time at the receiving location for the noise grade of 2.5 for June as shown in table X. The atmospheric noise curve (fig. 155) for June and noise grade 2.5 is read at various hours of the day for frequencies of 5 and 15 mc. The discrimination gain from figure 242, corresponding to the 15-foot whip receiving antenna, is subtracted from these values. The required ground-wave field intensity to overcome receiver noise is obtained from figure 243 for the two frequencies. The required ground-wave field intensity (for the reference type of service) is the greater of the two values for atmospheric and receiver noise. For any other type of service, the type of service gain is added. In this example, the type of service gain is 0 db. The required ground-wave field intensity is given in column 13 in table X for the various hours of the day.

c. Figure 232 shows maximum distance ranges for ground waves plotted against various hours of the day for 5 and 15 mc. These values are obtained from figure 231 by plotting the distances where the ground-wave field intensity is equal to that value required at the various hours of the day.

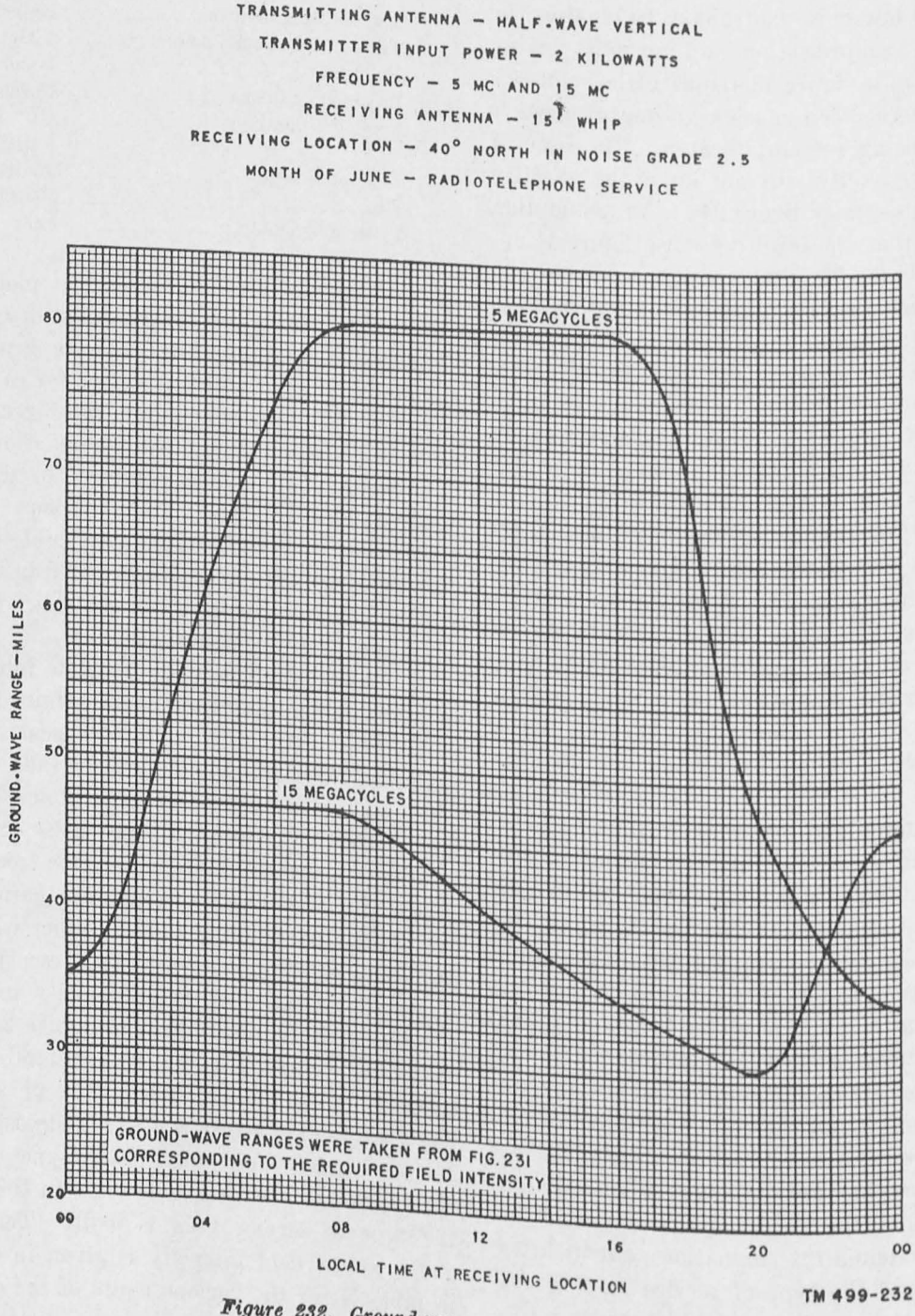


Figure 232. Ground-wave range—sample problem.

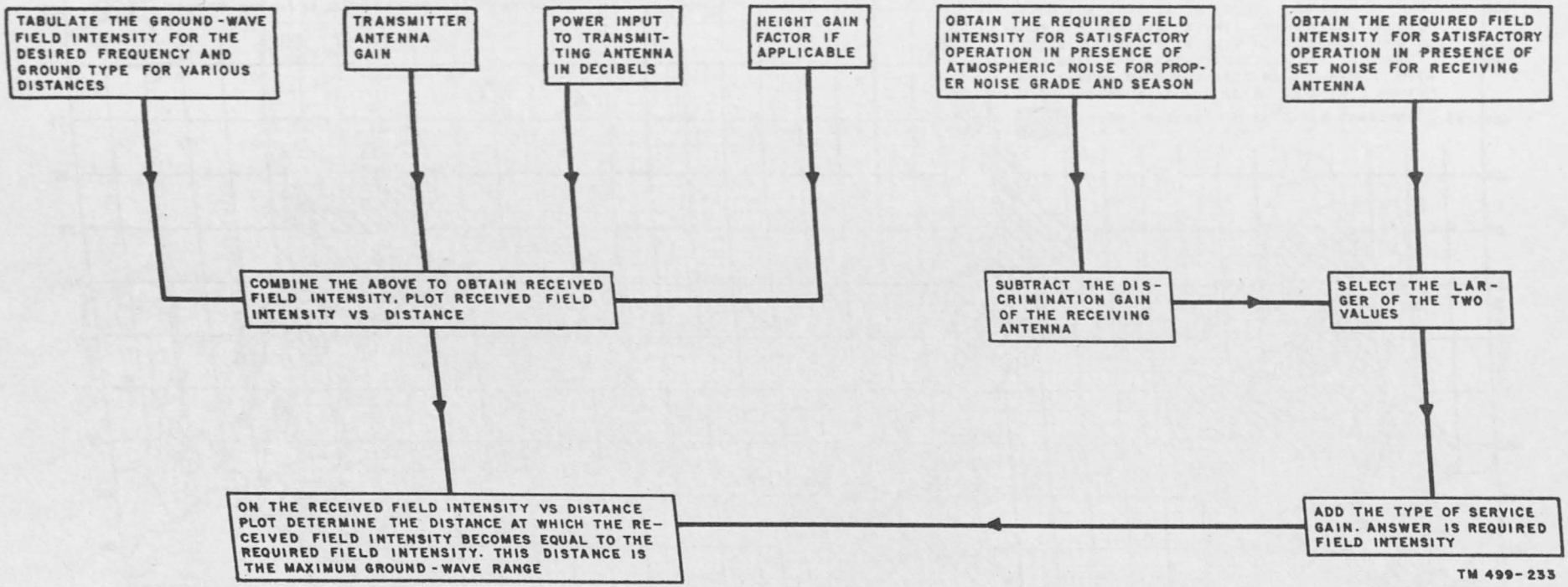


Figure 233. Flow chart—maximum ground-wave range.

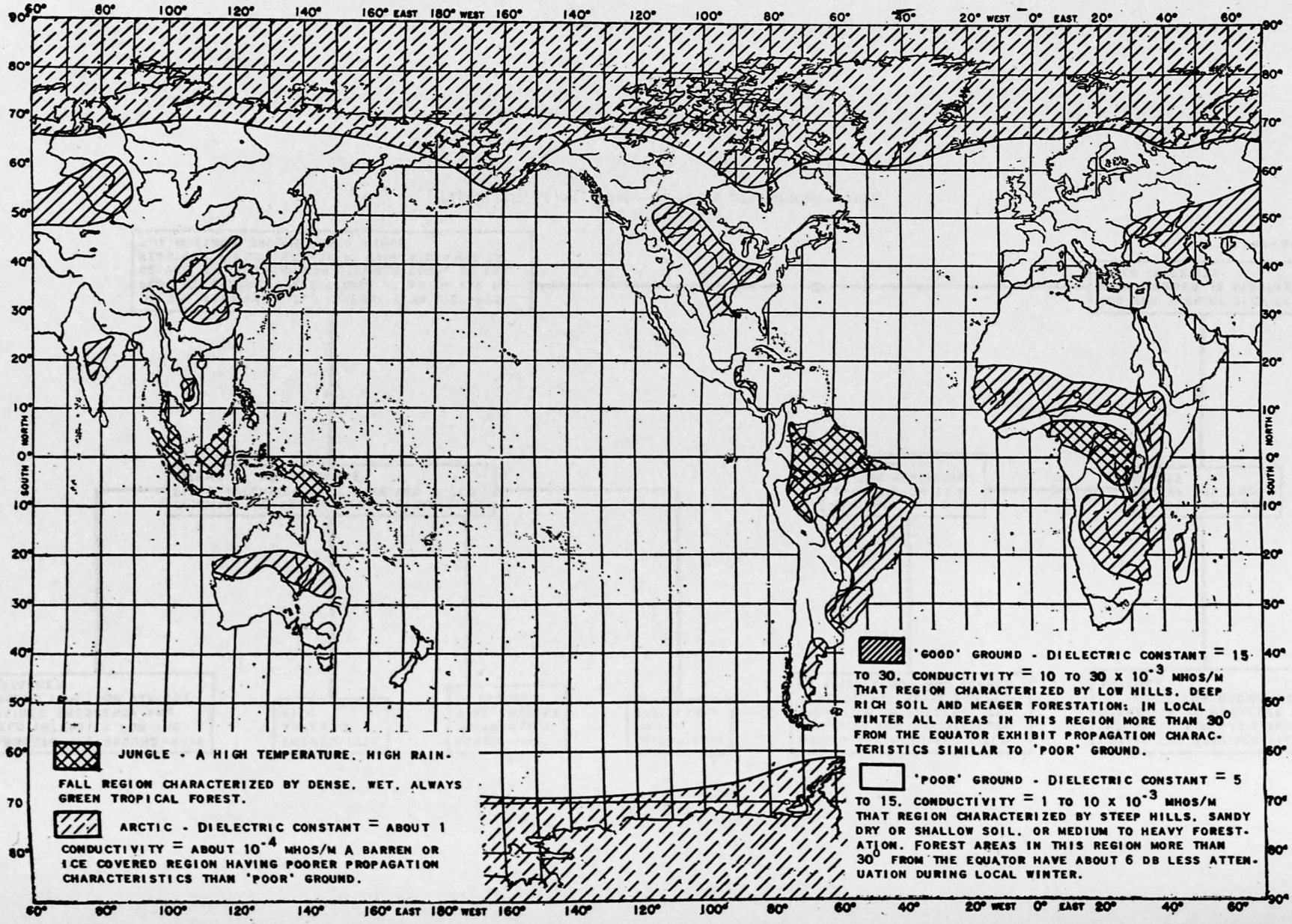


Figure 234. World map showing various types of terrain.

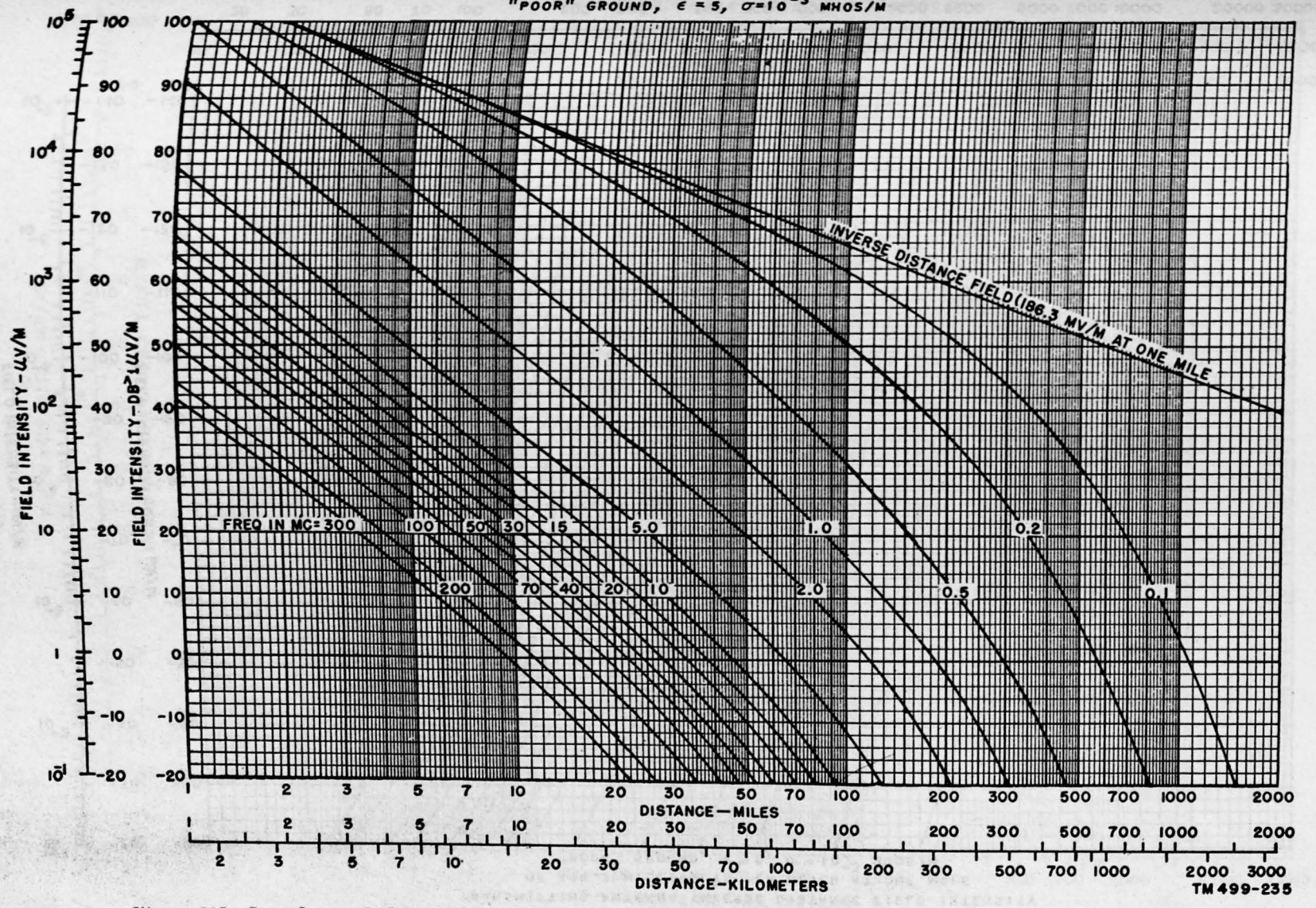


Figure 235. Ground-wave field intensity versus distance curves for various frequencies in mc, for vertical polarization, 1–2,000 miles—poor ground.

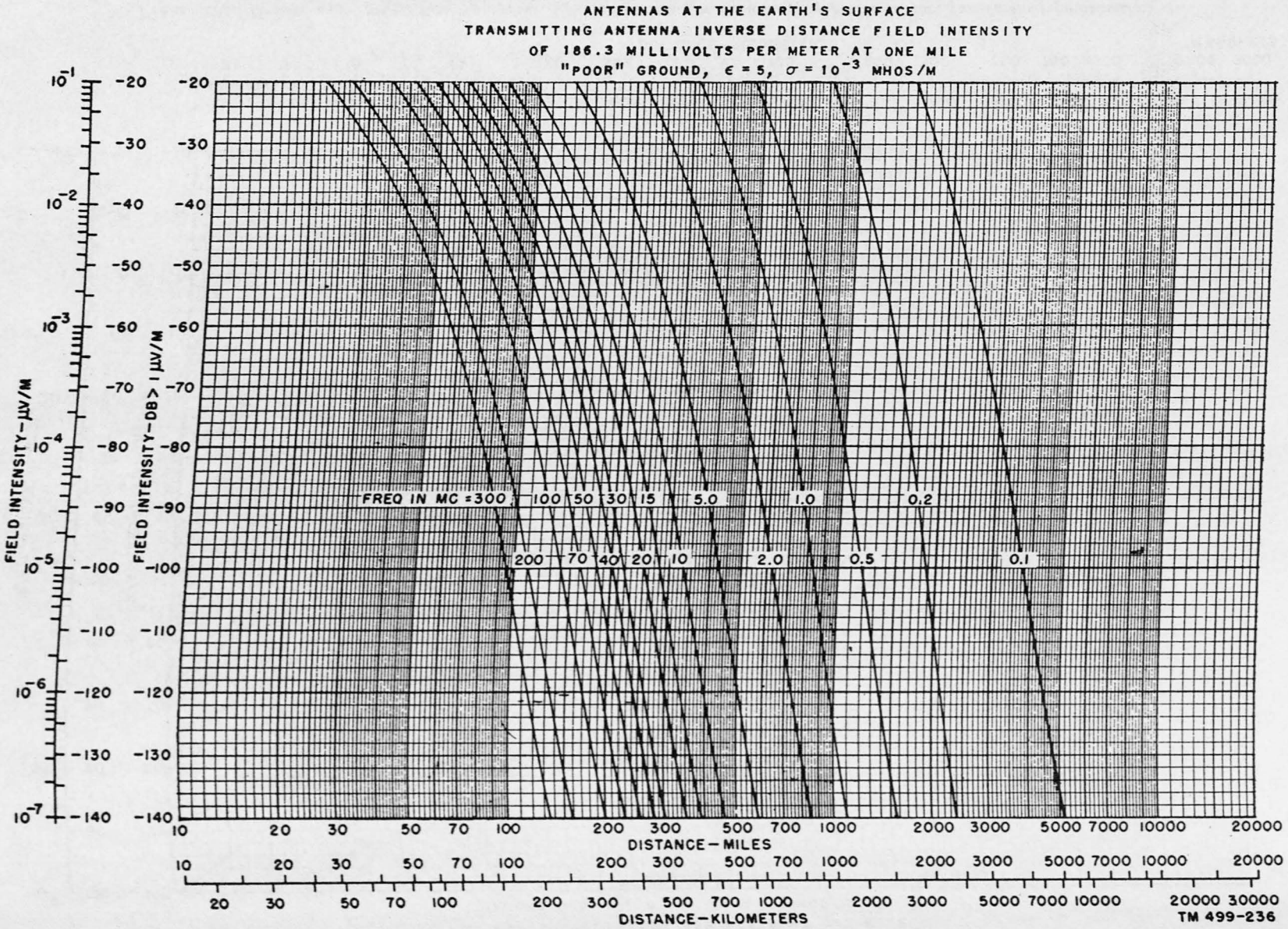


Figure 236. Ground-wave field intensity versus distance curves for various frequencies in mc, for vertical polarization, 10–20,000 miles—poor ground.

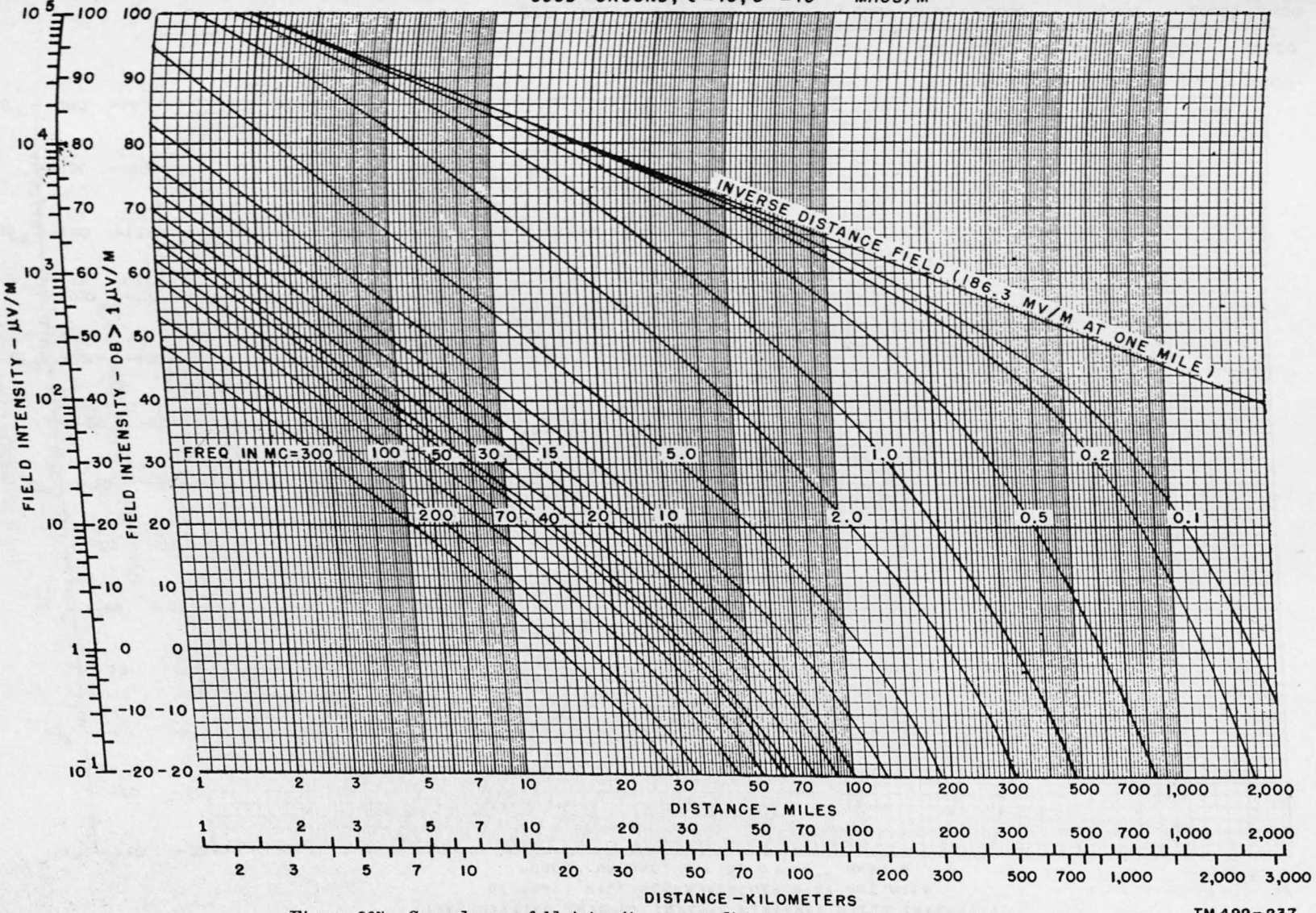


Figure 237. Ground-wave field intensity versus distance curves for various frequencies in mc, for vertical polarization, 1–2,000 miles—good ground.

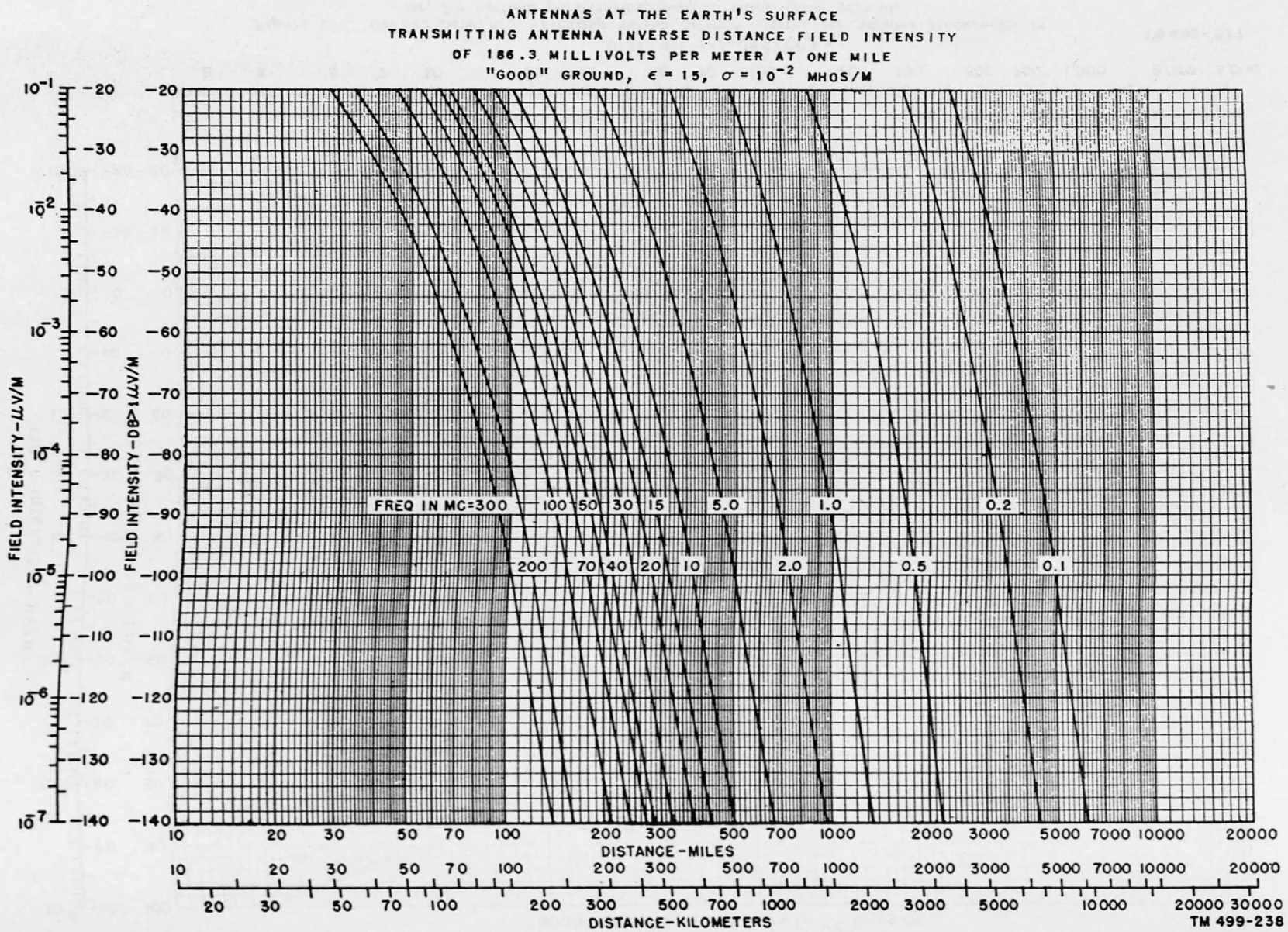


Figure 238. Ground-wave field intensity versus distance curves for various frequencies in mc, for vertical polarization, 10–20,000 miles—good ground.

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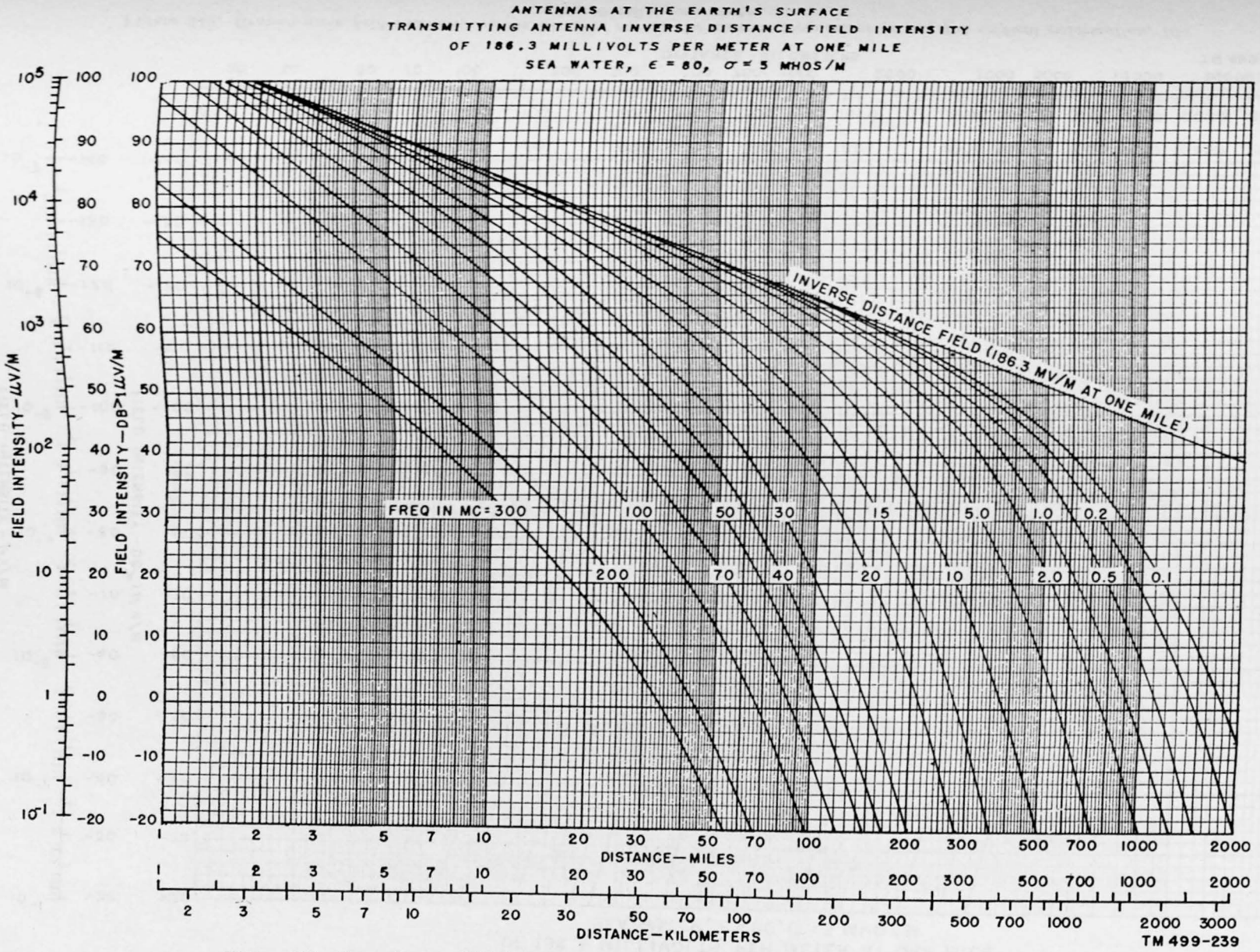


Figure 239. Ground-wave field intensity versus distance curves for various frequencies in mc, for vertical polarization, 1–2,000 miles—sea water.

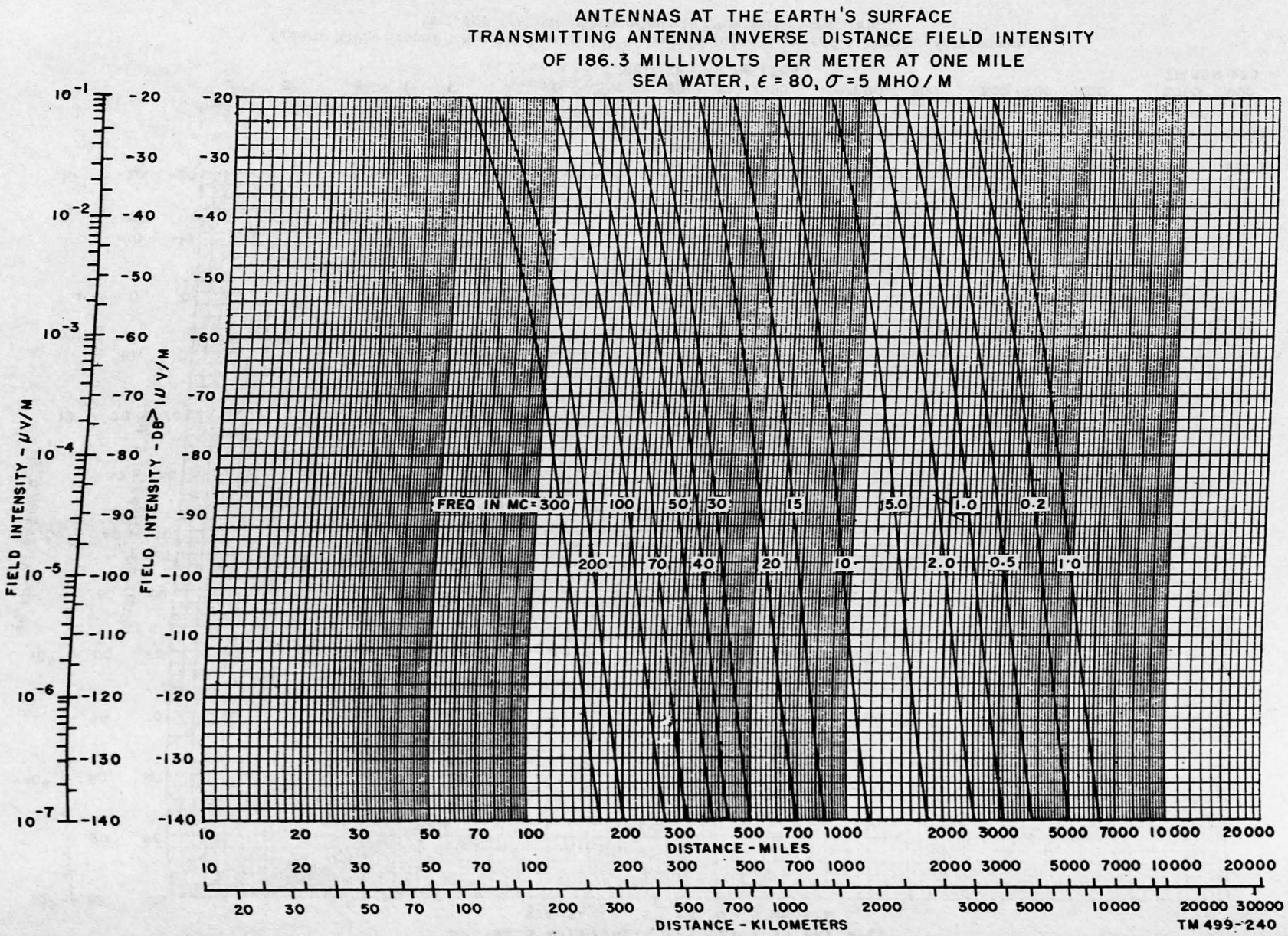


Figure 240. Ground-wave field intensity versus distance curves for various frequencies in mc, for vertical polarization, 10–20,000 miles—sea water.

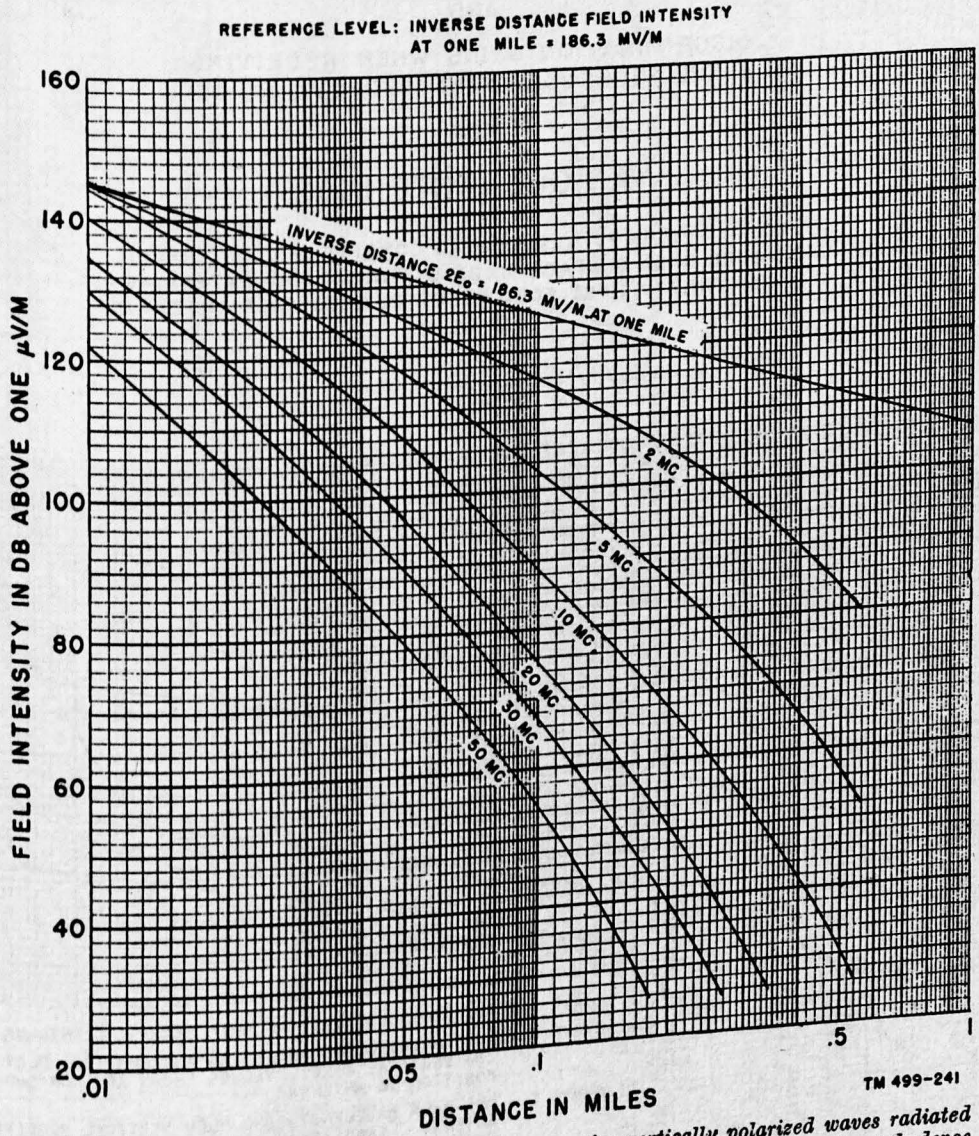


Figure 241. Ground-wave field intensity versus distance for vertically polarized waves radiated from antenna located on the surface of the earth at various frequencies in mc through dense jungle.

MINIMUM REQUIRED GROUND-WAVE FIELD INTENSITY
(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

VARIOUS ANTENNAS

GROUND SYSTEM IS ASSUMED TO CONSIST OF COUNTERPOISE OR BURIED OR SURFACE RADIAL WIRES EACH EXTENDING IN LENGTH AT LEAST EQUIVALENT TO HEIGHT OF ANTENNA

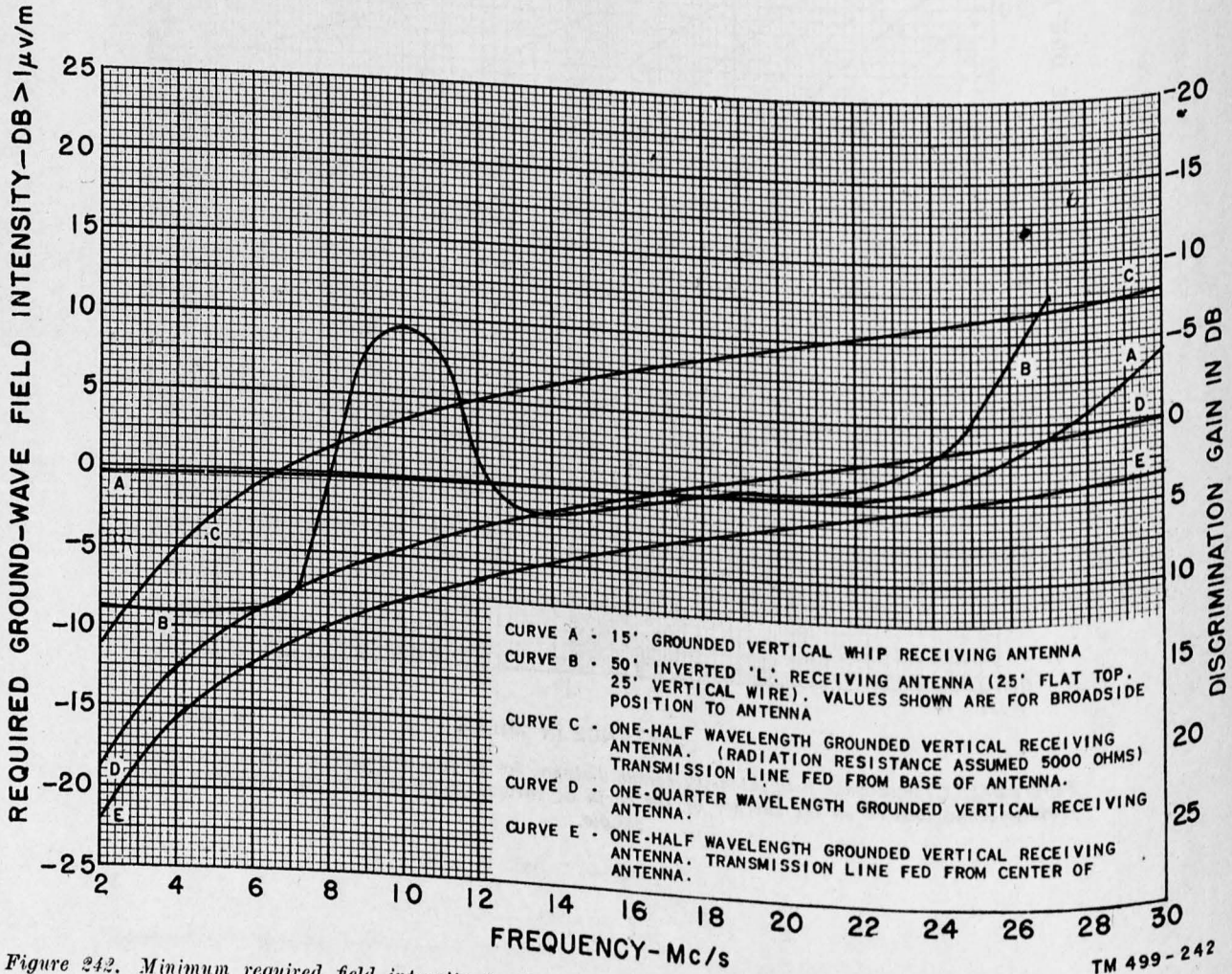


Figure 242. Minimum required field intensity in the presence of set noise, and discrimination gains in the presence of atmospheric noise, for various antennas.

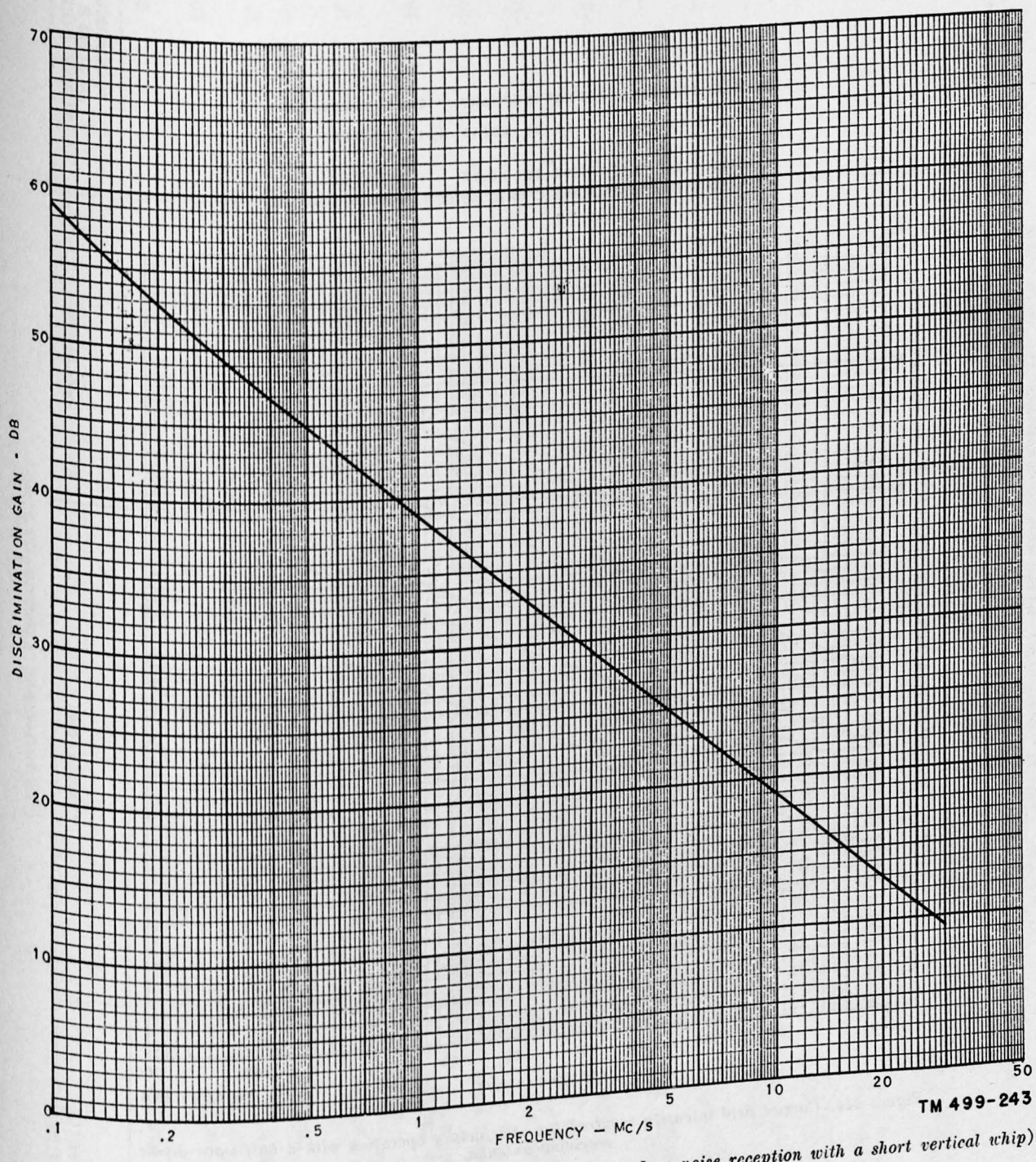


Figure 243. Discrimination gain of a half-wave dipole in free space (based on noise reception with a short vertical whip).

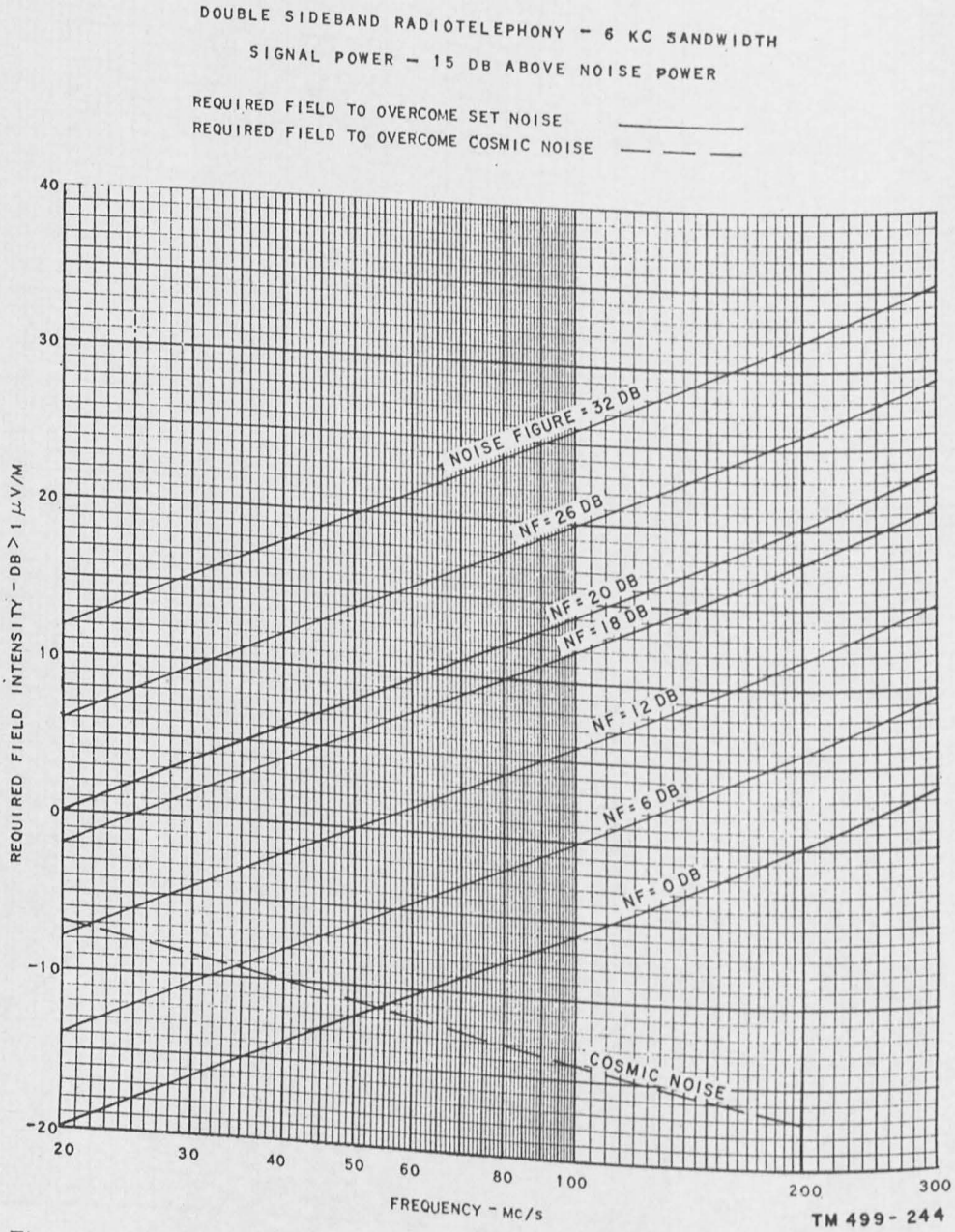


Figure 244. Carrier field intensity required for satisfactory operation with a half-wave dipole receiving antenna.

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

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Figure 245. Table of service gains, ground-wave communication, nonfading signal.

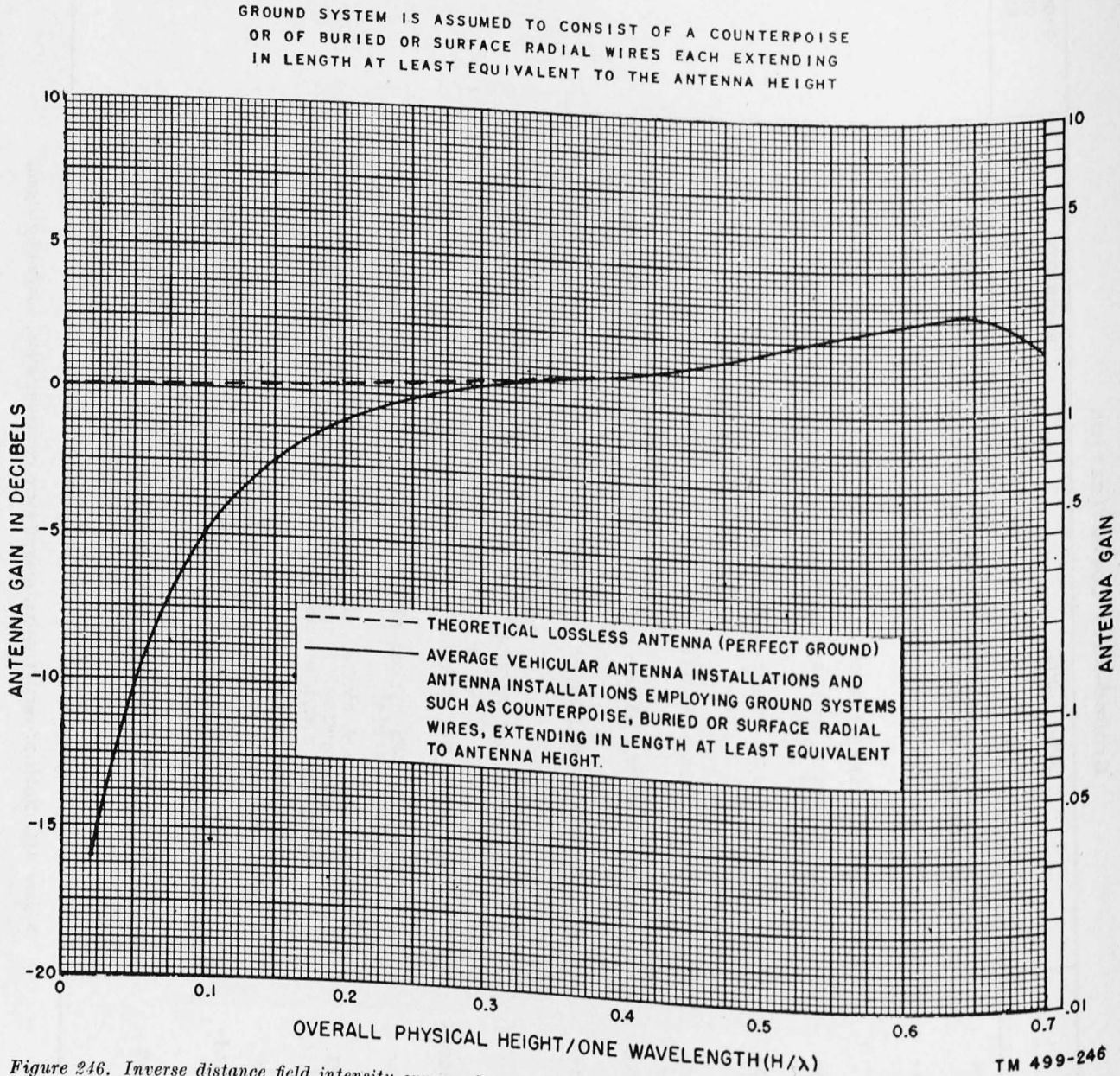


Figure 246. Inverse distance field intensity expressed as an anntenna gain in respect to 186.3 millivolts per meter at 1 mile, grounded vertical antenna.

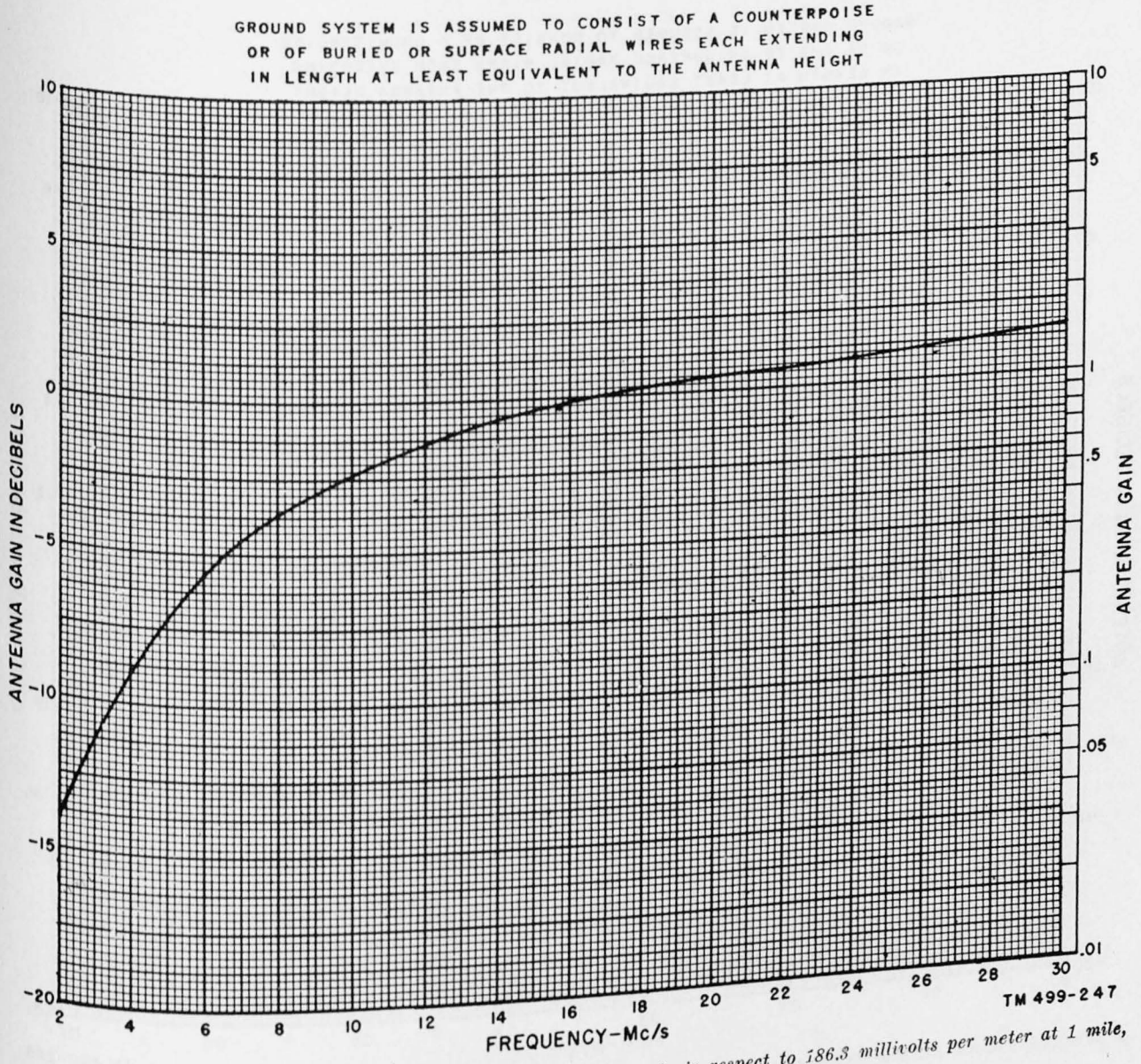


Figure 247. Inverse distance field intensity expressed as an antenna gain in respect to 186.3 millivolts per meter at 1 mile, 15-foot vertical whip antenna.

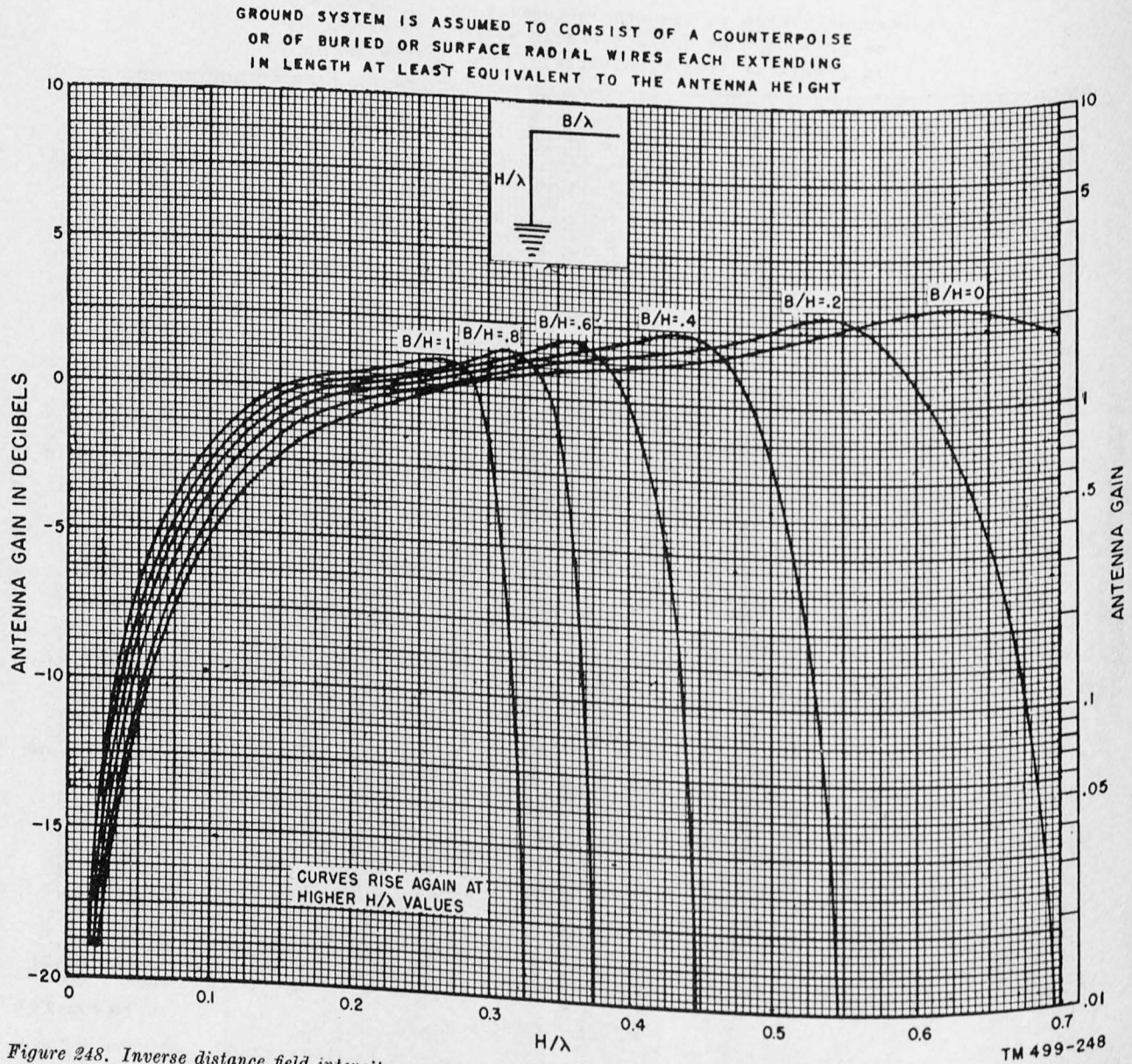


Figure 248. Inverse distance field intensity expressed as an antenna gain in respect to 186.3 millivolts per meter at 1 mile, top loaded ground vertical antenna.

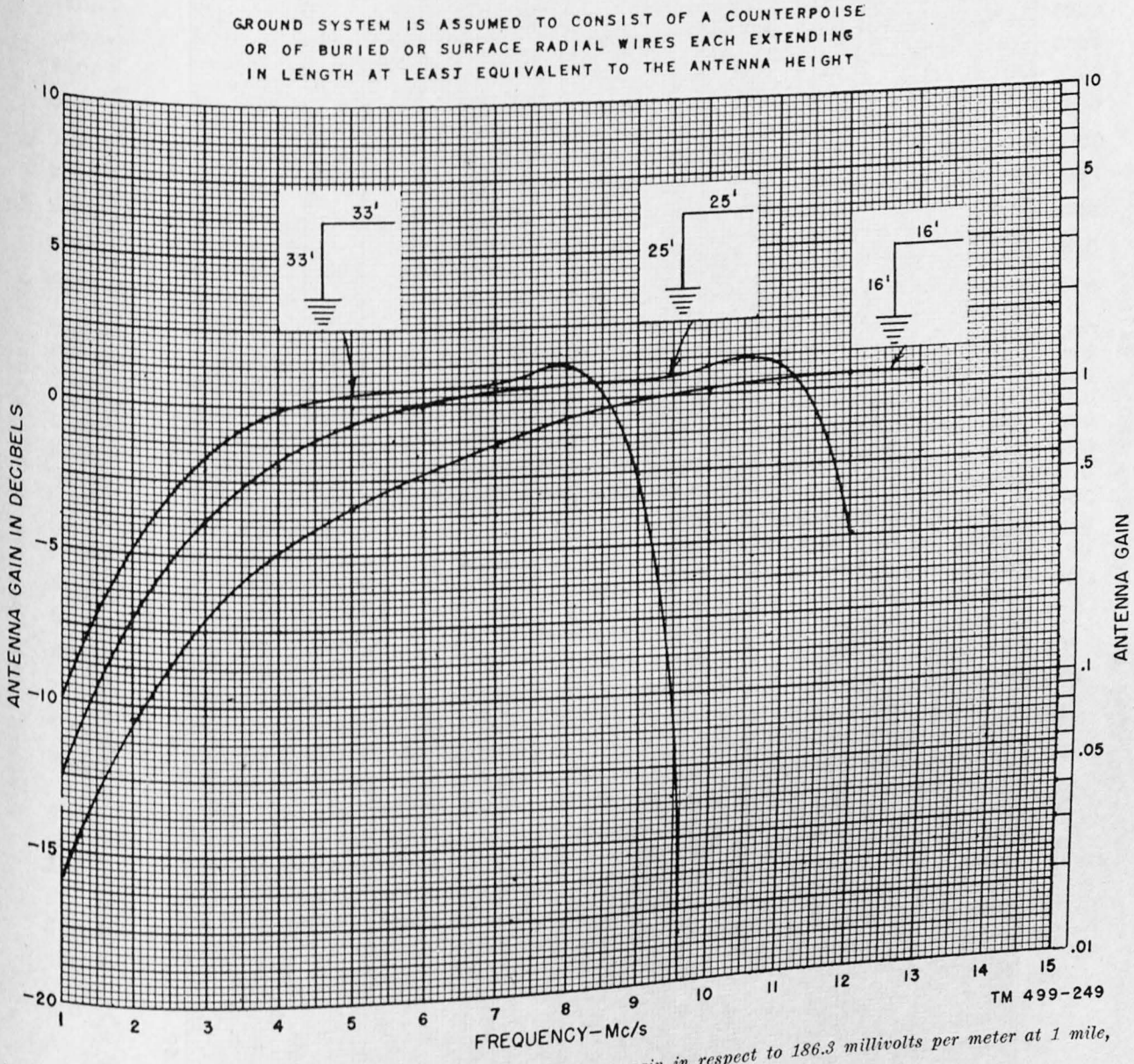


Figure 249. Inverse distance field intensity expressed as an antenna gain in respect to 186.3 millivolts per meter at 1 mile, inverted L antenna.

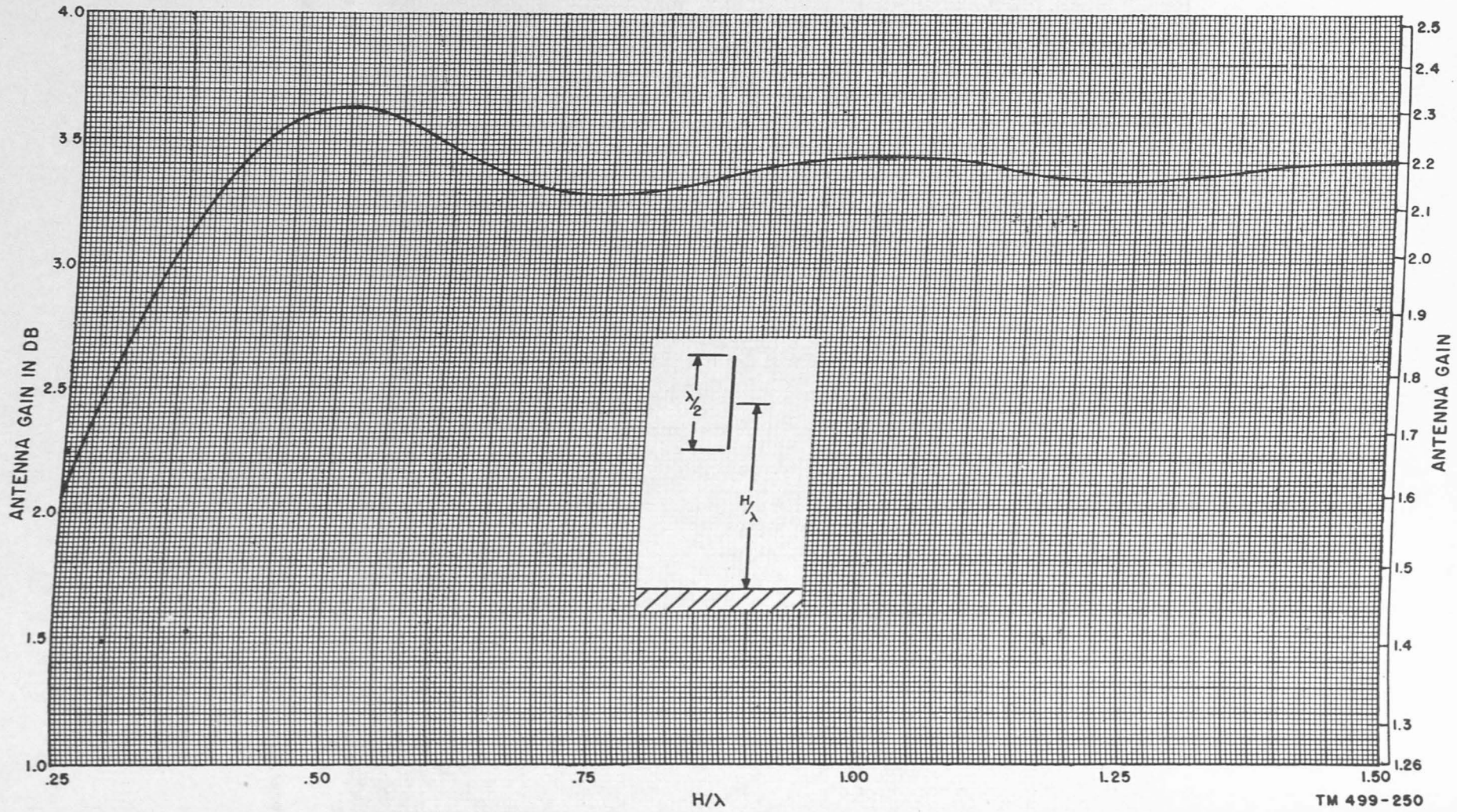


Figure 250. Inverse distance field intensity expressed as an antenna gain in respect to 186.3 millivolts per meter at 1 mile, half-wave vertical antenna erected above perfect earth at a height of H/λ.

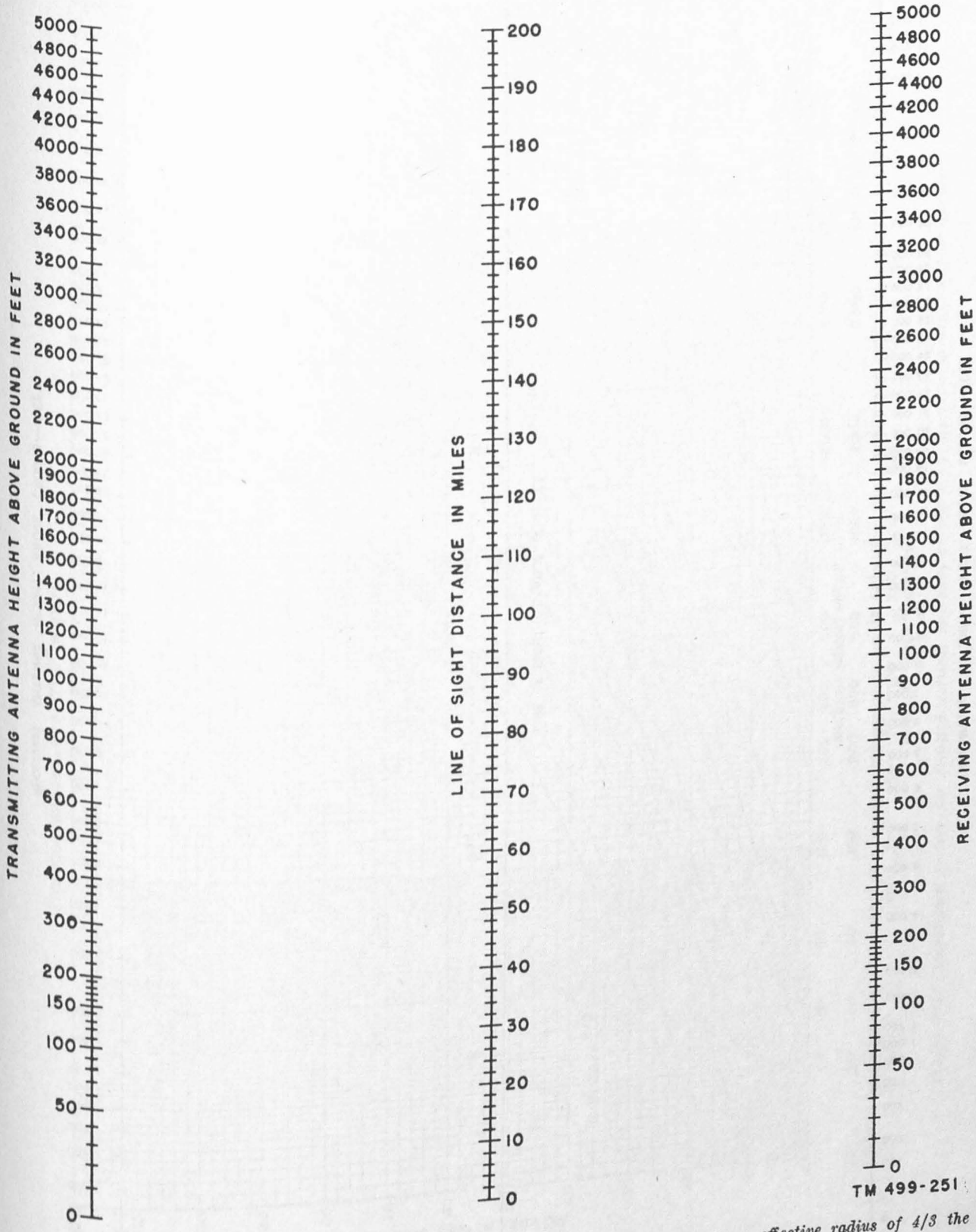


Figure 251. Line of sight distance for elevated antennas (for smooth spherical earth with an effective radius of 4/3 the actual values), antenna heights from 0 to 5,000.

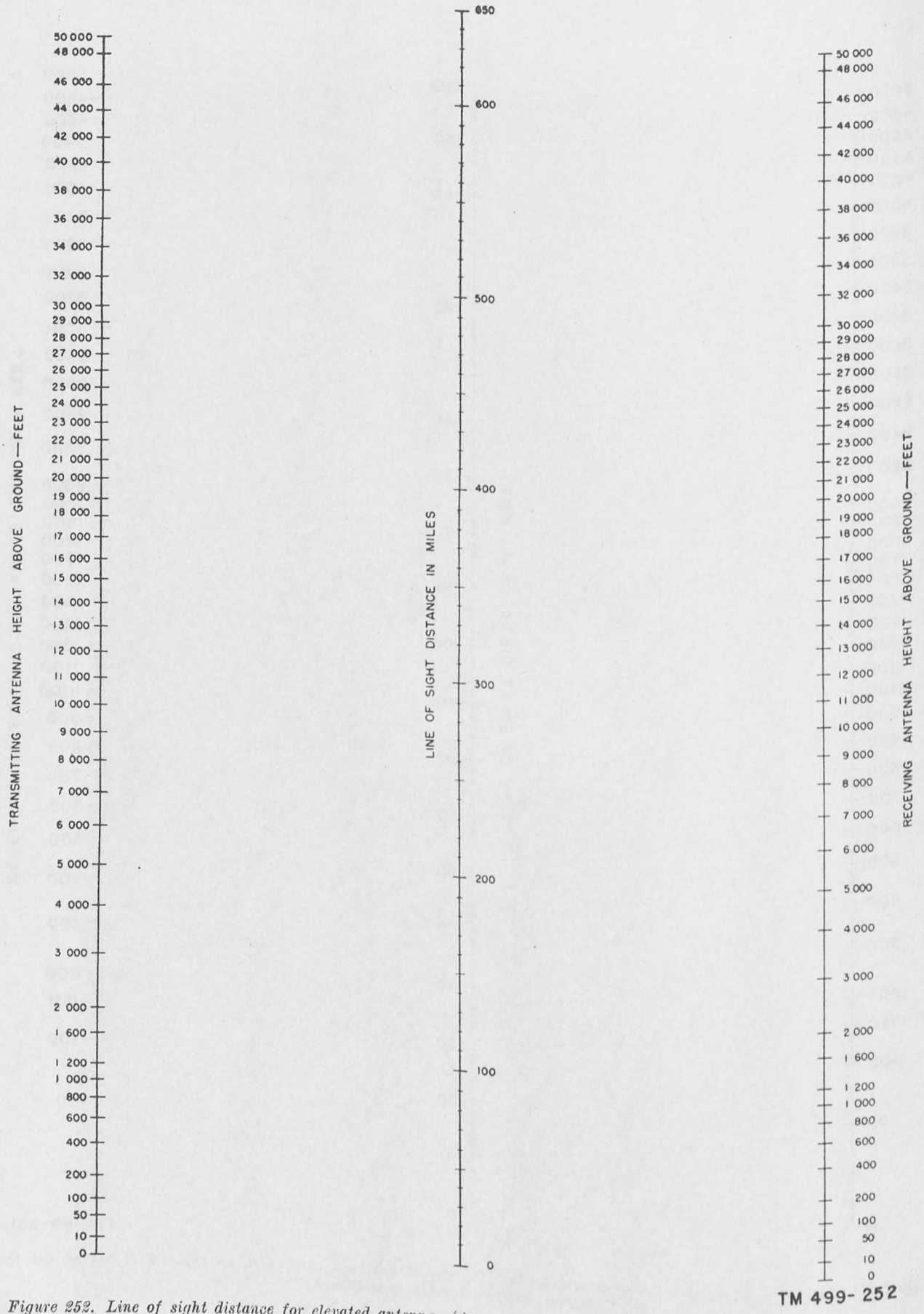


Figure 252. Line of sight distance for elevated antennas (form smooth spherical earth with an effective radius of 4/3 the actual value), antenna heights from 0 to 50,000 feet.

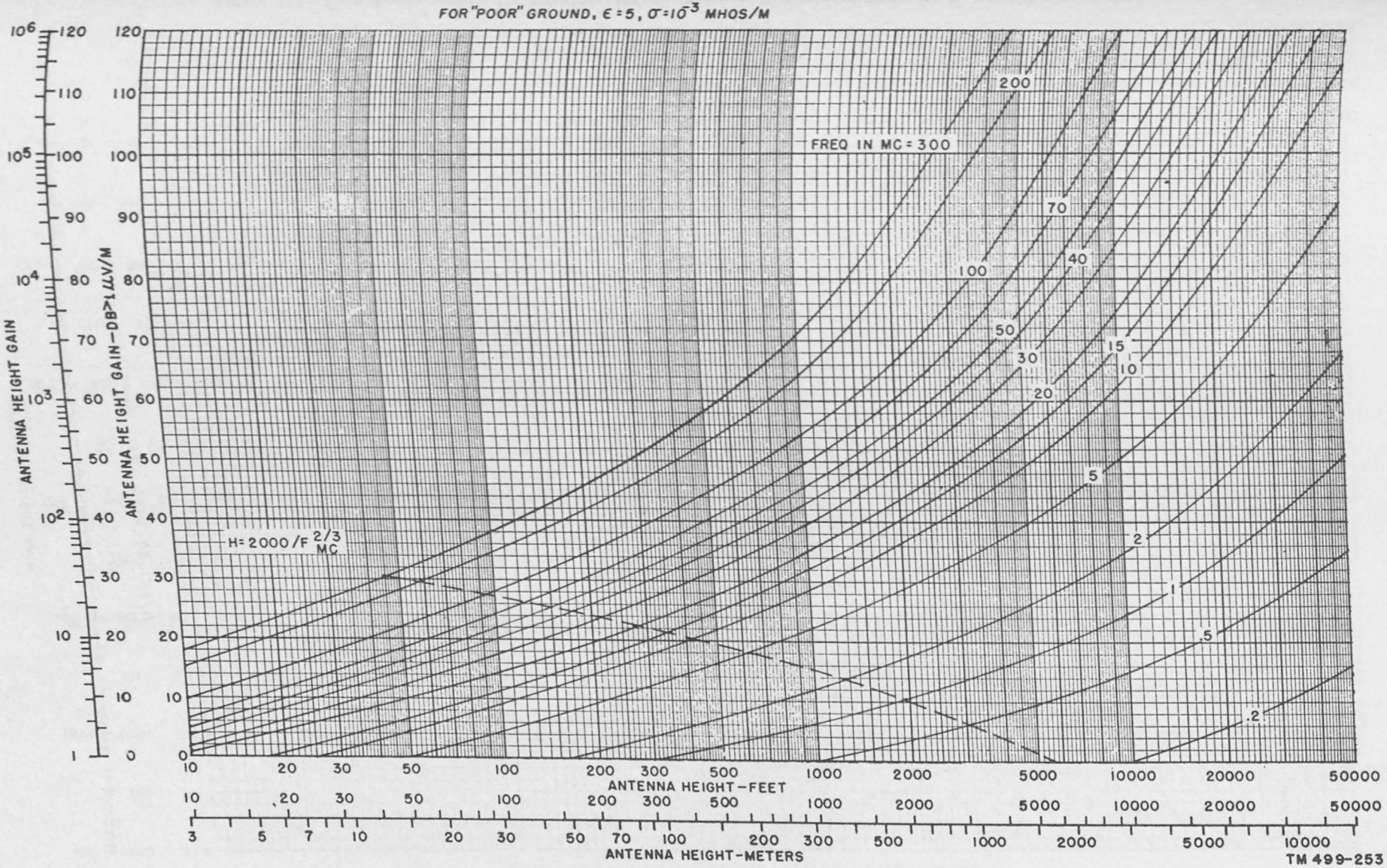


Figure 253. Height-gain factors for elevated vertical antennas at various frequencies in mc, for poor ground.

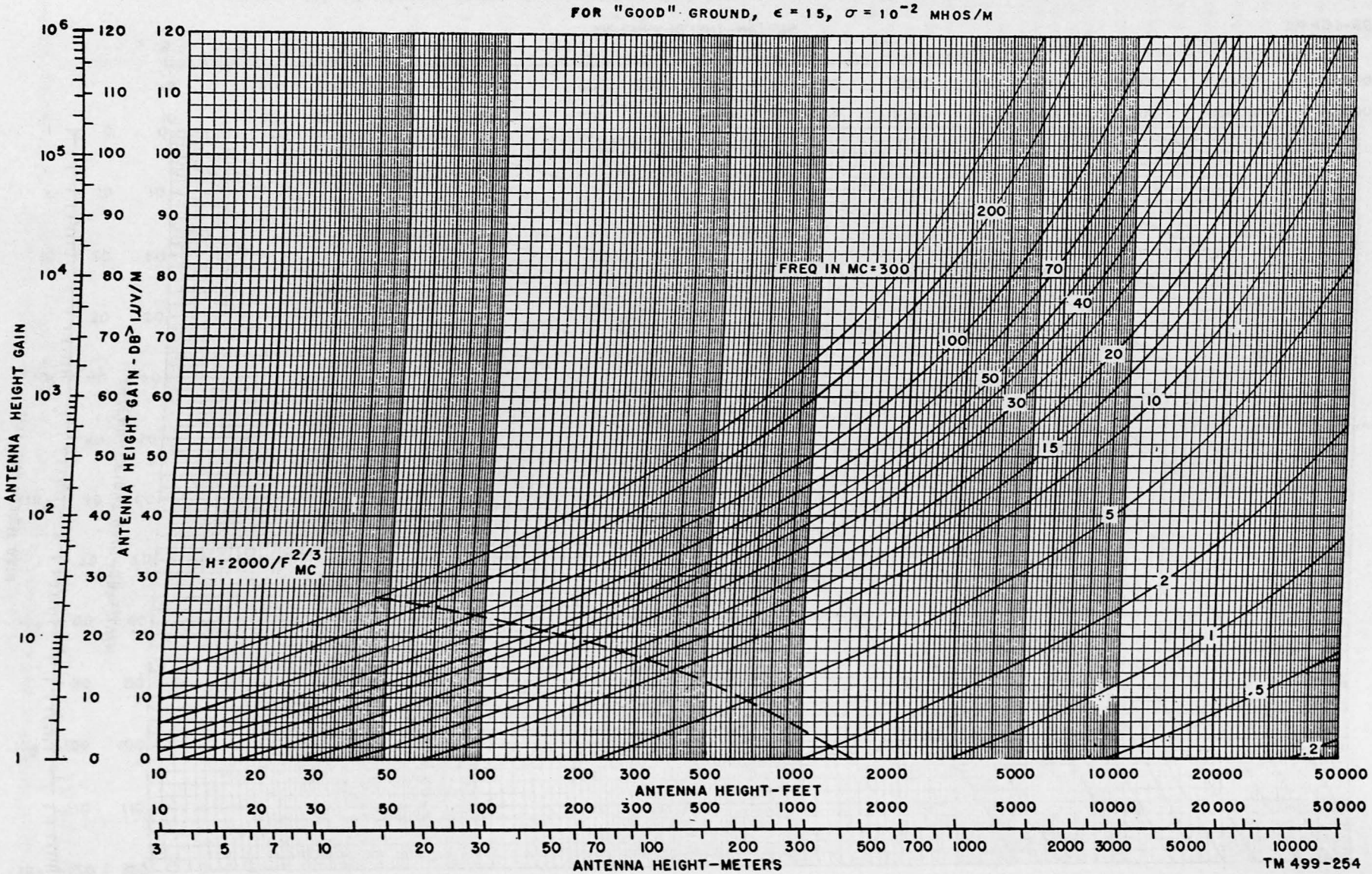


Figure 254. Height-gain factors for elevated vertical antennas at various frequencies in mc, for good ground.

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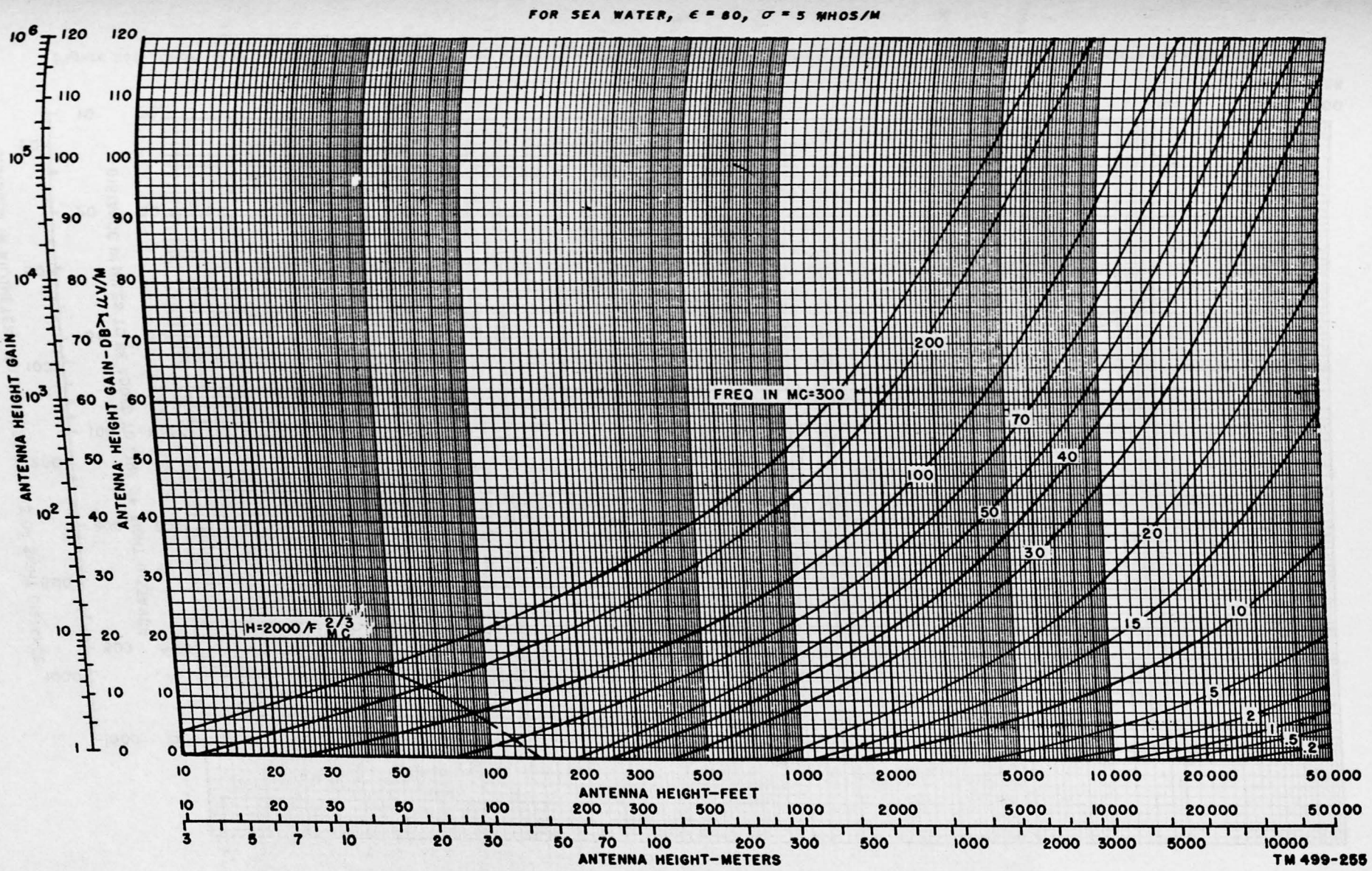


Figure 255. Height-gain factors for elevated vertical antennas at various frequencies in mc, for sea water.

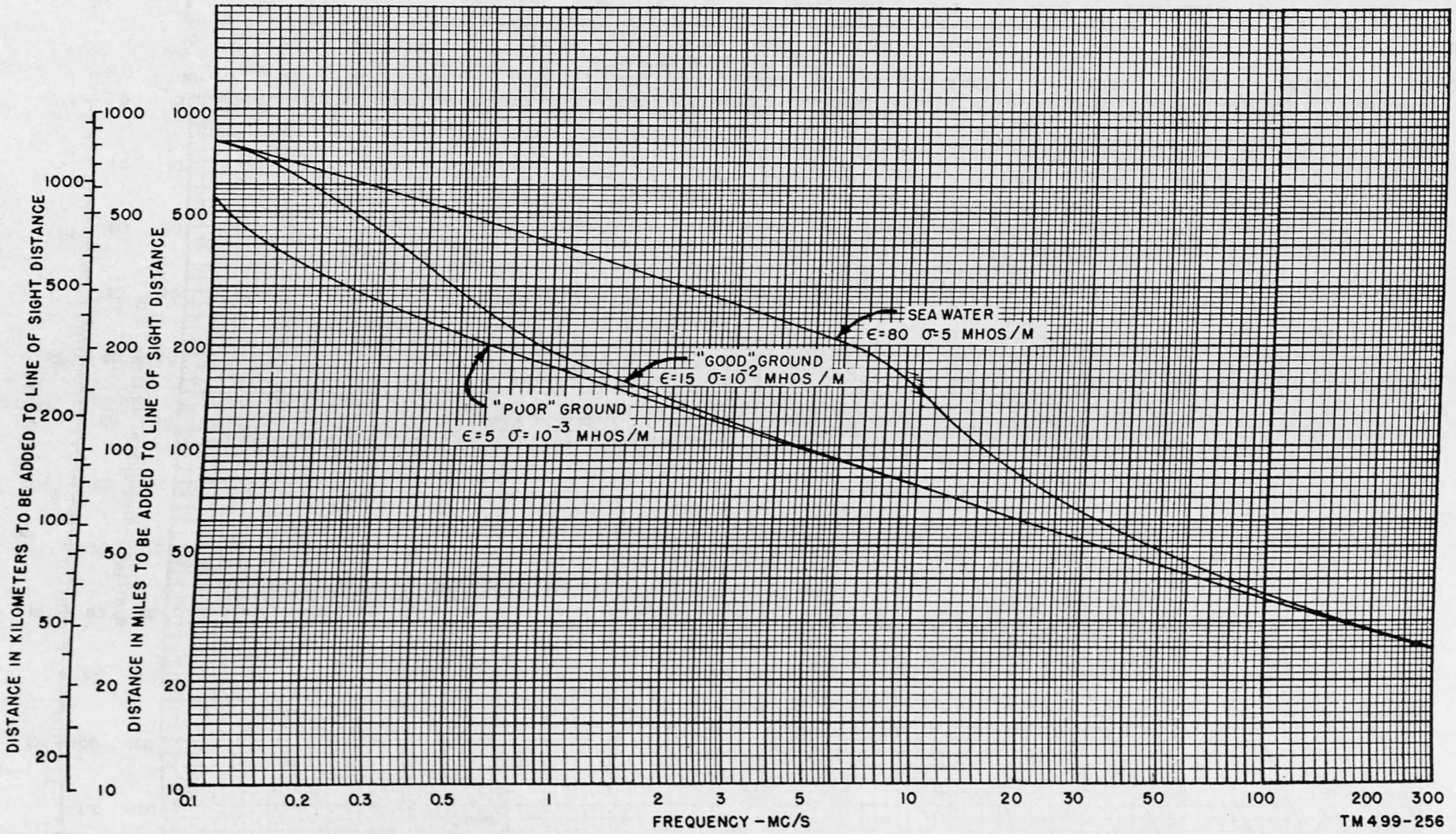


Figure 256. Chart showing value to be added to line of sight distance to determine minimum distance for which height-gain factors are applicable.

FOR PROPAGATION OVER "POOR" GROUND, $\epsilon = 5$, $\sigma = 10^{-3}$ MHOS/M
PLANE EARTH LIMITATION

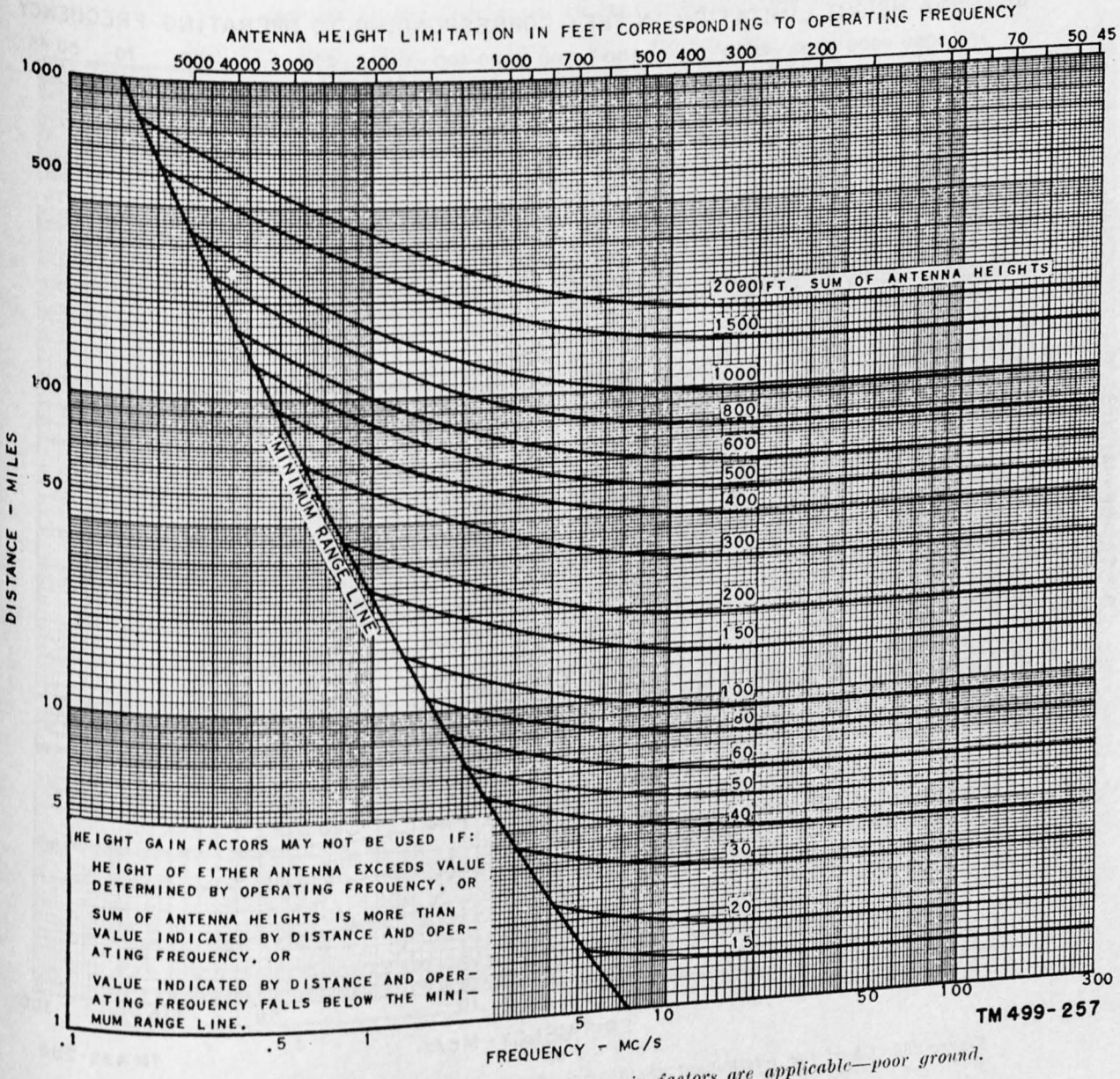


Figure 257. Chart for determining whether height-gain factors are applicable—poor ground.

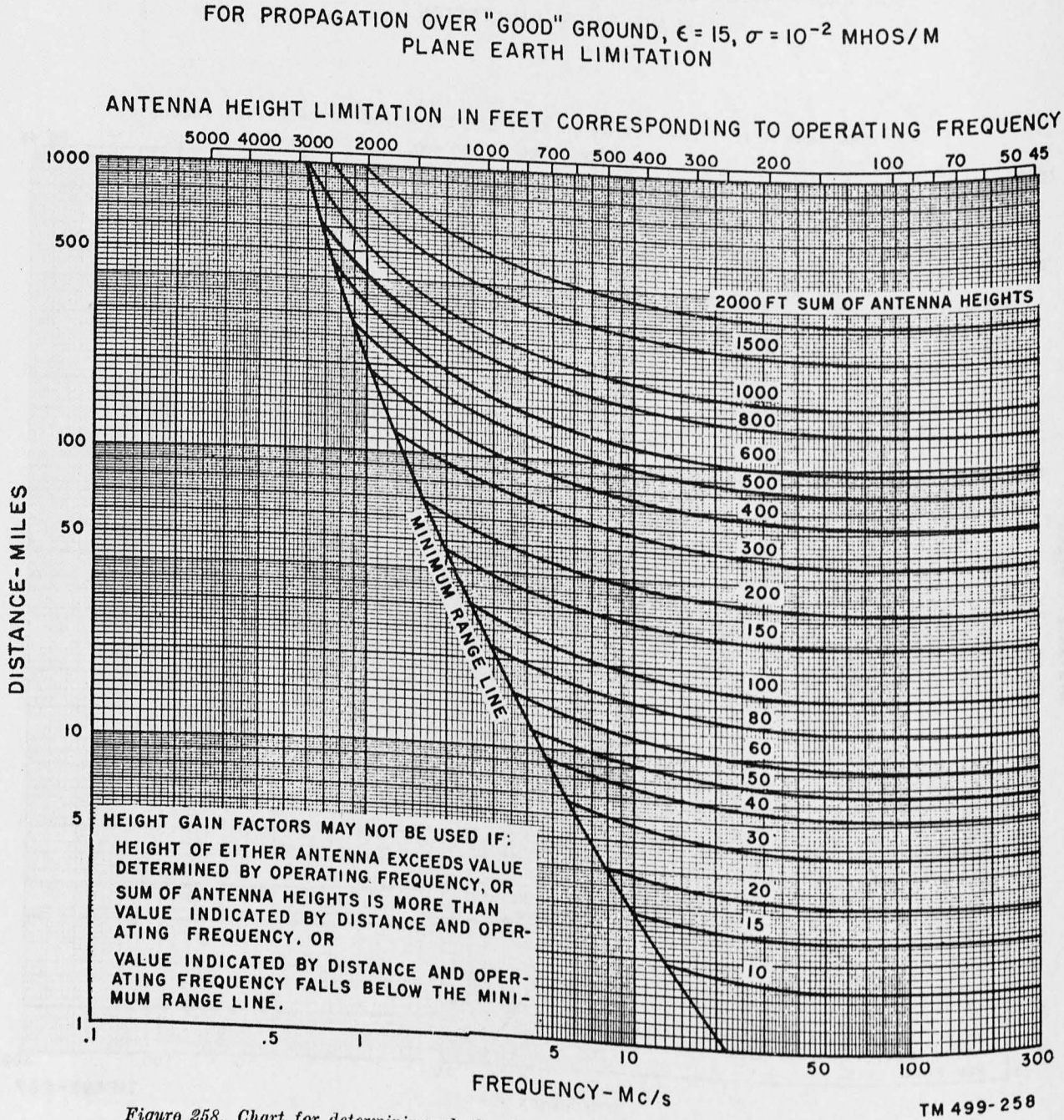


Figure 258. Chart for determining whether height-gain factors are applicable—good ground.

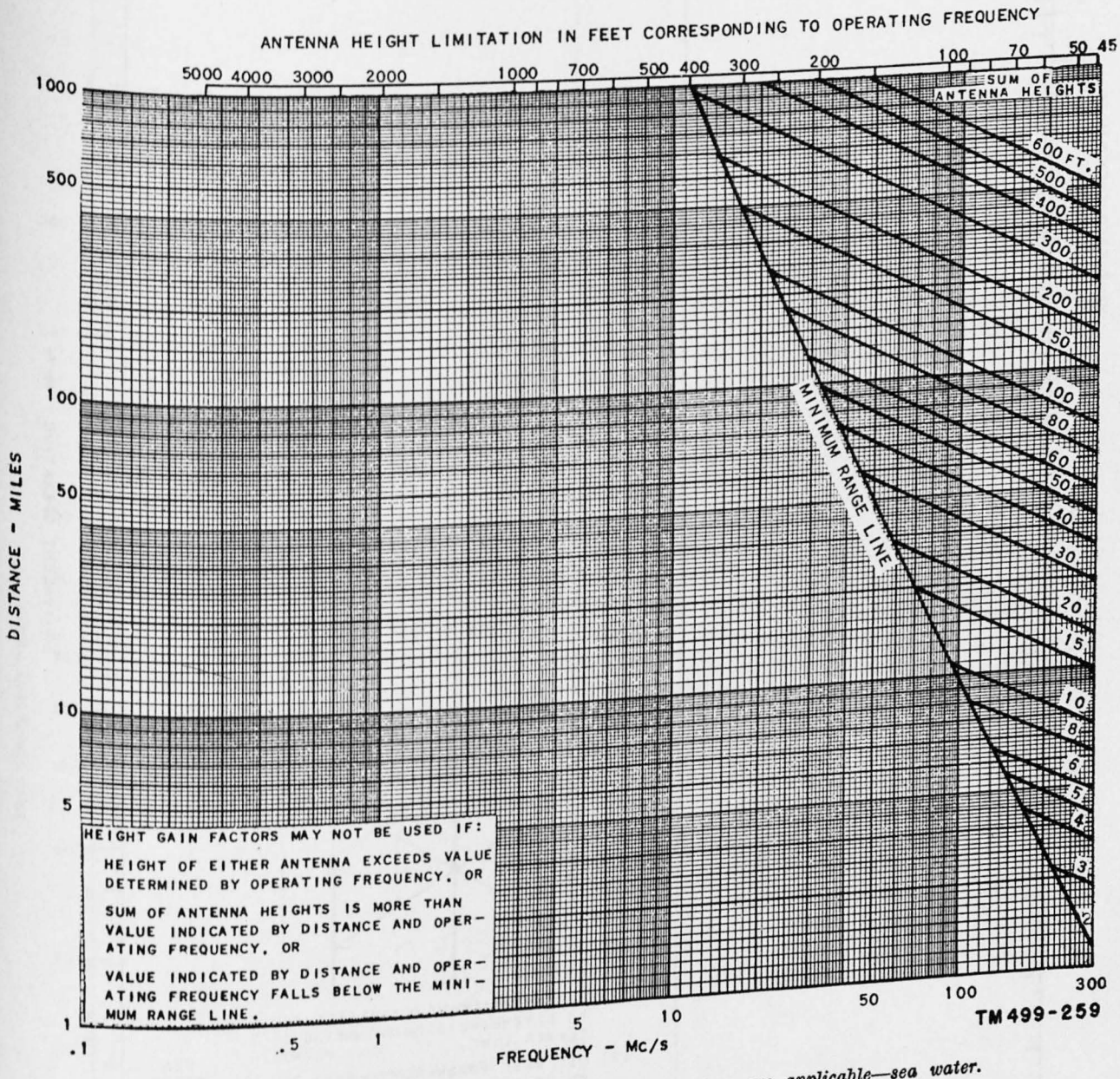


Figure 259. Chart for determining whether height-gain factors are applicable—sea water.

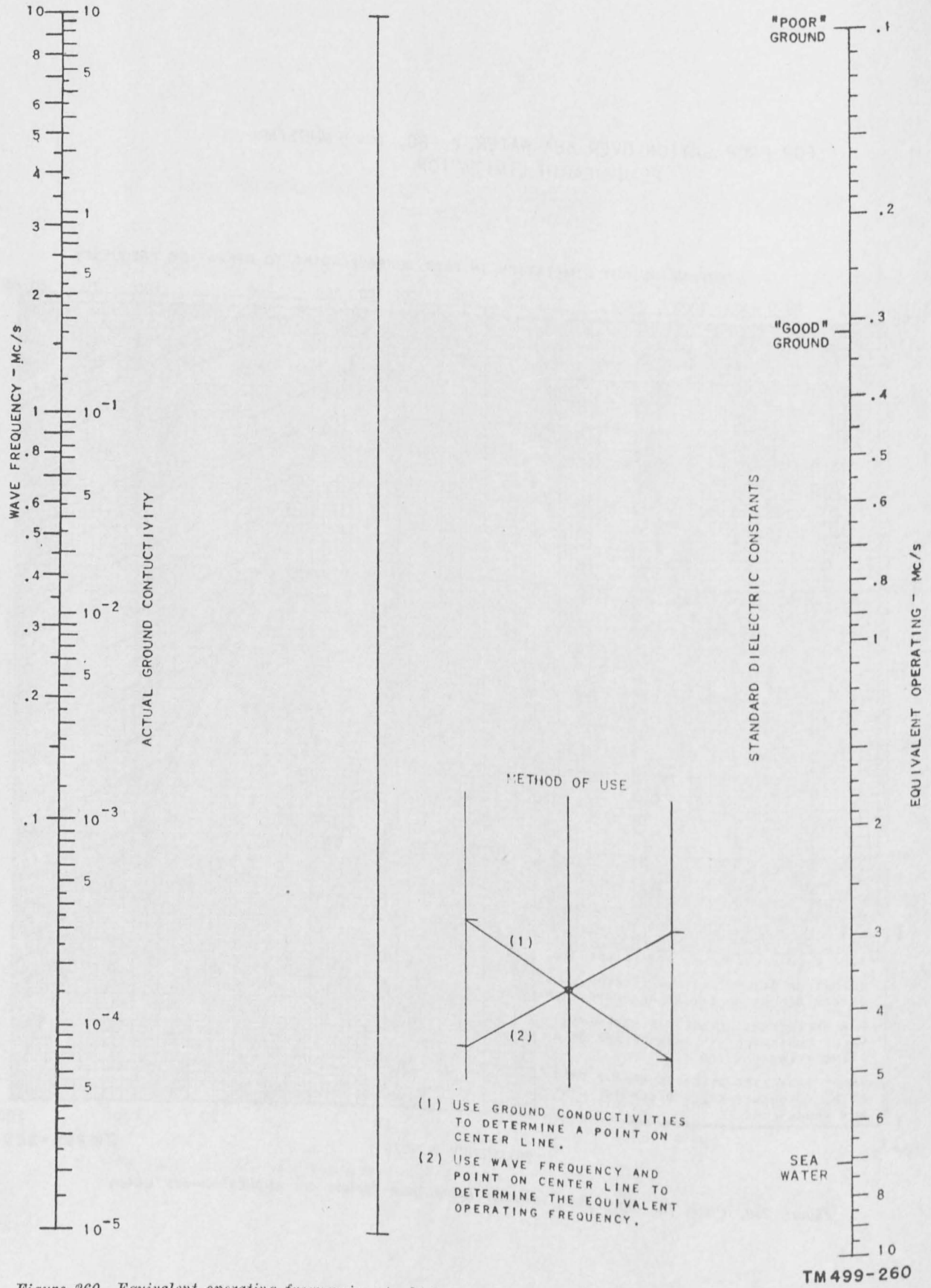


Figure 260. Equivalent operating frequencies at which the groundwave field intensity curves are read for conductivities other than poor ground, good ground, or sea water for low frequencies.

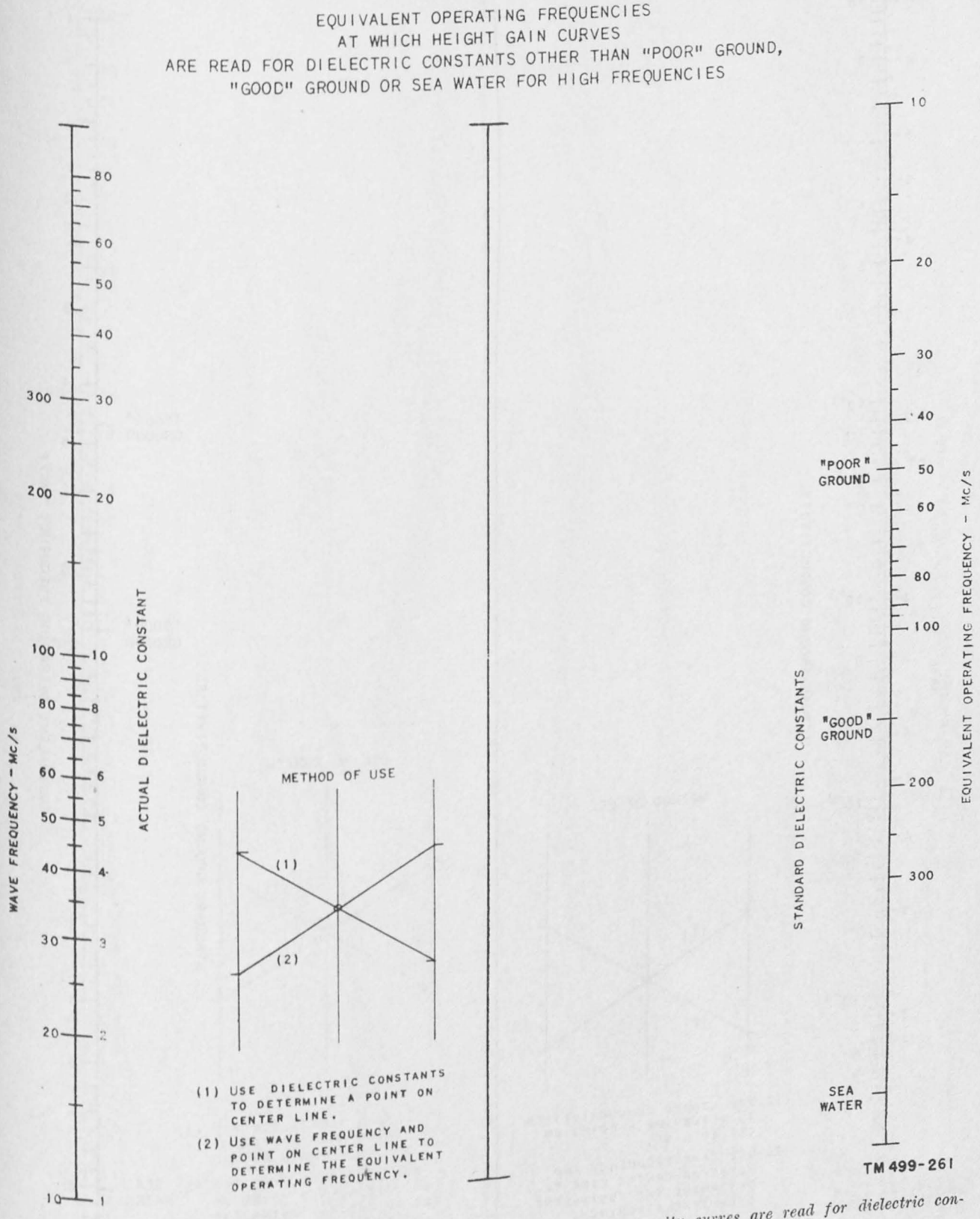


Figure 261. Equivalent operating frequencies at which the groundwave field intensity curves are read for dielectric constants other than poor ground, good ground, or sea water for high frequencies.

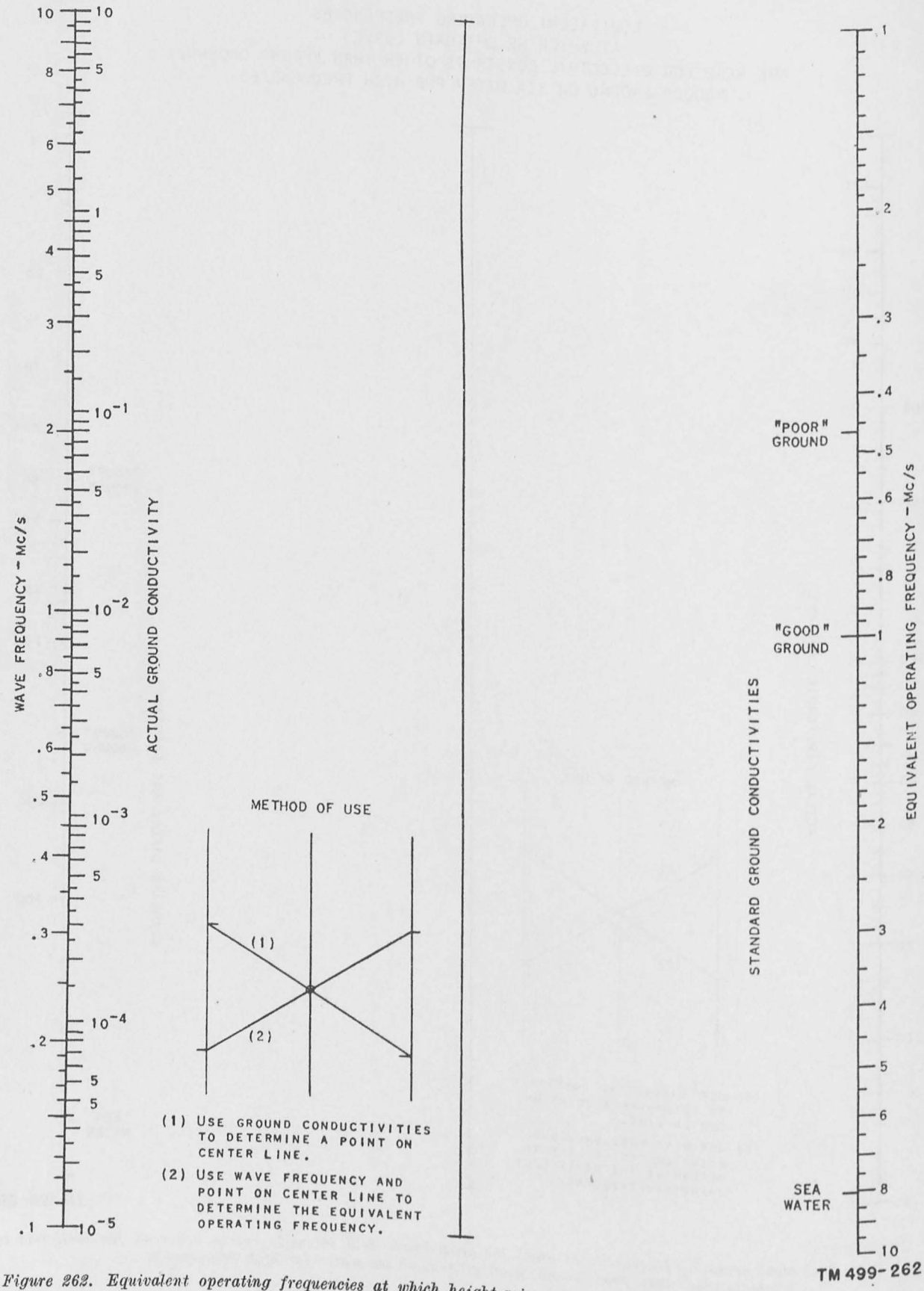


Figure 262. Equivalent operating frequencies at which height-gain curves are read for conductivities other than poor ground, good ground, or sea water for low frequencies.

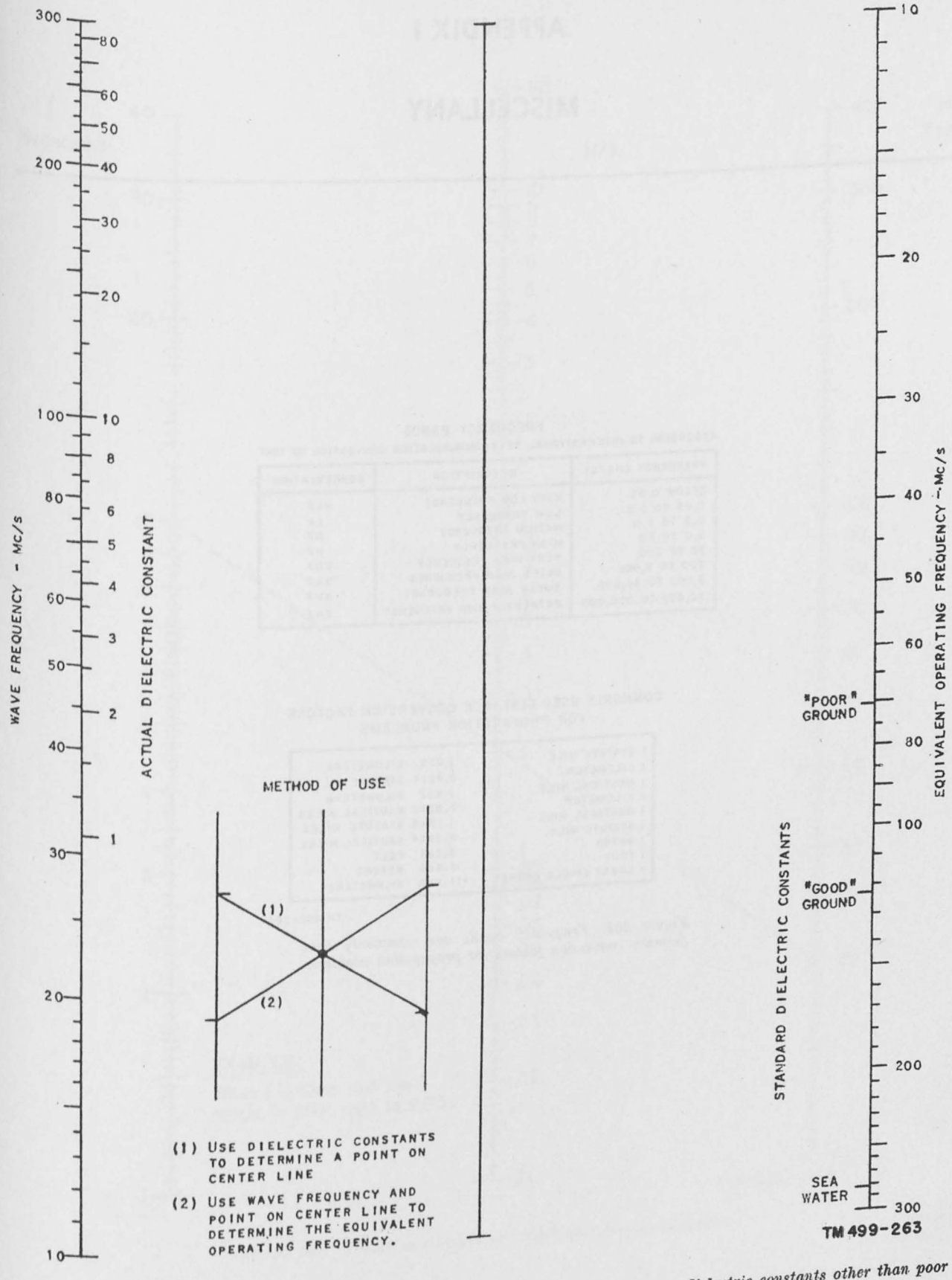


Figure 263. Equivalent operating frequencies at which height-gain curves are read for dielectric constants other than poor ground, good ground, or sea water for high frequencies.

APPENDIX I

MISCELLANY

FREQUENCY BANDS

ACCORDING TO INTERNATIONAL TELECOMMUNICATION CONVENTION OF 1947

FREQUENCY (MC/S)	DESCRIPTION	ABBREVIATION
BELOW 0.03	VERY LOW FREQUENCY	VLF
0.03 TO 0.3	LOW FREQUENCY	LF
0.3 TO 3.0	MEDIUM FREQUENCY	MF
3.0 TO 30	HIGH FREQUENCY	HF
30 TO 300	VERY HIGH FREQUENCY	VHF
300 TO 3,000	ULTRA HIGH FREQUENCY	UHF
3,000 TO 30,000	SUPER HIGH FREQUENCY	SHF
30,000 TO 300,000	EXTREMELY HIGH FREQUENCY	EHF

COMMONLY USED DISTANCE CONVERSION FACTORS
FOR PROPAGATION PROBLEMS

1 STATUTE MILE	1.609 KILOMETERS
1 KILOMETER	0.6214 STATUTE MILES
1 NAUTICAL MILE	1.853 KILOMETERS
1 KILOMETER	0.5396 NAUTICAL MILES
1 NAUTICAL MILE	1.1516 STATUTE MILES
1 STATUTE MILE	0.8684 NAUTICAL MILES
1 METER	3.281 FEET
1 FOOT	0.305 METERS
1 GREAT CIRCLE DEGREE	111.136 KILOMETERS

TM 499-264

Figure 264. Frequency bands and commonly used distance conversion factors for propagation problems.

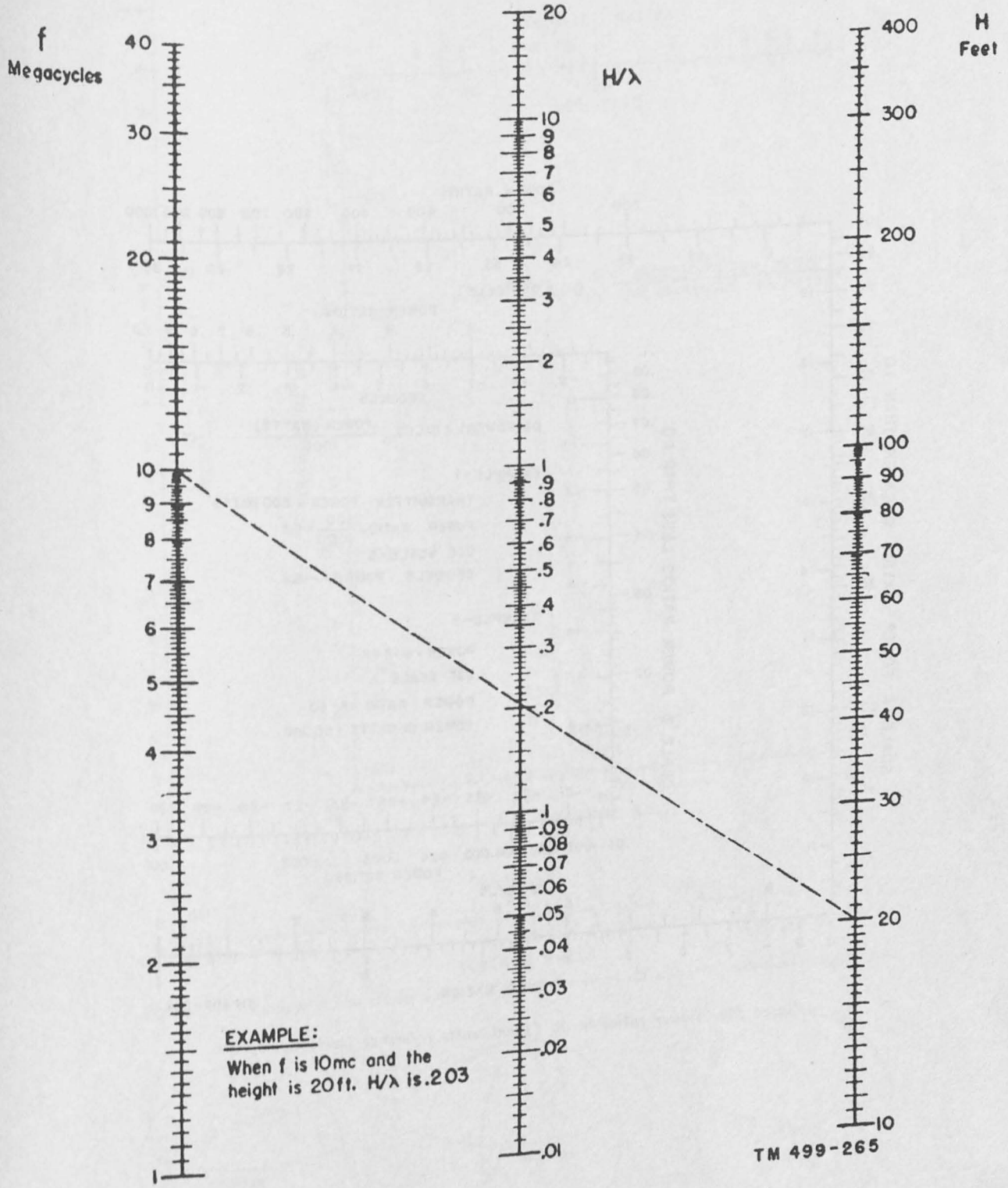


Figure 265. Height/wavelength or length/wavelength nomogram.

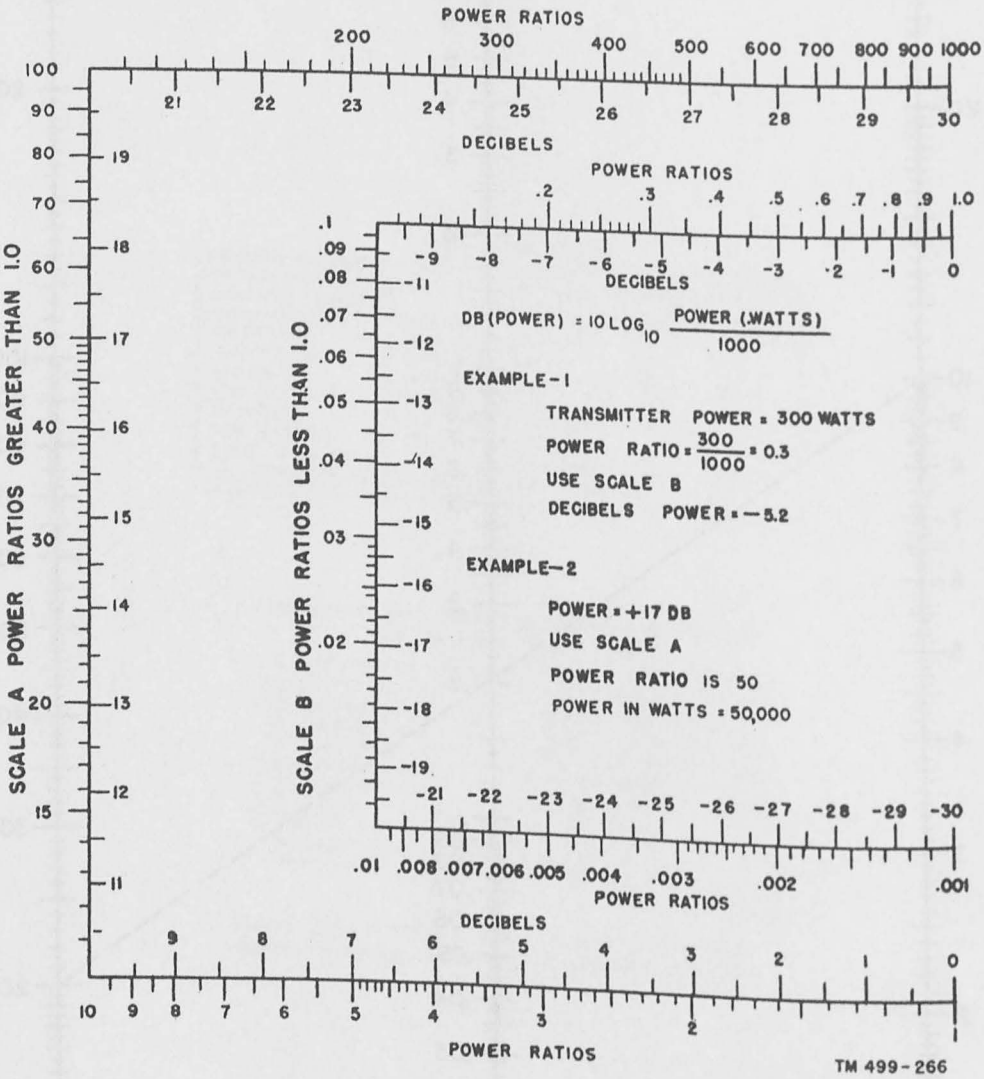


Figure 266. Power ratios in db (1,000 watts reference level) nomogram.

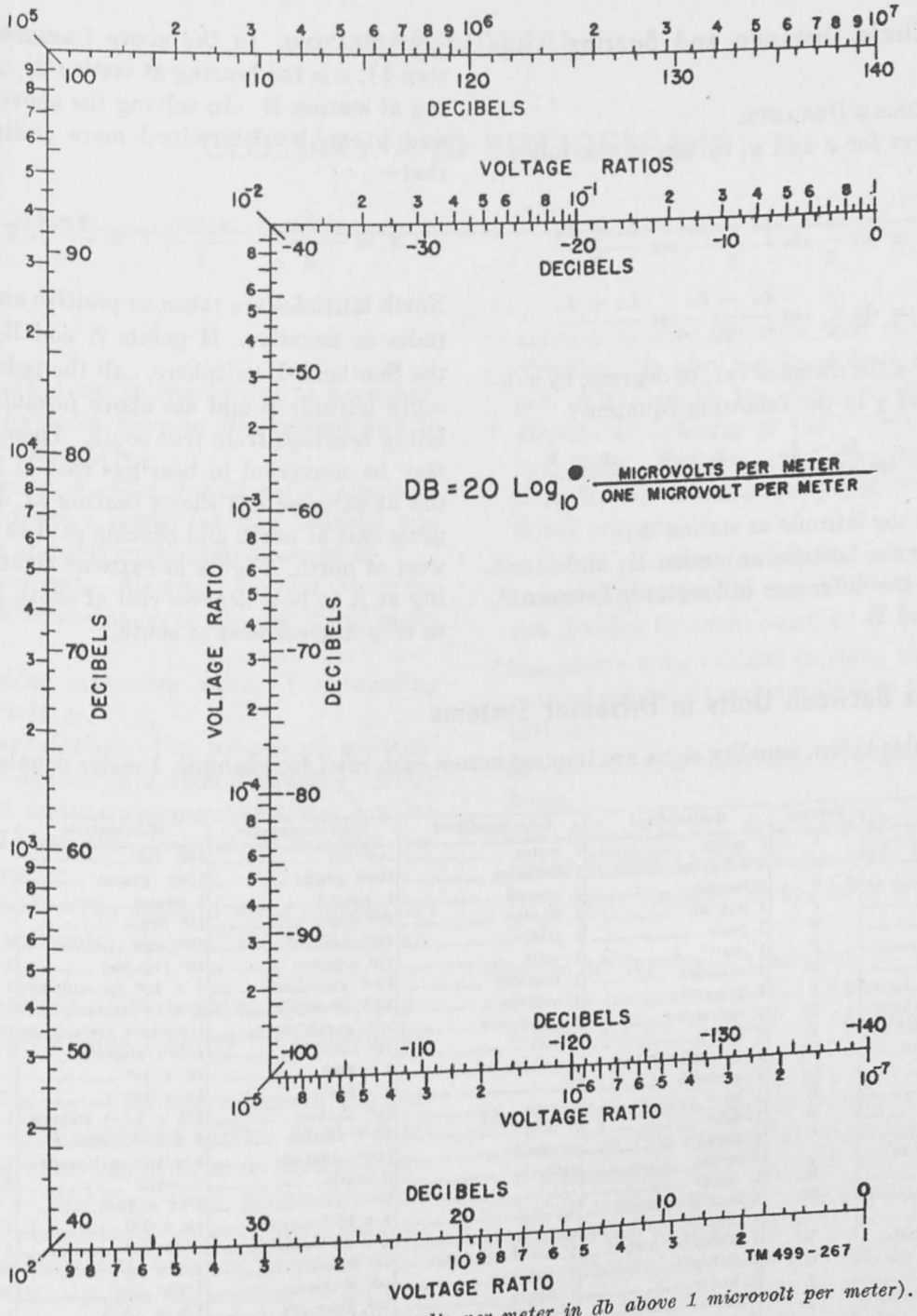


Figure 267. Voltage ratios in db (microvolts per meter in db above 1 microvolt per meter).

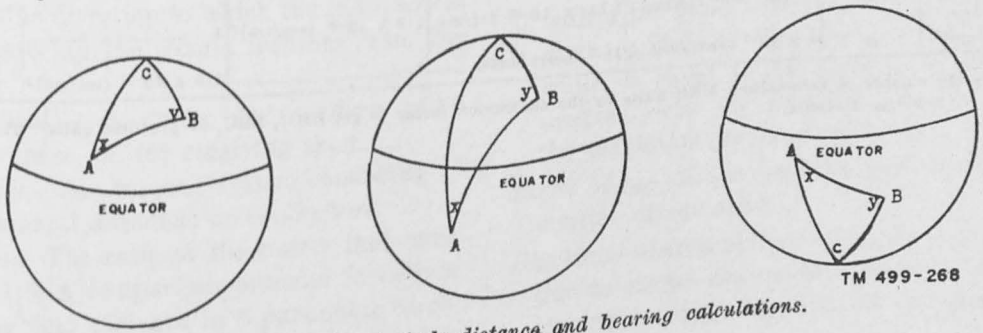


Figure 268. Great circle distance and bearing calculations.

1. Great Circle Distance and Bearing (fig. 268)

a. Great Circle Distance.

Step 1: Solve for x and y, by use of the following equations:

$$\tan\frac{y-x}{2} = \cot\frac{c}{2}\sin\frac{L_b - L_a}{2}\sec\frac{L_b + L_a}{2}$$

$$\tan\frac{y+x}{2} = \cot\frac{c}{2}\cos\frac{L_b - L_a}{2}\csc\frac{L_b + L_a}{2}$$

Step 2: Solve for distance (z), in degrees, by substituting x and y in the following equation:

$$\tan\frac{z}{2} = \tan\frac{L_b - L_a}{2}\sin\frac{y+x}{2}\csc\frac{y-x}{2}$$

Where: L_a is the latitude at station A;
L_b is the latitude at station B; and
C is the difference in longitude between A and B.

b. Bearing. In the above formulas (solved in step 1), x is the bearing at station A; y is the bearing at station B. In solving the above equation, x and y can be determined more easily by noting that—

$$X = \frac{y+x}{2} - \frac{y-x}{2},\quad Y = \frac{y+x}{2} + \frac{y-x}{2}$$

North latitudes are taken as positive and south latitudes as negative. If points A and B both are in the Southern Hemisphere, call the point of greater south latitude B and use above formulas for calculating bearings from true south. These results then may be converted to bearings east of north. Figure at extreme left shows bearing at A to be x degrees east of north and bearing at B to be y degrees west of north. Figure at extreme right shows bearing at A to be x degrees east of south bearing at B to be y degrees west of south.

2. Relations Between Units in Different Systems

In the table below, equality signs are implied across each row; for example, 1 meter equals 100 cm.

Quantity	Symbol	Rationalized	Unrationalized	Electromagnetic	Electrostatic	Practical units
Length	l	1 meter	1 meter	100 cm	100 cm	
Mass	m	1 kilogram	1 kilogram	1000 grams	1000 grams	
Time	t	1 second	1 second	1 second	1 second	
Force	F	1 newton	1 newton	10^5 dynes	10^5 dynes	
Work	W	1 joule	1 joule	10^7 ergs	10^7 ergs	1 joule.
Power	P	1 watt	1 watt	10^7 ergs/sec	10^7 ergs/sec	1 watt.
Charge	q	1 coulomb	1 coulomb	10^{-1} abcoulomb	3 x 10^9 statcoulombs	1 coulomb.
Current	i	1 ampere	1 ampere	10^{-1} abamp	3 x 10^9 statamp	1 ampere.
Electric field intensity	E	1 volt/meter	1 volt/meter	10^6 abvolt/cm	1/3 x 10^{-4} statvolt/cm	10^{-2} volt/cm.
EMF and potential dif.	V	1 volt	1 volt	10^8 abvolts	1/300 statvolts	1 volt.
Electric induction	D	1 coulomb/sq meter		4 x 10^{-5}	12 x 10^5	
Electric flux	ψ	1 coulomb		4 x 10^{-1}	12 x 10^9	
Resistance	R	1 ohm	1 ohm	10^9 abohms	1/9 x 10^{-11} statohms	1 ohm.
Conductance	G	1 mho	1 mho	10^{-9} abmhos	9 x 10^{11} statmhos	1 mho.
Capacitance	C	1 farad	1 farad	10^{-9} abfarads	9 x 10^{11} statfarads	1 farad.
Relative permittivity	ϵ	Numeric	numeric	Numeric	Numeric	Numeric.
Magnetic pole	M	1 weber		$10^8/_4$	1/12 x 10^{-2}	
Magnetic field intensity	H	1 amp-turn/meter		4 x 10^{-3} oersteds	12 x 10^7	10^{-2} a-t/cm.
Mmf		1 amp-turn		4 x 10^{-1} gilberts	12 x 10^9	1 amp-turn.
Magnetic induction	B	1 weber/sq meter	1 weber/sq meter	10^4 gauss	1/3 x 10^{-8}	10^4 max/sq cm.
Magnetic flux	ϕ	1 weber	1 weber	10^8 maxwells	1/300	10^8 maxwells.
Inductance	L	1 henry	1 henry	10^9 abhenrys	1/9 x 10^{-11}	1 henry.
Relative permeability	μ	Numeric	Numeric	Numeric	Numeric	
Permittivity of free space	ϵ	8.85 x 10^{-12} far/met	1.11 x 10^{-10} far/met	1/9 x 10^{-20} (sec/cm)^2	1	
Permeability of free space	μ	4 x 10^{-7} henry/met	10^{-7} henry/meter	1	1/9 x 10^{-20} (sec/cm)^2	

Note. Multiply the number of rationalized MKS units by the conversion factor to get EMU, ESU, or practical units. Thus, 5 volts = 5 x 10^8 advolts = 5 x $1/_{300}$ statvolts.

APPENDIX II

GLOSSARY AND BIBLIOGRAPHY

1. Glossary

Absorption.—Decrease in energy due to losses suffered by the radio wave in the ground and to the ions of ionosphere.

Absorption index, K.—The functional relationship between the sun's angle (at any latitude and local time) and the ionospheric absorption.

Alternating current.—Electrical current which reverses in direction at regularly recurring intervals.

Amplitude.—The maximum value of alternating current or voltage.

Amplitude modulation.—The process of superimposing intelligence on a radio-frequency carrier so that the audio-frequency variations are superimposed upon the amplitude of the high-frequency wave.

Angle of arrival.—The angle of wave propagation above the horizontal plane at the receiving antenna.

Angle of departure.—The angle of wave propagation above the ground plane at the transmitting antenna.

Angle of incidence.—The angle between the perpendicular to a reflecting surface at the point at which an electromagnetic wave strikes a surface and the direction from which the wave approaches the surface. A wave perpendicular to a surface has a zero angle of incidence.

Angle of refraction.—The angle between the perpendicular to a surface separating two different media and the direction to which the radio waves go when entering the second medium from the first.

Antenna (aerial).—A device for sending radio waves into space, or for receiving them.

Antenna array.—An antenna system consisting of several elemental antennas or conductors.

Antenna gain.—The ratio of the power that must be supplied to a comparison antenna to deliver a particular field strength in a particular direction to the power that must be supplied to an antenna to give the same field strength in this direction. It also can be defined as the power per unit area in the required direction of a directional antenna to the average power per unit area. Antenna gain measures the directivity of an antenna compared to a nondirectional antenna.

Arithmetic average (mean).—Average of magnitudes; the sum of the magnitudes of the quantities divided by their number.

Atmospheric noise.—Noise or static that is due to natural causes. It is due mainly to thunderstorm activity.

Attenuation.—The decrease of amplitude due to losses.

Audio frequency.—A frequency that can be detected as sound by the human ear. The range is from approximately 20 to 20,000 cycles per second.

Auroral absorption.—Absorption of radio waves due to auroral activity. Auroral activity is caused mainly by particle radiation from the sun.

Bandwidth.—The width of a range of frequency values. In this manual, when reference is made to a bandwidth of a receiver, the generally accepted term "effective bandwidth" is meant. The effective bandwith is defined as the width of a hypothetical rectangular response curve of a tuned radio circuit. This band would pass the rms value of signal or noise at all frequencies within the band with the same characteristics as at the middle of the band. The effective bandwidth is equal to the integral of the response squared over the frequency range divided by the maximum response squared.

Black body.—A theoretically perfect absorber and emitter of radiation.

Blackout.—Interruption of radio communication due to excess absorption caused by solar flares. During severe blackouts, all frequencies above

approximately 1,500 kilocycles are absorbed excessively in the daylight zone.

Breit and Tuve theorem.—The relationship between the equivalent triangular path for sky-wave propagation and the transmission distance.

Brewster angle.—The angle of incidence at which a vertically polarized wave (a wave polarized in the plane of incidence) undergoes a phase shift of 90° on reflection from the surface.

Broadcast transmission.—Radio transmission to an unlimited number of receiving locations.

Carrier frequency.—The frequency of the radio frequency wave upon which the intelligence is superimposed.

Carrier shift.—Transmission of radio-teletypewriter messages by shifting the carrier frequency in one direction for a marking signal and in the opposite direction for a spacing signal.

Central standard time.—Mean time based on the ninetieth meridian west longitude.

Channel.—A narrow band of frequencies of sufficient width for a single radio communication.

Characteristic impedance of free space.—The characteristic impedance of free space is the relationship between the electric and magnetic intensities of space due to the expansion of the impedance concept to electromagnetic fields.

Collision frequency.—The number of collisions between an electron and a molecule of a gas per unit time. It is dependent on the velocity of the electron and the mean free path between molecules.

Conductivity.—The reciprocal of the resistivity.

Continuous wave.—Radio waves of a constant amplitude and constant frequency.

Coordinates.—Two or more values locating a point in space.

Cosmic noise.—Radio static whose origin is due to sources outside the earth. The source may be similar to sunspots, or spots on the stars.

Crest factor.—The ratio between a peak value to the effective (root mean square) value.

Critical frequency.—The maximum frequency that an ionospheric layer will reflect at vertical incidence.

D layer.—The lowest regular ionospheric layer. Sky waves normally are not reflected by this layer but are absorbed by it.

Decibel.—The standard unit of power ratio is equal to 10 times the logarithm to the base 10 for the ratio of 2 powers.

Dellinger effect.—Sudden ionospheric disturbances which affect all sky-wave transmission in the daylight portion of the earth. Field intensities are reduced greatly due to this cause.

Deviation.—A term used in frequency modulation to indicate the amount the carrier or resting frequency increases or decreases when modulated. It usually is expressed in kilocycles.

Deviative absorption.—Absorption that occurs at frequencies near the critical frequency. It occurs in conjunction with the slowing up of radio waves near the critical frequency.

Dielectric constant.—The ratio between the specific inductive capacity of the material to that of a vacuum. The introduction of a dielectric like mica increases the capacity of a capacitor.

Diffraction.—Phenomena of the bending of electromagnetic waves around obstacles.

Dipole antenna.—A theoretical antenna of very short length used as a basis in many theoretical calculations. Any antenna may be said to be made up of a large number of dipole antennas.

Direct wave.—A wave that travels directly between the transmitter and receiver without reflections from any object.

Discrimination.—A receiving antenna discriminates against noise when it picks up signals more effectively than noise.

Distortion.—Distortion exists when the wave form of an electric wave is changed in an electric network.

Diversity gain.—The gain in reception due to the use of two or more receiving antennas. Signals induced in antennas separated by 5 wavelengths or more fade independently and better reception is obtainable in the presence of fading by the use of more than one antenna.

Double sideband.—In amplitude modulation, the intelligence is transmitted at frequencies both below and above the carrier frequency by the audio frequency value of the intelligence.

E layer.—One of the regular ionospheric layers with an average height of about 100 kilometers. This layer occurs during daylight hours and its ionization is dependent on the sun's angle.

Ecliptic.—Term used for the annual path of the earth around the sun.

Effective height.—A quantity used to define the transmission characteristics of an antenna. For a receiving antenna, the effective height defines the voltage induced in the antenna when multiplied by the incident field intensity.

Effective power.—Effective power is defined in this manual as the product of the antenna input power in kilowatts and the antenna gain.

Electrical interference.—Interference caused by the operation of electrical apparatus other than radio stations.

Electromagnetic wave.—A radio wave which is transverse in character and travels with the velocity of light in free space.

Elliptical polarization.—A wave polarized in such a manner that both the transverse electric and magnetic fields have unequal components at right angles to each other that are not in time phase. The electric vector at right angles to the direction of propagation rotates with its magnitude changing while in rotation.

Equinoxes.—The periods of the year when the sun is at the Equator.

Extraordinary ray.—One of the two rays in which an incident ray is split in the ionosphere. This wave is called an extraordinary ray because it does not follow the simple laws of refraction.

Faculae.—"Torches," bright spots near edge of sun.

Fading.—Rapid variations in field intensities that occur from minute to minute or in shorter time intervals.

F1 layer.—One of the regular ionospheric layers at an average height of about 225 kilometers which occurs during the daylight hours and follows the sun closely.

F2 layer.—The most useful of the ionospheric layers for radio wave propagation. It is the most highly ionized and highest of the layers, having an average night height of 225 kilometers and a midday height of about 300 kilometers. This layer is ionized throughout the day. Its ionization is least just before dawn and maximum early in the afternoon.

Field intensity.—The electrical strength of a field usually measured in terms of microvolts per meter.

Flocculi.—Solar markings photographed with the aid of a spectroheliograph.

Free space.—Empty space with no free electrons or ions present. It has approximately the electrical constants of air.

Frequency.—The number of complete cycles per second existing in the form of wave motion such as the number of cycles per second of an alternating current.

Frequency modulation.—The process of superimposing intelligence upon a radio frequency carrier by varying the frequency of a radio frequency carrier in accordance with the amplitude and frequency of an audio signal. The amount of variation depends upon the strength of the audio signal.

Galaxy.—One great system of stars, such as the milky way.

Good ground.—Earth with a conductivity of 10^{-2} and a dielectric constant of 15 in MKS units.

Great circle path.—The shortest distance between two points on a sphere. The plane of the path passes through the center of the sphere.

Greenwich civil time.—Mean time with reference to zero longitude.

Ground reflected wave.—Component of the ground-wave that is reflected from the ground.

Ground wave.—A radio wave that is propagated over the earth and ordinarily is affected by the presence of the ground. Ground waves include all components of waves over the earth except ionospheric and tropospheric waves. Ground waves are affected somewhat by the change in dielectric constant of the lower atmosphere.

Ground velocity.—The rate of energy travel in an electromagnetic wave. It is the velocity of propagation of the envelope of a wave.

Guided wave.—A wave whose propagation is concentrated in certain directions within or near the boundaries between materials of different properties located in the path at different places.

Gyrofrequency.—The natural frequency of rotation of ions about the magnetic field of the earth. For electrons, it is of the order of 700 to 1,600 kilocycles per second.

Harmonic.—A multiple of a fundamental frequency. The second harmonic is twice the frequency of the fundamental.

Heaviside layer.—The ionosphere usually is referred to as the heaviside layer. Some writers refer to the E layer as the heaviside layer.

Hertz antenna.—An antenna in which the ground is not an essential part. The resonant frequency of the antenna depends upon its length.

High-frequency band.—Frequencies ranging from 3 to 30 megacycles per second.

Highest probable frequency (HPF).—An arbitrarily chosen frequency value 15 percent above the F2 layer MUF for the circuit. For the E layer, the HPF is equal to the MUF.

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Histogram.—An experimental frequency distribution which shows the number of quantities of particular magnitudes.

Hop.—The excursion of a radio wave from the earth to the ionosphere and back to the earth. The number of hops indicate the number of reflections from the ionosphere.

Horizontally polarized waves.—A linearly polarized wave whose direction of polarization is horizontal. A horizontally polarized wave is one in which the electric intensity is parallel to the earth.

Image effect.—The effect produced on the field of an antenna due to the presence of the earth. Electromagnetic waves are reflected from the earth's surface and these reflections often are accounted for by an image antenna at an equal distance below the earth's surface.

Impulse.—A force acting for a comparatively short period of time such as a momentary rise in voltage.

Impulse noise.—Noise due to disturbances having abrupt changes and short duration. These noise impulses may or may not have systematic phase relationships.

Incident field intensity.—The field strength of a downcoming sky wave without including the effects of earth reflections at the receiving location.

Index of refraction.—The ratio between the velocity of an electromagnetic wave in free space and the phase velocity in the medium.

Induction field.—The field near an antenna into which energy is alternately stored and removed. Energy of this is not permanently lost to the antenna.

Interference fading.—Effect produced by different wave components, arriving from the same source, that have traveled along slightly different paths.

Intermediate frequency.—The fixed frequency to which all carrier waves are converted in a superheterodyne receiver.

Ion.—An electrified portion of matter of subatomic, atomic, or molecular dimensions.

Ionization.—The process of producing ions.

Ionosphere.—The highly ionized layers in the earth's upper atmosphere at heights above about 50 kilometers above the surface of the earth.

Ionosphere storms.—Periods in which the ionosphere is disturbed from the normal condition. The virtual heights and the critical frequencies are abnormal and, during intense storms, the ionosphere is diffused and expanded. Increased ionospheric absorption may be noted during very severe storms. These storms occur concurrently with magnetic storms and probably are caused by abnormal particle radiation from the sun.

K.—Absorption index relating the sun's angle at various latitudes and local times with the ionospheric absorption.

K_a.—The auroral absorption relating the average auroral absorption with the geographic location of the ionospheric reflection points.

K1.—The absorption index for the daylight end of a day-night path.

Km.—The absorption index for an entirely daylight path at the path midpoint.

$\overline{K}d$.—The absorption index for a route longer than 4,000 kilometers.

Kilocycle.—1,000 cycles per second.

Latitude.—The angular distance north or south from the earth's Equator.

Limiter.—The part of a frequency modulated receiver that limits all variations in carrier amplitude and, thus, removes noise present in the carrier as amplitude modulation.

Linearly polarized waves.—A transverse electromagnetic wave in which the electric and magnetic intensities have a constant direction.

Line of sight.—Distance to the horizon from an elevated point including the effects of atmospheric refraction. The line of sight distance for an antenna at zero height is zero distance.

Line of travel.—The path followed by an electromagnetic wave from one point to another.

Local time.—Time referred to the longitude of the observer. The hours begin at local midnight and continue through 24 hours of the day.

Longitude.—The angular distance east or west from the Greenwich meridian (zero degrees longitude).

Low angle radiation.—Radiation at low angles above the ground plane.

Lowest effective power (LEP).—The minimum product of the antenna input power in kilowatts and the antenna gain required for satisfactory communication over a particular radio route.

Lowest useful high frequency (LUF).—The lower limiting frequency for satisfactory sky-wave communication for a radio circuit at a particular time. The LUF is determined by the strength of the sky-wave signal in relation to that required

to overcome noise. The sky-wave field intensity is equal to the required field intensity at the LUF.

Magnetic storm.—Disturbance in the earth's magnetic field occurring concurrently with ionospheric storms. These probably are due to intense particle radiation from the sun.

Martyn's theorem.—Relationship between the equivalent path of a radio wave at oblique incidence to that of an equivalent path at vertical incidence.

Maximum usable frequency (MUF).—The highest sky-wave frequency that is usable for a particular radio circuit as a monthly median at some particular time.

Median.—The central tendency of a group of data as to position. The central value of a group of data when arranged according to magnitude.

Medium frequency band.—Frequencies ranging from 0.3 to 3 megacycles per second.

Minimum required field intensity.—The lowest value that the incident signal strength can be for satisfactory communication. This is determined by the noise level at the receiver.

Mode.—A particular ray path between the transmitter and the receiver. The one-hop E layer mode is a sky-wave line of travel from the transmitter to E layer and back to the receiving location with only one ionospheric reflection.

Modified effective power.—An equivalent transmitting antenna power used in this manual for lowest useful high-frequency problems for long-distance circuits. The modified effective power is equal to the transmitting antenna effective power (the sum of the transmitting antenna power and gain), receiving discrimination gain, and the type of service gain (with the sign reversed) when all quantities are expressed in decibels.

Modulation.—The process of superimposing intelligence upon a high-frequency radio wave.

Molecule.—The smallest known particle of any compound or element which retains its chemical and physical properties.

Noise.—Interference whose energy is distributed over a wide band of frequencies.

Noise figure.—A term used to rate the noise qualities of radio receivers. It is equal to the ratio between the signal-to-noise for an ideal receiver and an actual receiver.

Noise grade.—A number which defines the relative noise at a location with respect to other geographical positions throughout the world.

Nomogram.—Graphical presentation of a mathematical equation or relationship between experimental data. A required term of the equation can be determined by the use of index lines between known variables to find an unknown quantity.

Nondeviative absorption.—Absorption that occurs without any appreciable slowing up of waves. It is the normal sky-wave absorption.

Normal distribution.—The most common frequency distribution in statistics. Most errors in experimental sciences follow this distribution. The probability curve is bell-shaped with the greatest probability occurring at the arithmetic average. The areas between two abscissa values under the normal curve show the probability of occurrence of a particular value.

Oblique incidence.—Transmission of a wave obliquely up to the ionosphere and down again.

Omnidirectional antenna.—An isotropic radiator or antenna which radiates uniformly in all directions. Such an antenna cannot exist but is used commonly as the reference antenna upon which antenna gain values are based.

Optimum traffic frequency (FOT).—A frequency value 15 percent below the maximum usable frequency for F2 layer transmission. It is equal to the MUF in case of E layer transmission. Sky-wave circuits are preferred to operate at the FOT value to insure continuous operation, insuring against the day-to-day variations in maximum usable frequencies.

Optimum working frequency (OWF).—A frequency value 15 percent below the maximum usable frequency for a radio circuit. Sky-wave circuits are preferred to operate at the OWF values to insure against day-to-day variation in maximum usable frequency.

Penetration frequency.—The lowest frequency that a F2 layer transmission mode can have to penetrate the lower E layer. It is the E layer MUF corresponding to the radiation angle for the F2 layer transmission mode.

Phase modulation.—In phase modulation, the phase of the audio modulating signal is varied in accordance to the superimposed intelligence. Unlike amplitude modulation, in both phase modulation and frequency modulation, the average

energies of the modulated and unmodulated signals are the same.

Phase velocity.—The velocity at which a point of a certain phase travels in the direction of propagation. It is the velocity at which a wave crest travels.

Photon.—An amount of radiant energy equal to the quantum. It occupies a small volume and moves as a whole in one direction with the velocity of light.

Photosphere.—The visible solar disk.

Plane earth.—Earth that is considered to be a plane surface as used in ground-wave calculations.

Plane polarized wave.—A wave in which the electric and magnetic intensities are in a plane at right angles to the direction of propagation.

Plane wave.—An electromagnetic wave in which the wave front is a plane surface.

Poor ground.—Ground having a dielectric constant of 5 and a conductivity of 10^{-3} in MKS units.

Precipitation static.—Type of interference experienced in a receiver during snowstorms, rainstorms, and dust storms. Often caused by the impact of dust particles against the antenna, or the existence of induction fields created by nearby corona discharges.

Primary skip zone.—The area around a transmitter beyond the ground-wave range but within the skip distance. Radio reception is possible in this zone only by sporadic, scattered, and zig-zag reflections.

Pulse modulation.—Pulse modulation is one in which the energy is grouped into certain chosen intervals or pulses and is absent from other intervals. The modulation in the signal is carried by a change in the location, amplitude, number, and duration, or shape, of the pulses in response to the intelligence being transmitted.

Radiation resistance.—An arbitrary term used to express the power radiated by an antenna. It is the amount of resistance which, if inserted for the antenna, would consume the same amount of power that actually is radiated by the antenna.

Radio fade out.—A cessation or near cessation of sky-wave radio propagation through parts of the earth affected by sudden ionospheric disturbances.

Radio frequency.—Frequency in which radio transmission is useful for communication purposes. The useful range is from approximately 10 kilocycles to 30,000 megacycles.

Radio interference.—An undesired disturbance in reception, or that which causes the undesired disturbances. The interference may be caused by a disturbance in the transmitter, transmission medium, and the receiver.

Radio wave propagation.—The transfer of energy by electromagnetic radiation at radio frequencies.

Random noise.—Noise due to an aggregate of a large number of disturbances with random noise occurrences in time.

Ray path.—A straight geometric path between the transmitting and receiving location.

Rayleigh distribution.—The frequency distribution for an infinitely large number of quantities of the same magnitude but of arbitrary random phase relationships. Sky-wave field intensities follow the Rayleigh distribution from minute to minute or smaller time intervals.

Reciprocity theorem.—The reciprocal relationship for an antenna when it is transmitting or receiving. The effective heights, radiation resistance, and the radiation pattern are alike, whether it is transmitting or receiving.

Recombination coefficient.—In an ionized gas, it is the ratio of the time of recombination of ions divided by the product of the positive ion density and the negative ion density.

Reflected wave.—The wave reflected back into the first median when an incident wave strikes a boundary between the media.

Refracted wave.—The wave that travels in the second medium which is caused by a wave in the first medium incident to the surface separating the media. A radio wave traveling through a medium in which the refractive index continually is changing is caused to follow a curved path in the medium such as a radio wave follows in the ionosphere.

Reversing layer of sun's atmosphere.—A thin layer above the photosphere. It absorbs energy of certain frequencies emitted by the photosphere making lines (which otherwise would appear bright) dark in spectrographs.

Right Ascension.—The celestial longitude measured eastward in hours from the point where the earth's orbit crosses the celestial Equator (Vernal Equinox).

Root mean square (*rms*).—The root mean square

or effective value for a sine wave is 0.707 times the maximum value.

Scattered reflections.—Reflections composed for various components of different virtual reflection heights which cause interference and fading.

Sea water.—Sea water has a conductivity of 5 and a dielectric constant of 80 in MKS units.

Seasonal factor.—Factors used to adjust sky-wave absorption for seasonal variations. These variations are due primarily to fluctuations in the ionospheric layer heights with the sun's locations.

Selective interference.—Interference whose energy is concentrated in narrow frequency bands.

Set noise.—The inherent random noise in a receiver. It consists of fluctuation noises due to thermal currents in resistors and variations in emission currents of vacuum tubes.

Short wave.—Refers to radio frequencies above the commercial broadcasting band used for sky-wave communication. Range is from 1.5 to 30 megacycles.

Sid.—(See *Sudden ionospheric disturbances.*)

Side band.—Frequencies above and below the carrier frequency produced as a result of modulation.

Signal-to-noise ratio.—A measure of the signal to the noise in the same units.

Skip distance.—Minimum distance at which radio waves of a specified frequency can be transmitted at a specified time between two points on the earth by reflection from the regular ionized layers of the ionosphere. Reflected waves are received at smaller distances only by scattered or zig-zag reflections.

Sky wave.—A radio wave that reaches the receiving location after reflection from the ionosphere.

Snell's law.—Law relating the angle of incidence reflection, and refraction for a wave in a medium that is incident upon the surface separating that medium from another.

Spectrum.—A spectrum is a frequency band generally showing discrete frequency values.

Spherical wave.—A wave whose wave front is a spherical surface.

Sporadic E.—Ionization that appears at E layer heights. This ionization is more noticeable toward the polar regions and may be due to particle radiation from the sun. It occurs at all hours of the day.

Sporadic reflections.—Sharply defined reflections of substantial intensity from the sporadic E layer at frequencies greater than the critical frequency of the layer. They are variable with respect to time of occurrence, geographic location, and range of frequencies at which they are observed.

Static.—All forms of radio noise.

Subsolar.—The point on the earth's surface directly beneath the position of the sun.

Sudden ionospheric disturbance, or *SID.*—Sudden decrease in the ion intensity in the lower parts of the ionosphere caused by bright solar eruptions. These cause a sudden increase in the absorption of radio waves propagated throughout the lower parts of the ionosphere. The change usually takes place within a few minutes and generally returns to normal within a few hours.

Sunspot.—Dark spots on the sun's surface, the larger of which are visible to the naked eye when viewing the sun through a dark glass. Sunspots appear to be areas of solar activity.

Sunspot cycle.—Sunspot activity follows a cycle with an average of 11.1 years between successive minima. The usual cycle shows the variation of the 12-month running average sunspot number plotted against the months.

Sunspot number.—It is an index of solar activity and is expressed as being equal to a constant multiplied by the sum of 10 times the number of sunspot groups and the number of individual spots. The constant depends on the individual observer and his telescope.

Super high-frequency band.—Radio frequencies in the range from 3,000 megacycles to 30,000 megacycles per second.

Thermal noise.—Noise voltage generated in resistors due to minute currents caused by thermal motions of the conduction electrons.

Transconductance.—The relationship between the plate current and the grid voltage in a multielement vacuum tube. Rate of change of plate current with respect to the rate of change of grid voltage (plate voltage is fixed at a constant value).

Transmission curve.—A relationship between the secant of an angle of incidence at the ionosphere and the virtual layer height.

Transmission line.—A conductor or series of conductors used to carry electrical energy from a source to a load.

Transverse wave.—A wave in which the electric and magnetic intensities are transverse to the direction of propagation.

Traveling wave.—A wave that travels in one direction.

Troposphere.—That part of the earth's atmosphere in which the temperature generally decreases with altitude. Occupies the space from the earth's surface to a height of about 10 kilometers.

Tropospheric wave.—Radio wave that is propagated by reflection from a place of a rapid change in dielectric constant in the troposphere.

Type of service gain.—The relative signal strengths required for satisfactory communication for various types of modulation and intended usages.

Ultra high-frequency band.—The frequency range from 300 to 3,000 megacycles per second.

Ultraviolet.—Electromagnetic radiation at frequencies higher than the visible light. Has wavelengths of less than 4,000 angstroms (1 $A^{\circ} = 10^{-10}$ meters).

Vertical incident transmission.—Transmission vertically to the ionosphere and back. Vertical incident measurements generally are made to find characteristics of the ionosphere. These are converted into oblique incidence values by using transmission curves.

Vertically polarized wave.—An electromagnetic wave whose electric vector is in the vertical plane.

Very high frequencies.—Frequencies in the band from 30 to 300 megacycles.

Virtual height.—The height of the equivalent reflection point that will cause a radio wave to travel to the ionosphere and back in the same time required for an actual reflection. In determining the virtual height, the radio wave is assumed to travel at uniform speed and the height is determined by the time required to go to the ionosphere and back at the assumed velocity of light.

Wave.—A disturbance propagated through a medium. The graphical representation of a wave or a periodic variation.

Wave guide.—A system of material boundaries capable of guiding waves.

Wave length.—The distance in meters traveled by a wave during the time interval covered by a cycle. It is equal to the velocity divided by the frequency.

Wave normal.—The direction normal to the wave front in the direction of propagation.

Zeeman effect.—The splitting of spectral lines due to a magnetic field in the radiation source.

Zig-zag Reflections.—High-order multiple reflections which may be of abnormal intensity. They occur in waves which return to the starting point after multiple ionospheric reflections.

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